CMI

CARBON MITIGATION INITIATIVE

2015

ANNUAL REPORT

Science

Technology

Integration & Outreach

2015 ANNUAL REPORT CARBON MITIGATION INITIATIVE

PRINCETON UNIVERSITY

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Carbon Mitigation Initiative

Annual Report 2015

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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. The goal of the initiative is to lead the way to a compelling and sustainable solution to the carbon and climate change problem. 2015 concludes the first 15 years of the CMI program and marks the transition to the second renewal that will carry the program forward through 2020.

Interaction between Princeton and BP this year has been more extensive than in previous years. At BP's request, Princeton researchers spent several days in conversations with senior BP leaders, first in London in May and then in Houston in September. The two-day CMI annual meeting in Princeton attracted more BP participation than in any prior year. There were numerous teleconferences.

This thread of high-level and close interaction continues into 2016 as preparations are underway for Princeton to host the CMI annual meeting at BP's headquarters in London—the first time in CMI's 16-year history that the meeting has not been in Princeton. Holding the annual meeting in London creates opportunities for deeper involvement of BP with Princeton's program and suggests an increased determination on BP's part to pay attention to climate change.

The hallmark of CMI's research is connectivity across science, technology, and policy to offer an integrated assessment of Earth system 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 discussions.

The CMI program currently includes approximately 14 lead faculty and more than 50 research staff and students at Princeton. In 2015, 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 (CO_2) 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 (GFDL) of the US 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 CO_2 capture and storage. Capture studies include both biological and fossil fuel inputs. Storage studies emphasize leakage pathways and now also investigate storage in shales. A program on advanced batteries has begun.

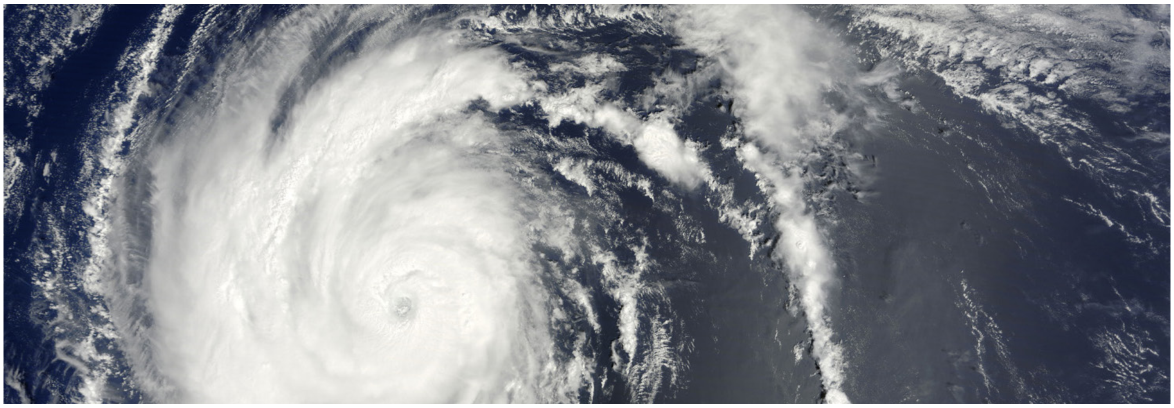
CMI Integration and Outreach introduces new conceptual frameworks that are useful for climate change policy. One effort seeks to make the emerging statistical analyses of extreme events more accessible. A second effort focuses on improving the risk-assessment framework for the current scientific understanding 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, vehicle, or addition to infrastructure is placed into service.

In this report, each of the PIs or teams of PIs has chosen to feature one research highlight from 2015 and has provided context for the work. These highlights are supplemented by a complete list of the year’s publications.

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

The Carbon Mitigation Initiative (CMI) held its 14th annual meeting at Princeton University on April 14 and 15, 2015. More than 100 participants gathered to discuss CMI’s most recent initiatives in the areas of science, technology, and integration and outreach. Attendees included Princeton faculty and students and colleagues from BP, the Geophysical Fluid Dynamics Laboratory (GFDL), the US Department of Energy (DOE), 9 national and international universities, and several environmental non-profit organizations and policy think-tanks. (Photo by Frank Wojciechowski)

CMI Science



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Research Highlights – At a Glance

Stephen Pacala: Tropical forests represent a key terrestrial carbon sink, yet their levels of carbon storage have been challenging to estimate due to the multi-layered structure of tropical forest tree communities. The Pacala group has used data from Panama's Barrow Colorado Island Rainforest to develop a model for investigating carbon storage in tropical forests with improved accuracy. Another challenge is understanding methane emissions from oil and gas infrastructure, due to the ephemeral nature of high-emitting sources. The Pacala group has created a new method for estimating methane emissions that combines systematic and biased sampling data with meteorological factors.

Jorge Sarmiento: Biological and geological processes occurring in the Southern Ocean around Antarctica have important impacts on global carbon and climate cycles. Recent modeling results show that the Southern Ocean acts as a key sink for atmospheric CO_2, thus mitigating global temperature increases caused by rising levels of CO_2. To examine the dynamics of these processes across space and time, Jorge Sarmiento is directing the world's first large-scale deployment of robotic floats equipped with biogeochemical measurement instruments. The project will enable unprecedented observations of pH, biological productivity, carbon cycling, and phytoplankton dynamics in the Southern Ocean.

Michael Bender: Studies of ice cores from Greenland show that the Greenland ice sheet has persisted for at least 1 million years. This result puts limits on the sensitivity of the Greenland ice sheet to climate change, and provides a test for models of the ice sheet.

François Morel: Increasing concentrations of atmospheric CO_2 lead to higher concentrations of dissolved CO_2 in surface seawater. This results in ocean acidification, which may affect the growth of the photosynthetic phytoplankton that form the basis of marine food webs. The Morel group has conducted both field and laboratory experiments to examine the effects of acidification on phytoplankton productivity. The results will enable future assessments and predictions of how CO_2 concentration changes impact marine ecosystems.

Stephen Pacala and Elena Shevliakova: Beyond assessing effects of greenhouse gas emissions on trends in global temperature increases, research efforts led by Pacala and Shevliakova have advanced analysis of extreme precipitation from observations and climate model simulations, as well as improved representation of processes that affect climate extremes on regional scales, such as urbanization and dust emissions.

Modeling Tropical Forest Carbon Storage and Estimating Methane Emissions

Principal Investigator: Stephen Pacala

At a Glance

Tropical forests represent a key terrestrial carbon sink, yet their levels of carbon storage have been challenging to estimate due to the multi-layered structure of tropical forest tree communities. The Pacala group has used data from Panama's Barrow Colorado Island Rainforest to develop a model for investigating carbon storage in tropical forests with improved accuracy. Another challenge is understanding methane emissions from oil and gas infrastructure, due to the ephemeral nature of high-emitting sources. The Pacala group has created a new method for estimating methane emissions that combines systematic and biased sampling data with meteorological factors.

Research Highlight

Modeling Tropical Forest Carbon Storage

The terrestrial carbon sink is thought to be dominated by tropical forests. Tropical forests store roughly twice as much carbon in living trees as temperate forests per unit area. About half of this disparity stems from the rapid year-round growth of tropical trees, which creates a few extremely large individuals.

The other half is caused by a spectacular difference that temperate zone dwellers notice immediately when first walking into a tropical forest: if one drops a weighted line from a helicopter through the canopy of a temperate forest, the weight will, on average, pass through the crown of one canopy tree, and sometimes (i.e. a quarter of the time), the crown of one sapling before hitting the ground. Old-growth temperate forests are often compared to cathedrals because of this property.

If one drops the same line through a tropical forest, it will pass through three or four tree crowns on average before hitting the ground. In other words, tropical forests have a canopy, a sub-canopy, a sub-sub-canopy, and finally, a layer of saplings with some space between their crowns. This material in the middle (the sub-canopy and sub-sub-canopy) is the main reason why tropical forests appear so full, chaotic, and claustrophobic to temperate dwellers. Again, the material in the middle is important to the global carbon cycle because it accounts for half the difference between the living carbon in tropical and temperate forests. Although our Earth System models can predict the existence of very large trees in the tropics, they have not been able to predict the material in the middle.

The most amazing thing about the plant growth in the middle is that it is highly organized in every moist tropical forest, despite its tangled appearance. If one plots the logarithm of tree diameter on the horizontal axis against the logarithm of tree abundance on the vertical axis, one sees that the material in the middle—all but the smallest and largest size classes—follows a tight inverse-square power law: a tree with twice the stem diameter has one-fourth the abundance. (Figure 1.1.1 shows the plot for the Barrow Colorado Island Rainforest in Panama). In contrast, size distributions for the temperate zone and for the driest tropical forests do not follow a power law.

The Pacala group has shown that the power law is a consequence of competition for light following large disturbances, many of which are created by thunderstorm microbursts. They developed a simple model that accurately predicts the data (see Figure 1.1.1) and showed with an extensive data analysis that the mechanism in the model is also operating in an extensively studied Panamanian rainforest. The mechanism in the model has already been added to the Geophysical Fluid Dynamics Laboratory/Princeton Earth System Model. Other modeling centers will also add to this mechanism to predict the fate of rainforest carbon. The publication reporting this model won the CMI Best Paper Award this year.[1]

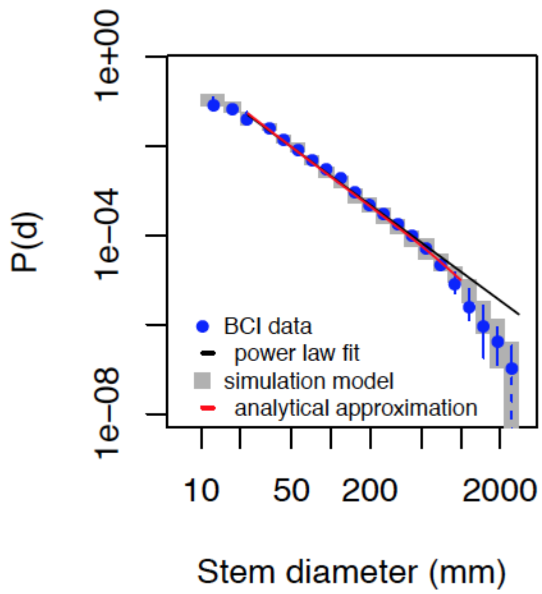

Figure 1.1.1. Size distribution of trees in a tropical forest. P(d) is the fraction of total stems with diameter d, blue bars indicate confidence limits, black line is an inverse-square ($y = x^{-2}$) power law, red line is from a simple analytically tractable model, and gray bars are predictions of a slightly more complex simulation model. Parameters in both models were estimated from Barrow Colorado Island (BCI) Rainforest data.

Estimating Methane Emissions

Other recent work from the Pacala group focuses on methane emissions from the Barnett Shale region in Texas. Attempts to measure fugitive emissions are bedeviled by the fact that most of the emitted methane at any one time is due to a few sources (2-5% of the sources). High-emitting sources are also ephemeral, and typically last for hours to days, so that the high-emissions sources jump around in space.

Previous studies have systematically sampled methane emissions to achieve an unbiased sample, but this procedure cannot provide a large enough sample of the rare high-emitters to characterize them with any accuracy. Moreover, a systematic sample has a counter-intuitively high probability of underestimating total emissions when total emissions are dominated by ephemeral and rare high emitters. A recent study claims that all previous emissions estimates, except one by the Pacala group, underestimate fugitive emissions by a factor of two for this reason.[2]

In its study of the Barnett region, the Pacala group supplemented a systematic sample of emissions from oil and gas infrastructure with a sample deliberately biased toward high emitters (to achieve a sufficient sample size of the large sources). When a source emits methane, the gas spreads horizontally and vertically as it drifts downwind, until its concentration falls beneath the detection limit of an instrument. This means that a source has a detectable plume length that grows with the size of the source and depends on meteorological conditions. By driving a grid of roads with a methane detector, one can detect and identify upwind sources. By inverting a meteorological model, one can also estimate the size of the emission of methane from a given source. But this method is biased toward high emitters because the long plumes of high-emitting sources are more likely to be detected than the short plumes of low emitters. This bias is large; it artificially elevated the mean emissions level in the Barnett campaign by a factor of 80.

Figure 1.1.2. Former CMI postdoctoral fellow Caroline Farrior was presented with the 2016 CMI Best Paper Award by Gardiner Hill, Director of Carbon Solutions, during a ceremony this past February. Farrior, who worked in Stephen Pacala's lab, was selected for her paper "Dominance of the suppressed: Power-law size structure in tropical forests" in recognition of the important finding that commonalities among tropical forests in their structure are due to simple and biologically intuitive mechanisms. The paper was published in the journal *Science* in early 2016.

To overcome this bias, the Pacala group developed a statistical method that correctly knits together systematic samples and biased samples obtained by searching a grid of roads. For the first time, this method successfully matched bottom-up estimates from on-the-ground samples with top-down estimates from aircraft, which greatly increased confidence in both types of estimates. This new method solved a long-standing problem, and has now greatly streamlined methane emissions estimates for other regions.

Other Work

In 2015, the Pacala group also produced a prototype of the terrestrial sink for a new Geophysical Fluid Dynamics Laboratory (GFDL)/Princeton carbon cycle model[3] and addressed the interaction of the hydrological and carbon cycles, focusing on drought kill.[4]

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Science

Update on the Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) Project

Principal Investigator: Jorge Sarmiento

At a Glance

Biological and geological processes occurring in the Southern Ocean around Antarctica have important impacts on global carbon and climate cycles. Recent modeling results show that the Southern Ocean acts as a key sink for atmospheric carbon dioxide (CO_2), thus mitigating global temperature increases caused by rising levels of CO_2. To examine the dynamics of these processes across space and time, Jorge Sarmiento is directing the world's first large-scale deployment of robotic floats equipped with biogeochemical measurement instruments. The project will enable unprecedented observations of pH, biological productivity, carbon cycling, and phytoplankton dynamics in the Southern Ocean.

Research Highlight

Launched in September 2014, the National Science Foundation-funded Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) project, directed by CMI member Jorge Sarmiento, is the world's first large-scale deployment of biogeochemical (BGC) Argo floats. Aiming to dramatically increase biogeochemical observations in the harsh and remote ocean around Antarctica, SOCCOM scientists have augmented conventional robotic Argo floats, which measure ocean temperature and salinity, with newly developed biogeochemical sensors to measure pH, nitrate, and oxygen. The project will allow unprecedented year-round monitoring of ocean pH, biological productivity, carbon cycling, and phytoplankton bloom dynamics in the Southern Ocean (for example, see Figure 1.2).

Currently more than 30 SOCCOM BGC floats are operating and by June, the end of the second float deployment season, 52 floats will be reporting from the Southern Ocean—more than a quarter of the way to the goal of 200 floats within six years. Data from the floats are made available to the public in real time on the SOCCOM website (http://soccom.princeton.edu), and will soon also be incorporated into the global Argo data system to provide easy access to researchers around the world.

Analysis of two years of data shows that the ice-capable floats successfully survive Antarctic winters beneath the ice and re-emerge to transmit data via satellite back to SOCCOM scientists on shore. The new biogeochemical sensors are also performing well—shipboard observations made when each SOCCOM float is deployed are used to calibrate the biogeochemical sensors, and have shown that the sensors' measurements are consistent with shipboard data. Newly developed methods for evaluating float measurements after deployment (including air calibration for oxygen, and an alkalinity algorithm for assessing nitrate and pH sensor performance over time), suggest that the sensors will likely be stable in the long term and that the floats may eventually be suitable for deployment without calibration by other research vessels and cargo ships, as is the case with conventional Argo floats.

In addition to actively participating in the SOCCOM project, the Sarmiento group continues to carry out model simulations of Southern Ocean biogeochemistry with support from CMI. This research provided the primary motivation for the SOCCOM project by illustrating the importance of the Southern Ocean to the planet's carbon and climate cycles, and modeling results continue to inform observational efforts.

New research initiated this year has focused on using high-resolution climate models to separate carbon cycle trends due to climate change from those due to natural climate variability, and to determine "times of emergence" of these signals. This work highlights the role of natural variability in enhancing or suppressing carbon cycle trends that observational programs like SOCCOM aim to quantify, and is helping to inform strategies for detecting changes in the ocean carbon sink.

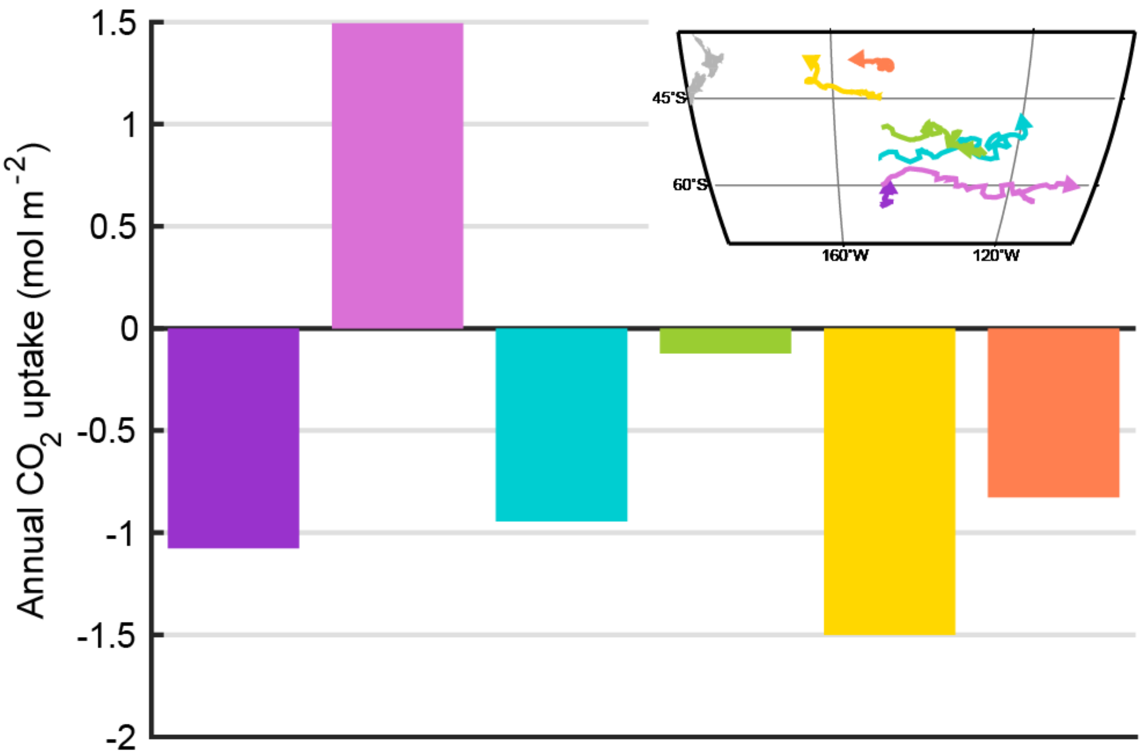

Figure 1.2. Annual net CO_2 flux estimated from data collected by SOCCOM floats deployed in the Southern Ocean in April 2014. Negative fluxes indicate CO_2 uptake by the ocean. Inset map shows trajectories of floats after two years; gray land area at upper left is New Zealand. Fluxes were calculated using float-measured pH, estimated alkalinity, ERA-Interim 6-hourly winds, and Wanninkhof gas exchange coefficient.[1]

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Science

The Greenland Ice Sheet, a Million-Year Record of Climate Change and Sea Level Rise

Principal Investigator: Michael Bender

At a Glance

Studies of ice cores from Greenland show that the Greenland ice sheet has persisted for at least 1 million years. This result puts limits on the sensitivity of the Greenland ice sheet to climate change, and provides a test for models of the ice sheet.

Research Highlight

In 2015, the Bender group completed a study of properties of the Greenland ice sheet during the last interglacial period (about 120,000–130,000 years ago) and earlier times. The ultimate motivation is to understand how much Greenland ice will melt, and thus cause sea level to rise, due to global warming.

The study included ice from the last interglacial period preserved in the GISP2 ice core drilled through the center of the Greenland ice sheet around 1995. This core contains a continuous climate record extending back to about 105,000 years ago. Below this continuous archive, there are about 200 meters of clean glacial ice with an intact climate record, but out of stratigraphic order due to the flow of the glacier. Some of this ice formed at temperatures (inferred from the isotopic composition of the ice) as least as warm as today, and is understood to have originated during the last interglacial period.

The Bender group dated all such samples by measuring the concentration of methane and the isotopic composition of oxygen in fossil air trapped in the ice. Antarctic ice core records extend back 800,000 years, and reveal how these two properties have changed with time, allowing researchers to date each ice sample. Plotting climate properties against time allowed reconstruction of the climate record at the center of Greenland during the last interglacial period.

This work shows that temperature at the summit of Greenland, in the center of the landmass, rose to its present value (-31˚C mean annual temperature) about 127,000 years ago, and continued rising until the temperature was about 5˚C warmer than during the current interglacial period. Temperatures began to fall around 120,000 years ago.

According to a related modeling study, this warming would have melted about half of the Greenland ice sheet, and meltwater flowing into the oceans would have raised sea level by about 4 meters. This rise would have occurred toward the end of the warmest period in our record, around 120,000 years ago, and such a sea level maximum has been observed in ancient beaches at several locations around the world.

At the very bottom of two other Greenland ice cores, there is about 5 meters of ice that was deposited under warm temperatures at some unknown time in the past. We have developed a method to date this ice based on the isotopic composition of argon in the fossil air. This property has continuously changed with time at a known constant rate. Argon dating of ice from the Dome C core, from Southern Greenland, shows that ice was present in this region during the last interglacial period. In other words, the melting of Greenland did not progress to the point where the vulnerable southern region was deglaciated.

In an ice core taken from the summit, in central Greenland, ice at the base of the core dates to at least 1 million years of age. This great antiquity is further evidence that Greenland was not completely deglaciated during the last interglacial period, during a previous, longer interglacial period around 400,000 years ago, or during the shifts in climate patterns (for example, to somewhat higher carbon dioxide (CO_2) concentrations and less cold glacial periods) observed between 800,000 and 1 million years ago.

This work shows that, with the level of warming possible in the coming centuries, melting of the Greenland ice sheet may contribute several meters to sea level rise over several thousand years. The results also present a target for ice sheet and climate models that can be tested against these observations. The evidence is encouraging, in that it demonstrates that no climate change over the past million years was sufficient to melt the ice sheet entirely.

Figure 1.3. On July 12, 1992, Sigfus Johnsen of the University of Copenhagen triumphantly holds up the deepest section of the GRIP core, at 3,029 meters depth, drilled through the ice at the summit of the Greenland ice sheet. The brown color is due to dirt in the ice. The dirt originates from soil, lake water, bogs, and mud, and dates roughly to the time when the ice sheet formed. For 20 years, the age of this ice remained unknown for lack of an accurate dating method. Michael Bender recently invented a method based on the isotopic composition of argon in trapped air, applied it to this 24-year-old ice archived in freezers in Copenhagen, and found that this ice is at least 1 million years old.

Effects of Ocean Acidification on Marine Phytoplankton

Principal Investigator: François Morel

At a Glance

Increasing concentrations of atmospheric carbon dioxide (CO_2) lead to higher concentrations of dissolved CO_2 in surface seawater. This results in ocean acidification, which may affect the growth of the photosynthetic phytoplankton that form the basis of marine food webs. The Morel group has conducted both field and laboratory experiments to examine the effects of acidification on phytoplankton productivity. The results will enable future assessments and predictions of how CO_2 concentration changes impact marine ecosystems.

Research Highlight

About one-third of human-generated CO_2 emissions into the Earth's atmosphere dissolve in surface seawater, increasing the CO_2 concentration and decreasing the pH of the seawater. The resulting ocean acidification leads to a host of interrelated chemical and biological consequences. Among the documented biological effects of seawater acidification are changes in the growth of some species of phytoplankton, the photosynthetic organisms that form the primary production base of marine food webs.

In several instances, increased phytoplankton growth rates have been observed at high CO_2 concentration, but other experiments have shown no effect or a negative effect. These variable results make it difficult to generalize and to predict how oceanic primary production may respond to ocean acidification. Over the past several years, with support from the Carbon Mitigation Initiative and the National Science Foundation, the Morel group has been carrying out laboratory and field experiments aimed at elucidating the physiological responses of marine phytoplankton to increasing CO_2/decreasing pH. The results will enable assessment, and eventually prediction, of future changes in phytoplankton ecology and ocean productivity.

The inconsistent results reported for the effect of ocean acidification on phytoplankton may result from opposite, and partly compensating, effects of increasing CO_2 and decreasing pH on the rates of photosynthesis and respiration by the organisms. The Morel group explored these possibilities by independently varying the CO_2 concentration and the pH in cultures of a model diatom species (see Figure 1.4), and simultaneously quantifying the organisms' rates of photosynthesis and respiration using oxygen isotopes.

The results have demonstrated that many organisms maintain constant photosynthesis and respiration rates over a range of pH and CO_2 conditions that encompass predicted CO_2 changes over the next century and beyond. This remarkable outcome results from the ability of the organisms to maintain efficiently, and with very low energy expenditures, a constant intracellular CO_2 concentration for photosynthesis (via their "carbon concentrating mechanism") and a constant internal pH, despite variations in the external seawater. Species for which maintaining their internal chemistry is either less efficient or more costly will be comparatively more affected by ocean acidification, leading to a shift in species assemblages. These changes have been observed in the few field experiments conducted to date.

High Latitudes

Because high latitudes are inordinately subject to global change (rapid warming and large decreases in pH) the Morel group extended these studies to psychrophilic (i.e., cold-adapted) phytoplankton species. These organisms support some of the most productive regions of the oceans and, because of a short food chain, some of the most efficient and spectacular ecosystems on Earth: from phytoplankton to krill to seals and whales. This work included both field experiments at Palmer Station in the West Antarctic Peninsula and complementary laboratory experiments with model phytoplankton species.

The experiments revealed some fascinating biochemical adaptations that allow certain cold-adapted phytoplankton to grow rapidly at very low ambient temperatures. These include very high cellular concentrations of key proteins (such as Rubisco, the enzyme responsible for the fixation of CO_2 during photosynthesis) that cannot be adapted to turn over rapidly when temperatures are near freezing. However, increasing CO_2 did not have a significant effect on growth rates, despite a clear downregulation of the organisms' carbon concentrating mechanism. This result reflects the very low amount of energy required to maintain a high intracellular CO_2 concentration, even under very low temperature conditions.

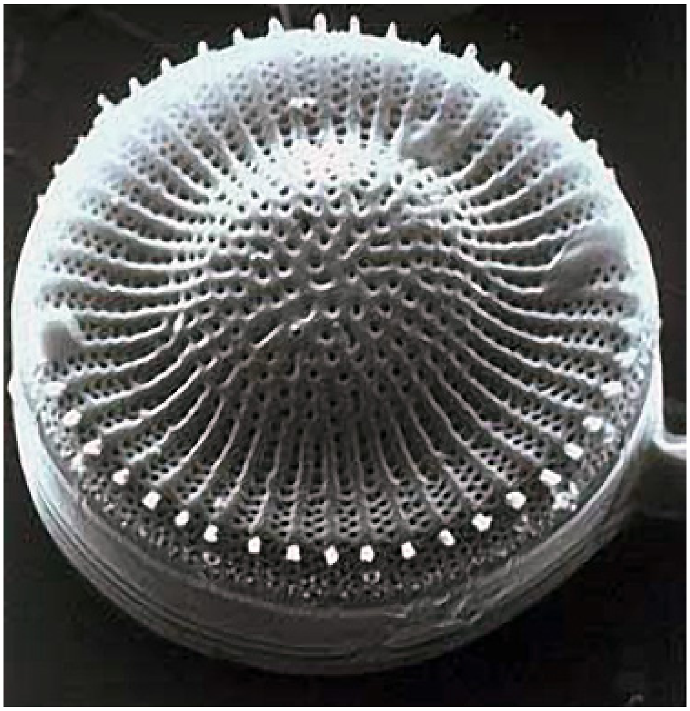

Figure 1.4. Scanning electron micrograph of *Thalassiosira weissflogii,* a coastal marine diatom. The diameter is approximately 10 micrometers—about one-tenth the width of a typical human hair or the thickness of a typical sheet of paper. This diatom, which is typical of species that are responsible for a large fraction of photosynthetic production in large regions of the temperate oceans, was used to study the physiological responses of marine phytoplankton to increasing CO_2/decreasing pH in the laboratory.

Trace Metals

A poorly studied but potentially important consequence of the CO_2-induced acidification of the surface ocean is a change in the bioavailability of trace metals, which play a critical role in the productivity and population dynamics of marine ecosystems. The Morel group conducted laboratory and field experiments designed to quantify the effects of acidification on the bioavailability of iron and zinc, two metals that are essential to the growth of phytoplankton.

In all laboratory and field experiments, acidification decreased the bioavailability of iron, a metal known to limit primary production in large regions of the oceans. This result is consistent with the predicted decrease in the labile concentration of iron under acidic conditions. In the case of zinc, both positive and negative effects on bioavailability were observed at low pH in the laboratory, depending on the mix of organic compounds present in the medium. This variability in response to acidification was also observed in the field and was consistent with changes in the chemical lability of zinc measured by electrochemistry.

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Climate Variability and Changes in Future Extremes

Principal Investigators: Stephen Pacala and Elena Shevliakova

At a Glance

Beyond assessing effects of greenhouse gas emissions on trends in global temperature increases, research efforts led by Pacala and Shevliakova have advanced analysis of extreme precipitation from observations and climate model simulations, as well as improved representation of processes that affect climate extremes on regional scales, such as urbanization and dust emissions.

Research Highlight

During the last few decades, the main focus of numerous climate studies has been on changes in the Earth's mean climate and how anthropogenic emissions of greenhouse gases will affect future climate projections. However, a growing body of research has acknowledged a need to understand past and future changes in climate variability and climate extremes.

In 2015, CMI postdoctoral fellow Monika Barcikowska, in collaboration with Geophysical Fluid Dynamics Laboratory (GFDL) scientists, refined statistical tools to analyze changes in extreme precipitation.[1] The new analysis identified two dominant patterns of multi-decadal scale internal climate variability over the North Atlantic. The study assessed the impact of these patterns on Mediterranean winter precipitation using long (1,000 to 4,000 years) GFDL CM2.1 and CM2.5 preindustrial simulations. The first pattern resembles the North Atlantic Oscillation, which could explain over 30% of decadal winter precipitation variability observed in the regions of Spain, Morocco, Italy and the Balkans. The second pattern has a longer period, which varies from approximately 55 to 62 years.

The joint Atmospheric and Ocean Sciences Program (AOS)-CMI postdoctoral fellow Dan Li has completed implementation and evaluation of the urban component in the GFDL Earth System Model (ESM) framework. This analysis involved historical (1850 to 2005) simulations with the GFDL urban tile, forced by the high-frequency ESM output, for historical and future climates. This enabled characterization of how, over given historical periods, the magnitude of urban heat island effect has interacted with climate variability and change in the continental United States.[2,3] A new set of additional simulations has explored implications of urbanization for current regional climate and climate variability using a novel stretch-grid (~10 km over North America, ~25 km over the rest of the world) implemented in the GFDL atmospheric general circulation model.

In a third project, CMI postdoctoral fellow Stuart Evans developed a capability to interactively simulate land dust emissions in the GFDL climate models.[4] Previously, land dust source emissions were prescribed based on 1990s observations and did not change throughout historical or future simulations. This study involved performing a set of 500-year simulations for preindustrial climate conditions with the new land dust emission configuration. Analysis of the new simulations with interactive dust emissions has shown that land surface is indeed important to accurately model dust variability and its implications for climate variability. By accounting for soil moisture and vegetation, the new runs produce inter-annual variability that closely matches satellite observations and recreate the relationships seen in observations between specific dust sources and major climate indices such as El Niño. The new capability is enabling a novel exploration of the interplay between enhanced incidences of dust and droughts in different regions of the world, particularly Australia (Figure 1.5) and Africa.

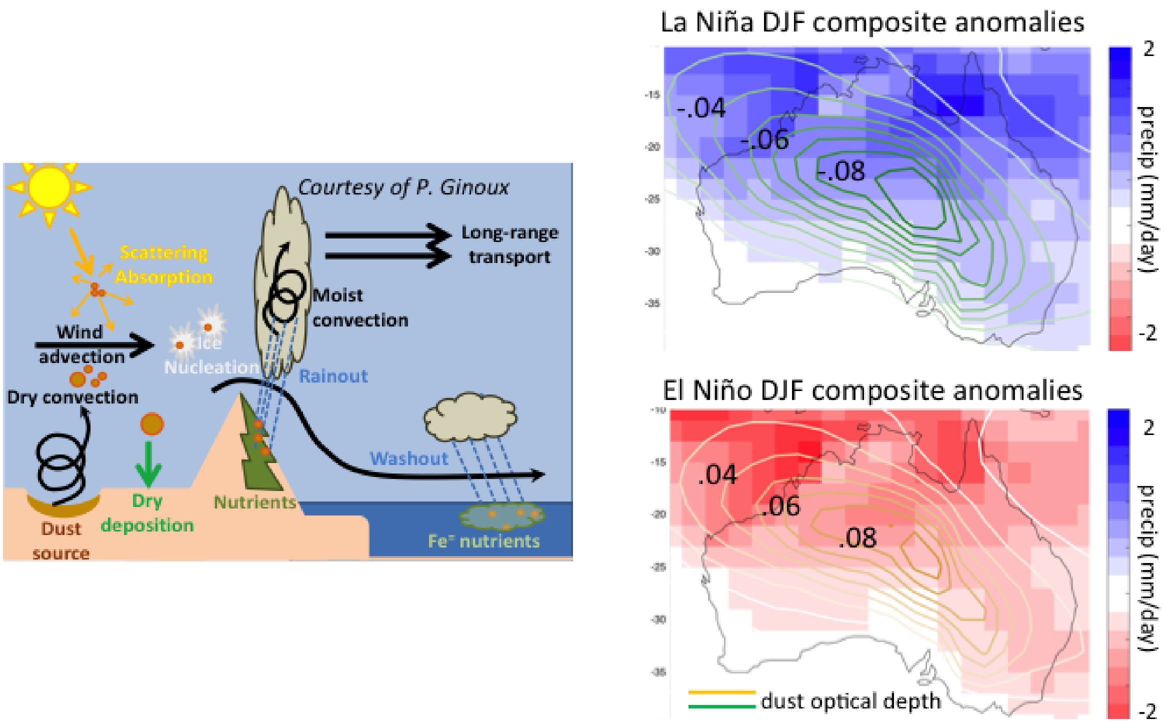

Figure 1.5. (Left) Schematic diagram of dust-ecosystem-climate interactions, showing how the "Dusty" CM3 model connects Australian dust emissions with the El Niño–Southern Oscillation (ENSO). (Right) DJF composite anomalies of Australia in La Niña and El Niño phases of ENSO, showing relationships between precipitation and dust optical depth. ENSO leads to precipitation anomalies, which in turn lead to dust anomalies. Contours of optical depth are superimposed on a color scale for deviation from mean precipitation.

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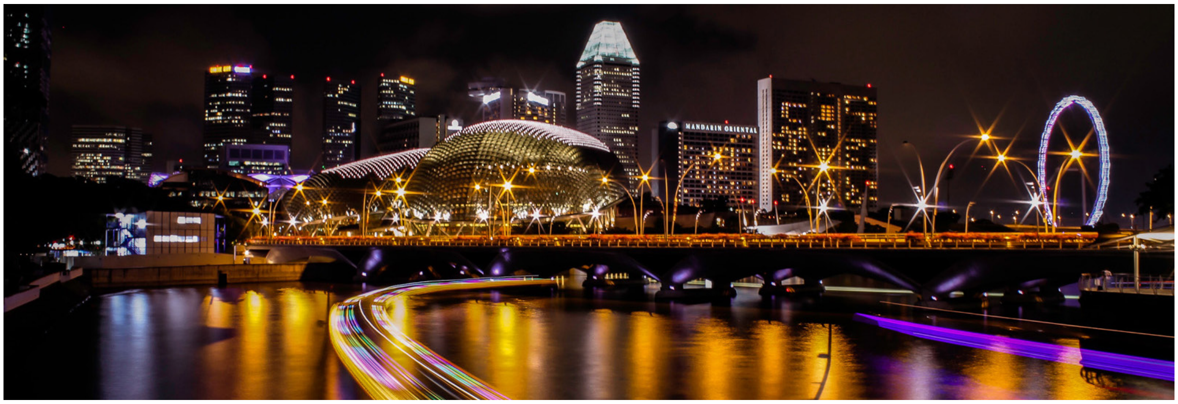
CMI Technology



CMI Technology studies energy conversion in conjunction with carbon dioxide (CO_2) capture and storage. Capture studies include both biological and fossil fuel inputs. Storage studies emphasize leakage pathways and now also investigate storage in shales. A program on advanced batteries has begun.

Research Highlights – At a Glance

Michael Celia: The capture and belowground storage of carbon dioxide (CO_2) emissions from power plants and other sources has the potential to mitigate climate change by preventing the release of these emissions into the atmosphere. The presence of abandoned oil and gas wells in areas that are otherwise suitable for geological storage may compromise storage integrity. Both CO_2 and brine may leak out from old wells, potentially contaminating groundwater supplies and possibly leading to CO_2 leakage into the atmosphere. The Celia group has combined modeling approaches with empirical data collection to estimate the risks of leakage along abandoned wells in the Wabamun Lake area of Alberta, Canada.

Howard Stone: Climate changes involve atmospheric motions, ocean flows, and evolution of ice on land and in the sea. These dynamics are necessarily interrelated; insights into individual processes can help to illuminate poorly understood aspects of global climate dynamics, such as factors affecting the maintenance of sea ice cover in the Arctic basin. Sea ice cover can impact fresh water fluxes, local ecology, and ocean circulation. The Stone group is providing simplified models for understanding the movement of ice through narrow straits, which can affect flow and mixing in the ocean.

Daniel Steingart: Building more energy-efficient systems depends on the ability to optimize and regulate the performance of energy-storing batteries. The Steingart group has developed a new type of zinc material that overcomes many of the limitations of zinc storage batteries. This material may be useful for long-term energy storage in grid-scale and electric vehicle applications.

Technology

Estimating Leakage of CO_2 and Brine Along Abandoned Oil and Gas Wells

Principal Investigator: Michael Celia

At a Glance

The capture and belowground storage of carbon dioxide (CO_2) emissions from power plants and other sources has the potential to mitigate climate change by preventing the release of these emissions into the atmosphere. The presence of abandoned oil and gas wells in areas that are otherwise suitable for geological storage may compromise storage integrity. Both CO_2 and brine may leak out from old wells, potentially contaminating groundwater supplies and possibly leading to CO_2 leakage into the atmosphere. The Celia group has combined modeling approaches with empirical data collection to estimate the risks of leakage along abandoned wells in the Wabamun Lake area of Alberta, Canada.

Research Highlight

CMI principal investigator Michael Celia was recently elected to the National Academy of Engineering, which is one of the highest professional honors for US engineers. Celia was recognized for his "contributions to the development of subsurface flow and transport models in groundwater remediation and CO_2 sequestration."

Early research by the Celia group led to the development of models to estimate leakage risk along old wells with a focus on CO_2 injection into deep saline aquifers.[1-12] These models predict the movement of both CO_2 and brine within the injection formation, leakage upward (or downward) of both fluids along old wells, and flows from leaky wells into other permeable formations along the vertical direction. While these models were applied to realistic field settings, such as the Alberta Basin in Canada,[13,14] the models were always limited by a lack of data on properties of potentially leaky (old) wells, specifically effective permeability.

More recent work facilitated the estimation of effective permeability values for the leakage of both CO_2 and brine along old wells. This work has included a program with BP and others as partners.[15] The program involved reentering old wells and performing vertical interference tests (VITs) outside of the wells' casings.[16-19] The tests produced estimates of the effective behind-casing permeability for the sampled well regions. Data from a separate, ongoing field measurement program focusing on methane emissions from old wells has also produced estimates of effective permeabilities along the entire length of a set of leaking old wells in Pennsylvania.[20]

Subsequently, the Celia group combined the original modeling with the new data sets to produce quantitative estimates of expected leakage rates for a specific potential injection site in the Alberta Basin. The site is in the Wabamun Lake area, and the injection formation is the Nisku Formation (see Figure 2.1). The collective data from the measurement programs were used to define overall statistics for well permeabilities, and those statistics were applied to the old wells in the Wabamun Lake area. The model includes 11 permeable formations along the vertical direction, with a total of

1,146 old (potentially leaky) wells in an area of 2,500 square kilometers (see Figure 2.1). The efficient computational models developed earlier by the Celia team enabled the researchers to run 1,000 simulations of the problem, assigning different well permeability values based on statistics from the measured data sets. The mean leakage rate for the fraction of injected CO_2 that reaches the shallow aquifers after 50 years of injection is less than 0.001%, and 95% of the results fall below 0.002%. The total amount of CO_2 that leaks out of the injection formation, independent of whether it reaches the shallow zone, also stays well below 0.1% after 50 years. Moreover, the amount of brine that leaks is consistently much lower than the amount of CO_2.

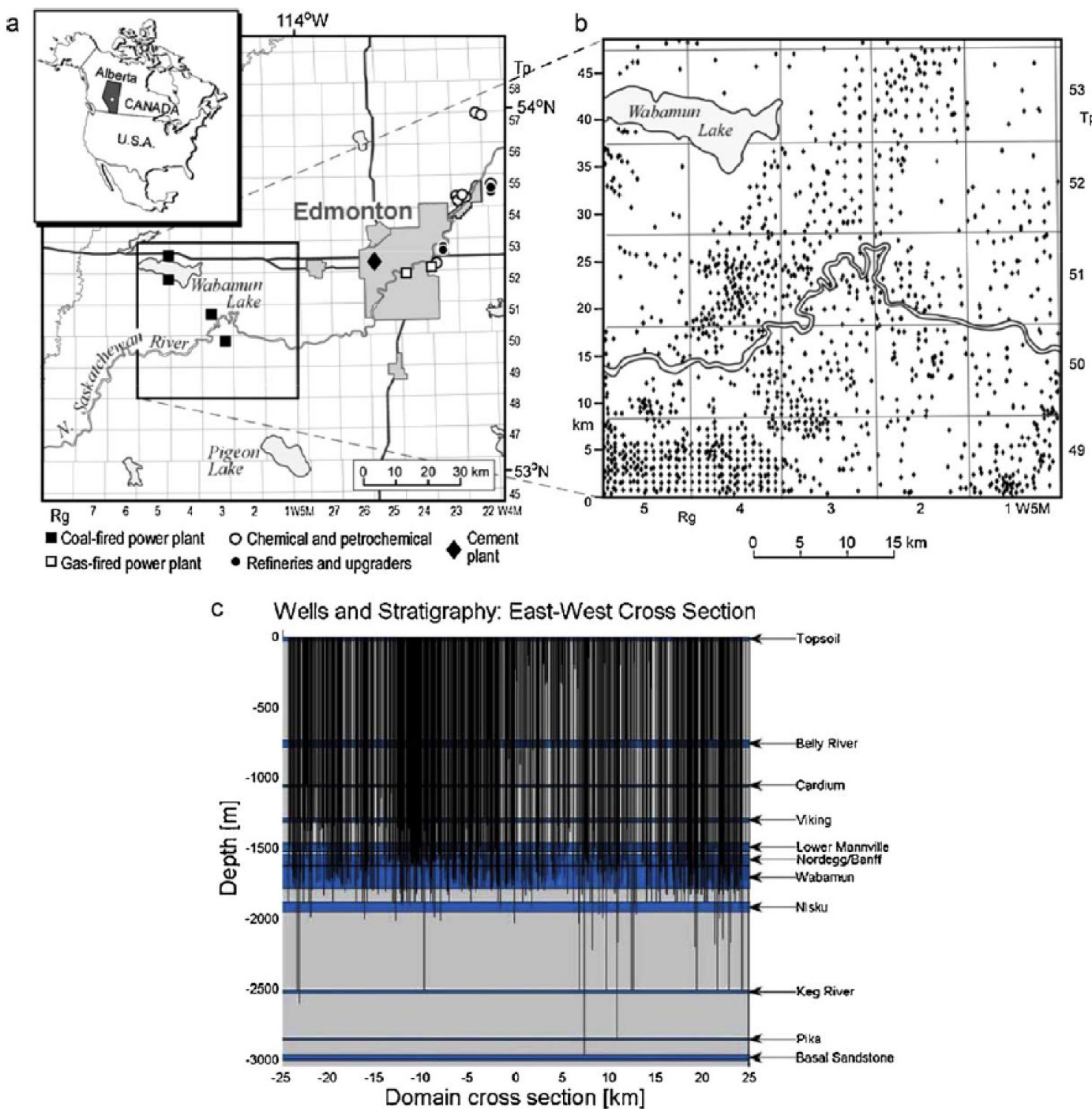


Figure 2.1. Maps showing (a) the location of the Wabamun Lake area, (b) the locations of existing wells within the 2,500-square-kilometer study area, and (c) the depth of each well, with permeable formations shown along the vertical direction.

Technology

All results to date indicate that leakage from the Nisku Formation should be expected to be very low, assuming the properties of the old wells in this area can be estimated from the statistics derived from different sets of well data (which do not involve wells from Alberta). The amount of brine that leaks into shallow aquifers is much lower than the amount of CO_2, indicating that shallow drinking water supplies should be safe from any significant leakage of CO_2 or displaced brine. While a broader analysis using these leakage models is ongoing, the overall conclusion is not expected to change.

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Modeling Ice Bridges to Refine Predictions of Ocean Dynamics

Principal Investigator: Howard A. Stone

At a Glance

Climate changes involve atmospheric motions, ocean flows, and evolution of ice on land and in the sea. These dynamics are necessarily interrelated; insights into individual processes can help to illuminate poorly understood aspects of global climate dynamics, such as factors affecting the maintenance of sea ice cover in the Arctic basin. Sea ice cover can impact fresh water fluxes, local ecology, and ocean circulation. The Stone group is providing simplified models for understanding the movement of ice through narrow straits, which can affect flow and mixing in the ocean.

Research Highlight

Ice bridges are stationary, rigid structures composed of sea ice, which are commonly formed in the many straits and channels throughout the Canadian Arctic Archipelago. Under certain conditions, the ice bridges are stable and span the width of the strait, connecting the two neighboring landmasses. These ice bridges appear seasonally and persist for several months, impacting both the local climate and ecology in two significant ways. First, since they are solid structures spanning the strait, they inhibit the flow of sea ice from colder regions into warmer waters. Second, by regulating the motion of ice, they affect the dynamics of flow and mixing in the ocean, thus influencing ocean salinity and regulating the transport of gases and nutrients that are crucial for ecological processes (e.g., the growth of photosynthetic plankton that form the base of marine food chains).

While ice bridges are regularly and predictably observed in the field, the precise mechanical conditions under which they form are not well understood. Improved models for predicting the dynamics of ice bridges would lead to a fuller picture of global changes in sea ice. Failure to form an ice bridge during a particular season can, for instance, result in an irrecoverable loss of sea ice through flow into warm oceans and subsequent melting. The Stone group seeks to provide simple predictors for the conditions required for the formation and maintenance of ice bridges and to study the physical mechanisms involved in the bridge formation process.

Although most studies of ice flows implement numerical models, the mechanics community has a long history of developing simplified models for studying flow in narrow geometries. The Stone group is drawing upon these techniques, developing a model that includes the role of mechanical stresses in response to wind, which is more central to ice bridge formation than other secondary processes such as the rotation of the Earth, or ice melting and freezing. This model will provide oceanographers and climate scientists with simple tools by which to understand the complex dynamics of sea ice, while speaking more broadly to the scientific community on problems of global importance. Preliminary work has focused on developing a theory to predict the flux of ice expected in situations without ice bridges, which agrees well both with field measurements and large-scale computational models. The theory also makes predictions for the critical ice thickness (defined to account for the wind stress, the compressive strength of the ice, and the channel width) beyond which the flow becomes entirely arrested, which is also consistent with numerical studies.

The Stone group's current efforts are focused on modeling the process by which the flow becomes arrested, eventually leading to the formation of an ice bridge. Such behavior also arises in other engineering and science problems, such as the flow of granular materials, including soil, in confined geometries, which suggests a broader scope for understanding other physical and geological processes.

In the future, the group aims to build an experimental laboratory model of ice flow. Ice bridge formation on the surface of the ocean may result from collisions between floating masses of ice as they flow through a strait. The experimental model would examine the flow of a large number of floating rigid objects (not necessarily ice) through a narrow channel as a representation of the geophysical system. The model will serve to validate the theoretical aspects of the work, as well as illuminate features of the complex mechanical behavior of ice at the geophysical scale. A long-term goal is to understand the eventual breakup of ice bridges using a model that incorporates processes such as ice melting and water flow.

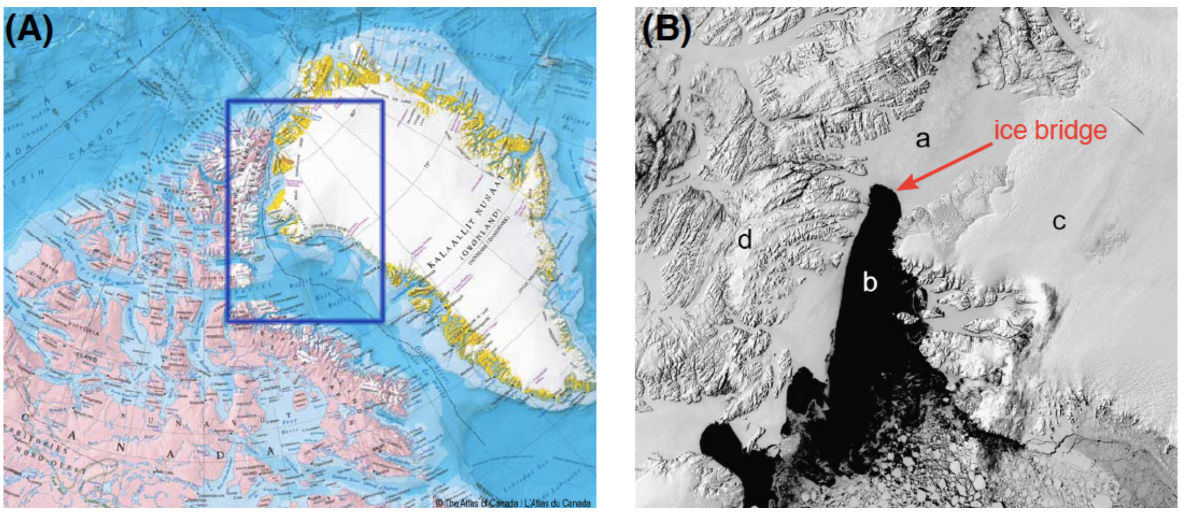

Figure 2.2. (A) Map showing the Nares Strait between northwestern Greenland and Ellesmere Island, Canada. The Nares Strait is a site for seasonal ice bridge formation. Source: Environment Canada, Government of Canada. (B) Satellite image indicating the location of a stable ice bridge in the Nares Strait, marking the boundary between (a) the ice sheet and (b) open water in the strait (data taken May 25, 2001). Greenland and Ellesmere Island are marked (c) and (d), respectively. Image adapted from: Dumont, D., Y. Gratton, and T. E. Arbetter, 2009. Modeling the dynamics of the North Water Polynya ice bridge. J. Phys. Oceanogr., 39: 1448–1461. http://dx.doi.org/10.1175/2008JPO3965.1.

Short Circuits for Better Batteries

Principal Investigator: Daniel Steingart

At a Glance

Building more energy-efficient systems depends on the ability to optimize and regulate the performance of energy-storing batteries. The Steingart group has developed a new type of zinc material that overcomes many of the limitations of zinc storage batteries. This material may be useful for long-term energy storage in grid-scale and electric vehicle applications.

Research Highlight

Zinc is a low-cost, abundant material, and its strong reducing potential combined with stability in water give it a high energy density. These properties have made zinc an excellent choice of anode material in a wide range of battery designs for more than 200 years. However, zinc also presents some challenges for use in a storage battery.

During charging, zinc undergoes morphological changes, and may produce dendrites—microscopic conductive fibers that can short-circuit a battery. Zinc also exhibits low utilization during discharge. Low utilization is related to a combination of corrosion and passivation effects: zinc oxide formed during standard operation and/or corrosion will block remaining reaction sites if not considered in the battery design.

To overcome these challenges, the Steingart group has created a hyper-dendritic zinc morphology with a high surface area that allows for rapid discharge in a free-standing system with no binding material or conductive additives, while still maintaining significantly higher utilization levels than typical zinc morphologies. At rates of 2.5 amperes per gram of material, the high-density zinc has a utilization level approximately 50% higher than typical zinc granules or dust. Tuning the electrolyte with specific additives further increases the utilization level of the material at high-rate discharge by up to 30%.

Zinc has many favorable characteristics for large-scale energy storage: high volumetric energy density, low cost, low toxicity, global abundance, and chemical compatibility with water-based electrolytes. Silver-zinc batteries have been successfully used as primary and secondary cells in a range of demanding applications, including those requiring large scale, high power and high energy density. These include critical military applications, such as guidance systems for torpedoes and missiles.

However, zinc electrodes present some significant challenges, and anode failure is a key factor in the reduced cycle life of these batteries. These challenges include morphology changes and dendrite growth during deposition, which can lead to problems such as the short circuit of a cell, and poor utilization efficiencies during the discharge step, which is a dissolution reaction, arising mainly from corrosion and passivation effects. As such, typical zinc utilization levels are limited to 60% or lower. Careful engineering and materials science can extend the cycle life of the electrode; however, these issues still present a major limitation for secondary batteries using a zinc electrode.

Over the last year the Steingart group has furthered engineering of a zinc morphology formed in a counterintuitive manner, generating zinc that produces dendrites "on purpose." The dendrites are about 30 nanometers long; at the length scales critical for batteries, they create reliable foams at the micron scale. Many properties of these foams are superior to those of standard zinc particles and plates—including energy utilization, power density, and cycle life. In the next year the Steingart group will further explore the fundamental basis for this improvement, and will work to build new types of batteries that take advantage of the hyper-dendritic zinc.

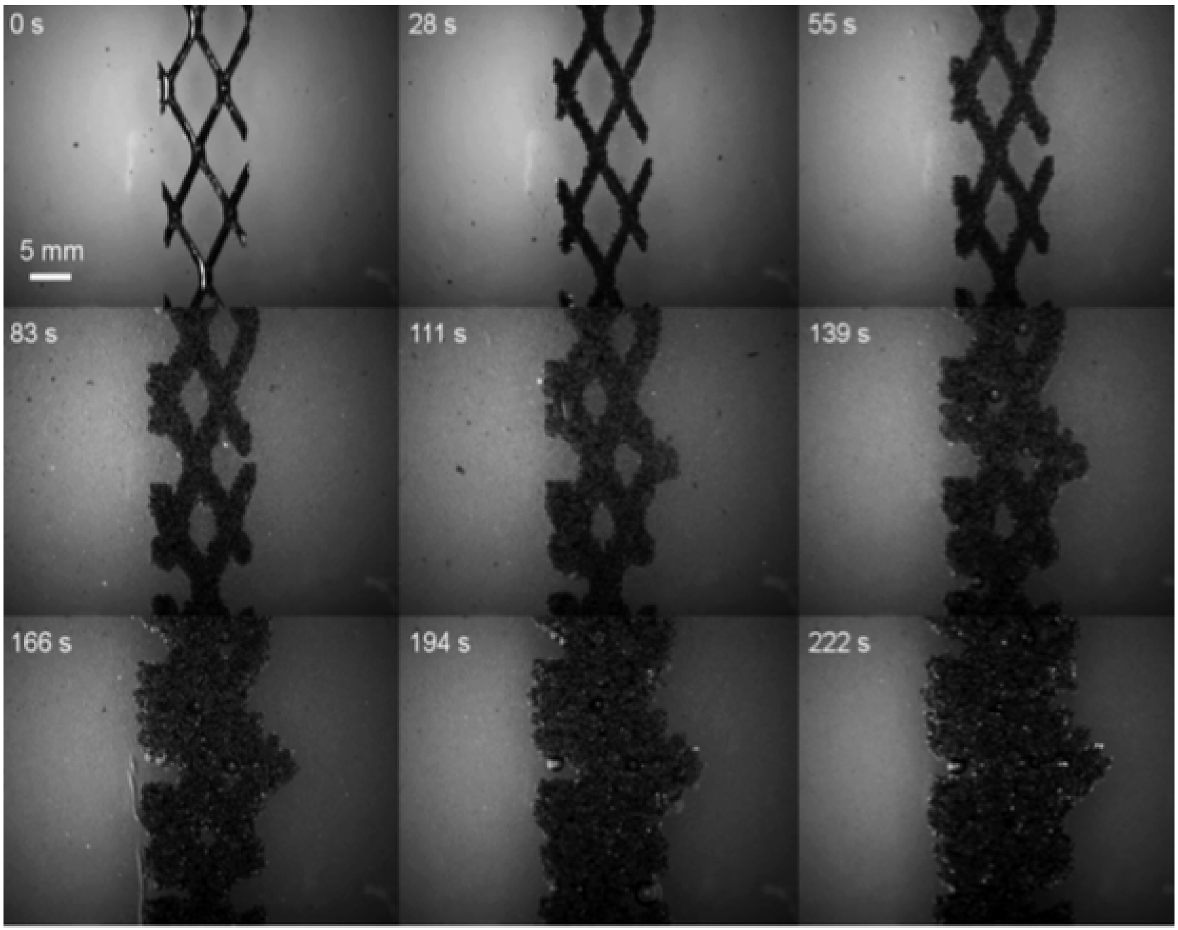

Figure 2.3.1. Formation of hyper-dendritic zinc over a period of four minutes. The zinc was formed at a potential of -2.0 V vs. an HgO reference electrode. Note that the sharp features shown at t=0 are "smoothed over" by t=222s. Time in seconds is indicated in the upper left corner of each image.

Such batteries can be operated and built in a variety ways. The way in which the battery is formed is counterintuitive, in that dendrites are grown, on purpose, so aggressively that the growth front becomes even and predictable at the micron scale even though it is rough at the nano scale. In previous work, the group also showed that short circuits in zinc batteries are not a safety concern, as the short-circuit product is simply zinc oxide. Because short circuits are no longer a concern, the battery may be designed to "short circuit" occasionally to regenerate.

If this design is successful, batteries will be able to hold more energy and last longer, with the compromise that the enhanced surface area my lead to more battery self-discharge due to corrosion, and that the structure is still dynamic and may have to be reformed occasionally. Some batteries utilizing hyper-dendritic zinc may be built for around $30 per kilowatt-hour. At such prices, the marginal cost of storage becomes reasonable for long-term (3- to 10-hour) power on a daily basis. Current batteries are designed such that round-trip efficiency is very high, but the cost is at least $150 per kilowatt-hour.

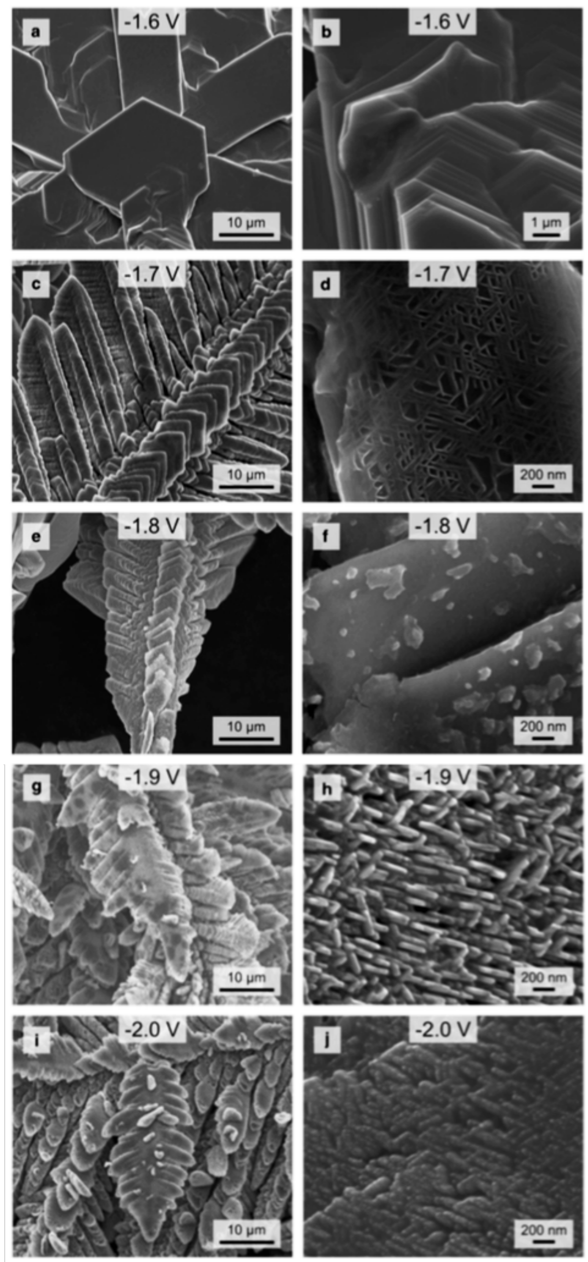

Figure 2.3.2. Scanning electron microscope images of electrodeposited dendritic zinc in alkaline solution at various voltages. Note that the characteristic size of the fundamental zinc hexagons decreases as a function of overpotential, so that the initial dendrites are on the order of 10 µm wide, but the final hexagons produced at -2.0V are on average 50 nm wide—200 times smaller.

Technology Publications

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Zheng, Z., S. Shin, and H.A. Stone, 2015. Converging gravity currents over a permeable substrate. J. Fluid Mech., 778: 669-690. http://dx.doi.org/10.1017/jfm.2015.406.

CMI Integration and Outreach

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, vehicle, or addition to infrastructure is placed into service.

Research Highlights – At a Glance

Robert Williams, Eric Larson, and Thomas Kreutz: Meeting current targets for reducing greenhouse gas emissions to mitigate climate change will require major changes in the makeup of the US electricity sector in the coming decades. A study by the Energy Systems Analysis group identifies incentives for carbon capture and storage (CCS) as a promising and economically viable approach to meeting emissions reduction goals. The study includes a thought experiment that analyzes how the contributions of different CCS technologies, along with shifts to renewable energy sources, could enable the US to achieve an 83% reduction in greenhouse gas emissions from power generation by 2050.

Michael Oppenheimer: To achieve incremental, near-term greenhouse gas emissions reductions, both governmental and private stakeholders can be encouraged to form partnerships driven by diverse political and economic incentives. These initiatives may take a variety of forms, and may serve to enhance the emissions reductions promised by existing international agreements.

Robert Socolow: A new academic field, Destiny Studies, should be created to foster coherent thinking about future time and the planetary vulnerabilities that will constrain what we are able to do. Today, when we make decisions that affect future generations, we are inconsistent and not guided by general principles. Notably, we are confused about future time—for example, we have difficulty distinguishing 500-year and 50-year time frames. Climate change and its solutions make particularly stringent demands on thinking about the future and are ripe for Destiny Studies.

Toward a Low-Carbon Future for US Electricity

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

At a Glance

Meeting current targets for reducing greenhouse gas emissions to mitigate climate change will require major changes in the makeup of the US electricity sector in the coming decades. A study by the Energy Systems Analysis group identifies incentives for carbon capture and storage (CCS) as a promising and economically viable approach to meeting emissions reduction goals. The study includes a thought experiment that analyzes how the contributions of different CCS technologies, along with shifts to renewable energy sources, could enable the US to achieve an 83% reduction in greenhouse gas emissions from power generation by 2050.

Research Highlight

One ongoing activity launched in 2015 by the Energy Systems Analysis Group involves exploring strategies for getting the carbon capture part of the faltering global carbon capture and storage (CCS) enterprise back on track, and the potential role of CCS in a low-carbon future for US electricity.[1] The CCS focus stems from the prospect that without CCS, achieving a low-carbon global energy future is likely to be much more costly and perhaps impossible,[2] and the growing popular belief that CCS is too costly to become a major carbon-mitigation option.[3]

CCS progress has been slow partly because first-of-a-kind project costs have been higher than expected. Many projects were canceled because government incentives were inadequate to enable them to go forward. In the US, the shale gas revolution has stymied CCS market launch. But CCS costs are likely to be reduced through experience (learning by doing). Incentives are needed to realize cost reductions, and are economically justified[4] if there are good prospects for cost reduction through technology cost buydown.

The proposed CCS initiative involves expanded federal research, development, and demonstration on advanced carbon dioxide (CO_2) capture concepts, the phased introduction of a greenhouse gas emissions price sufficient to ensure that all fossil-fuel based power plants built after 2030 will have CCS, and—the centerpiece—a national Low Carbon Electricity Portfolio Standard (LCEPS). The initiative is a variant of the successful worldwide approach for advancing renewables via technology-push (support for research, development, and demonstration) and market-pull (feed-in tariffs, tax credits, and renewable portfolio standards). Cost reductions and growth have been especially dramatic recently for photovoltaic technology.[5]

The LCEPS would mandate low-carbon electricity as a growing fraction of electricity from 2021 to 2050. Wind, solar, hydro, nuclear, and CCS technology providers would compete to provide this low-carbon electricity. The Standard would also offer technology cost buydown incentives for options offering good prospects for cost reductions via learning by doing.

Current nuclear technologies would not qualify for early technology cost buydown incentives because historically nuclear technologies have had negative learning rates,[6] but advanced concepts with good prospects for cost-cutting (e.g., factory-manufactured modular reactors) might qualify later. For wind and solar, which have good prospects for continuing cost reduction,[7] incentives might be continued as current tax credits. Incentives for promising CO_2 capture options would be determined by a market mechanism such as a reverse auction.[8]

The extent to which CCS costs can be reduced via experience is not known, because there has been no significant CCS experience. However, commercial experience with related technologies suggests that cost reductions through experience are plausible, especially if government requires, as a condition for receiving subsidies, information-sharing on cost-reduction opportunities among successive projects. Moreover, the study shows that for the approach chosen for carrying out technology cost buydown, with captured CO_2 sold for enhanced oil recovery, the US government can afford to find out, by supporting a few projects, the actual learning rates for promising CO_2 capture technologies. This is because, if the technology cost buydown process takes place when crude oil prices are $75 per barrel or higher,[9] the gross new federal corporate income tax revenues from subsidized projects (arising from new domestic production of liquid fuels displacing imported oil) would typically be greater than required subsidies—an outcome first recognized by the National Enhanced Oil Recovery Initiative.[10]

The study found that, of the five near-term CCS options considered, two offer good prospects for becoming competitive after 2030 as new power plants if earlier demonstration and technology cost buydown activities are successful: NGCC-CCS, a natural gas combined cycle; and CBTLE-CCS, a system coproducing synthetic liquid fuels and electricity (30% of output) from coal and biomass with enough biomass (34%) to realize zero net greenhouse gas emissions,[11] based on earlier research.[12]

The study explored, via a thought experiment, whether these CCS technologies, plus wind and solar, might provide the basis for a plausible low-carbon future for US electricity. The thought experiment was constructed to realize an 83% reduction in greenhouse gas emissions for US power generation by 2050.[13] Key assumptions include:

1. Existing coal-generating capacity is retired from 2031 to 2050 at a constant rate of 13 GWe per year, leading to retirement of all coal plants by 2050.

2. Concomitant CBTLE-CCS and NGCC-CCS deployment, such that coal input capacity remains constant at the 2030 level and enough NGCC-CCS capacity is deployed to match electricity generation at the rate for retired coal plants.

3. The remaining power not met in 2050 by nuclear, hydro, or geothermal power is provided by a mix of NGCC and intermittent renewables (wind and solar), assuming that three-quarters of total NGCC power is in plants with CCS—which implies widespread adoption of CCS retrofits. The implicit deployment rates[14] are sufficiently modest that they are plausibly feasible with the assumed policy incentives.

Under these assumptions, the US electricity generation mix in 2050 (see Figure 3.1) includes NGCC (37%), CBTLE-CCS (23%), wind and solar (16%), nuclear (16%), conventional hydro (6%), and geothermal power (2%)—a diversified electricity supply portfolio,[15] for which 69% is baseload electricity—slightly less than the 72% average for baseload power from 1998 to 2014. Although the CBTLE-CCS power share in 2050 is less than coal's 39% share in 2014, CBTLE-CCS also provides

5.2 million barrels per day of zero-emissions transportation fuels in 2050, so that coal use via CBTLE-CCS in 2050 is slightly more than coal use for power in 2005. Moreover, CBTLE-CCS is a promising way whereby reduced oil import dependence[16] and carbon mitigation goals might be pursued simultaneously.

The 2.5 gigatons per year of CO_2 storage rate for the US in 2050 implies the necessity of a partnership between the power industry and the oil and gas industries that would manage CO_2 storage. The 625 million tons per year of biomass then required can plausibly be provided by agricultural and forest residues not currently being used[17] and by growing biomass on abandoned cropland[18] (thereby avoiding food/fuel conflicts). The biomass required is modest because: (a) CBTLE-CCS requires only about 40% as much biomass energy per gigajoule of liquid transportation fuel output as a conventional cellulosic biofuel such as cellulosic ethanol, and (b) attractive CBTLE-CCS economics based on costly marginal biomass supplies can be realized under a strong carbon mitigation policy.[19]

The proposed CO_2 capture or similar public policy initiative is needed to facilitate realization of the envisioned or similar 2050 outcome, because historically major energy system transformations have required 80 to 130 years[20]—far longer than the time during which climate scientists say evolution to a low-emissions energy future must take place to keep major climate change damages to tolerable levels.

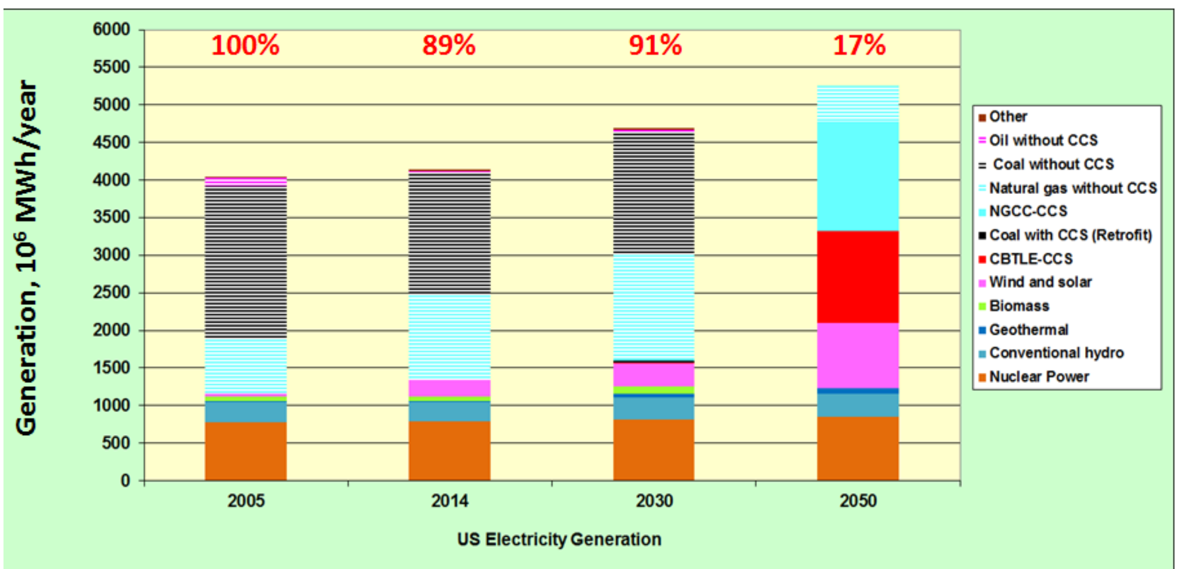

Figure 3.1. Thought experiment for US electricity to 2050. Numbers at bar tops are greenhouse gas emissions relative to 2005. The thought experiment is constructed as a variant of the Reference Scenario for 2040 of Annual Energy Outlook 2015.[21] The 2005 and 2014 bars represent historical data. The 2030 bar represents the Reference Scenario projection adjusted to allow for early deployment of 22 capture plants storing CO_2 via enhanced oil recovery during the technology cost buydown process. The 2050 bar represents the thought experiment as described in the text. The following are additional assumptions for the thought experiment:

- Total generation and generation by each of nuclear, hydro, and geothermal supplies in 2050 are extrapolations of 2040 values from the Reference Scenario, assuming average Reference Scenario growth rates for 2035 to 2040.
- Biomass use for power generation in 2050 other than via CBTLE-CCS is zero.
- Oil use for power generation in 2050 is zero.

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[5] Unsubsidized photovoltaic module costs fell twelve-fold from 2000 to 2014. Falling costs have led to rapid deployment. In the US, photovoltaic generating capacity additions from 2011 to 2014 totaled 16.3 GWe, 1.4 times the capacity added for the natural gas combined cycle, the fossil fuel technology of choice for new US power in this period.

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[8] Phillips, B., 2010. Using Reverse Auctions in a Carbon Capture and Sequestration (CCS) Deployment Program. Boston: Clean Air Task Force.

[9] Plausibly the total cost of producing an additional barrel of US crude oil post-2025 with growing developing world oil demand.

[10] National Enhanced Oil Recovery Initiative, 2012. Carbon Dioxide Enhanced Oil Recovery: A Critical Domestic Energy, Economic, and Environmental Opportunity.

[11] CBTLE-CCS would also be characterized by ultra-low emissions of SO2, NOx, PM2.5, and Hg.

[12] Liu, G., E.D. Larson, R.H. Williams, T.G. Kreutz, and X. Guo, 2011. Making Fischer-Tropsch fuels and electricity from coal and biomass: performance and cost analysis. Energy and Fuels, 25(1): 415-437. doi:10.1021/ef101184e.

[13] Consistent with the Administration's goal of reducing overall greenhouse gas emissions for the US energy economy by 83% by 2050.

[14] 7.8 GWe/year and 2.0 GWe/year for CBTLE-CCS and NGCC-CCS, respectively.

[15] Power companies and their regulators often worry about electricity supply diversity loss that would arise if the power system were to become "overly dependent" on natural gas.

[16] For comparison, US net oil imports were 5.1 million barrels per day in 2014.

[17] US Department of Energy, 2011. US Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry. R.D. Perlack and B.J. Stokes (Leads), ORNL/TM-2011/224. Oak Ridge, TN: Oak Ridge National Laboratory.

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Fostering New Collaborations to Curb Climate Change

Principal Investigator: Michael Oppenheimer

At a Glance

To achieve incremental, near-term greenhouse gas emissions reductions, both governmental and private stakeholders can be encouraged to form partnerships driven by diverse political and economic incentives. These initiatives may take a variety of forms, and may serve to enhance the emissions reductions promised by existing international agreements.

Research Highlight

Since its initial adoption in 1992, the United Nations Framework Convention on Climate Change (UNFCCC) has made progress in strengthening the commitments of national governments to reduce greenhouse gas emissions, with a notable agreement on Nationally Determined Contributions reached in late 2015. While these pledges are significant, they are not legally binding and are unlikely to be sufficient to meet the goal of a peak and subsequent decline in global emissions in the near future.

To complement the efforts of the UNFCCC, Oppenheimer and his colleagues have proposed a framework involving a variety of initiatives that engage both public and private actors, taking advantage of stakeholders' diverse motivations, which are not necessarily directly related to mitigating climate change. This "building blocks" approach holds the potential to spur emissions reductions in an incremental, low-risk fashion. The researchers suggest that the UNFCCC may play a key role in encouraging, developing, and improving such initiatives.[1]

Oppenheimer, together with New York University environmental law specialists Richard Stewart and Bryce Rudyk, has evaluated alternative paradigms for building strategies to leverage diverse motivations for emissions reductions. These include:

1. Clubs of private or public entities whose members agree to follow a set of rules. Members may have different incentives for following the rules. One example of such a club is the International Smart Grid Action Network, an association of 24 national governments and the European Commission that collaborates on the development and adoption of clean energy technologies. In the private sector, another potential model is that of the Forest Stewardship Council, a group of businesses and environmental NGOs that has established a certification system to set industry standards and respond to consumer demand for sustainable products.

2. Linkages that extend the missions of existing international agreements and organizations. The Montreal Protocol on Substances that Deplete the Ozone Layer, for instance, has been adjusted six times since it was adopted in 1987. As further information becomes available, new ozone-depleting chemicals have been added to the Protocol, and the group is considering the addition of substitutes for these chemicals that are also greenhouse gases. Oppenheimer, Stewart, and Rudyk suggest that the Association of Southeast Asian Nations might expand its Agreement on Transboundary Haze Pollution, which obligates countries to limit pollution from land and forest fires, to include provisions aimed at reducing greenhouse gas emissions.

3. Dominant actors that take measures prompting others to follow similar rules. The impacts of this model are evident from the so-called "California effect," which has encouraged other jurisdictions to adopt more stringent motor vehicle emissions laws, and the "Brussels effect," in which European Union consumer product regulations have led to stricter standards in the global marketplace.

Stimulating the spread and impact of such strategies will require increased and sustained support for enterprising individuals within the relevant institutions. Oppenheimer and his colleagues suggest that the UNFCCC may serve as a key champion for spurring and developing effective partnerships.

They conclude that the UNFCCC has the potential to provide vital information, organize stakeholders, contribute technical and financial resources, and raise the visibility of emerging efforts. These activities may be coordinated through the UNFCCC's Technical Expert Meetings and other events held in conjunction with each Conference of the Parties, while the UNFCCC's Non-State Actor Zone for Climate Action (NAZCA) may serve as a clearinghouse to monitor emissions reductions resulting from cooperative programs.

Figure 3.2. Display of flags at the 2015 United Nations Climate Change Conference (COP 21) in Paris. (Wikimedia, Surfnico)

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Destiny Studies: Creating Our Near and Far Futures

Principal Investigator: Robert Socolow

At a Glance

A new academic field, Destiny Studies, should be created to foster coherent thinking about future time and the planetary vulnerabilities that will constrain what we are able to do. Today, when we make decisions that affect future generations, we are inconsistent and not guided by general principles. Notably, we are confused about future time—for example, we have difficulty distinguishing 500-year and 50-year time frames. Climate change and its solutions make particularly stringent demands on thinking about the future and are ripe for Destiny Studies.

Research Highlight

Many of us spend a lot of time thinking about the future well beyond our lifetimes. Yet when we make decisions that affect future generations, we are inconsistent and not guided by general principles. Notably, we are confused about future time. We find it hard to separate the far future (say 500 years from now) from 50 years from now. Five hundred years ahead, we have almost no idea what people will be like, but we are pretty sure that people's needs and capabilities in 50 years will resemble ours. A new academic field could help us think coherently about future time and the planetary vulnerabilities that will constrain what we are able to do. This discipline might be called Destiny Studies.

Sea level rise is a particularly dramatic example of the challenge of coping with future time. Sea level rose 120 meters to its current level as Earth emerged from the last ice age, and it then was uncharacteristically constant over the past 5,000 years. Now sea level rise is resuming. A complete melting of the Greenland ice sheet would yield seven meters of sea level rise, and a similar rise is at stake from the West Antarctic Ice Sheet.

For the sake of argument, suppose we knew that ahead there would be one meter of sea level rise per century, continuing for many centuries. The impact of one, two, four, and eight meters of sea level rise on Florida and the Gulf Coast is seen in Figure 3.3.1. For such a future, the corresponding dates would be 2100, 2200, 2400, and 2800, respectively. Destiny Studies asks: How much do we care, and should we care, about a southern Florida that is underwater in the year 2500? Does it matter that our descendants 500 years from now might be far more or far less prepared to deal with sea level rise—or much like us? Does it matter that we cannot know how they will perceive their obligations to generations that are in *their* future?

Long-term storage of waste is another subject in need of Destiny Studies. In a quest for ethically responsible nuclear waste disposal, policymakers soon after World War II sought to establish an operative time frame. They drew on the half-lives of isotopes—notably, the half-life of plutonium 239, which is 24,100 years. The standards that emerged, in essence, invoke a human being living close to a disposal site 24,100 years from now, farming and eating and drinking much as today, who is to be protected from getting cancer from leaking radiation. There are very few other domains where present actions are circumscribed by obligations of such durability. With hindsight, hubris was at work. For every proposed disposal site, a red team seems always able to come up with leakage mechanisms that the blue team can't reject, when the time frame for near-perfect storage is many millennia.

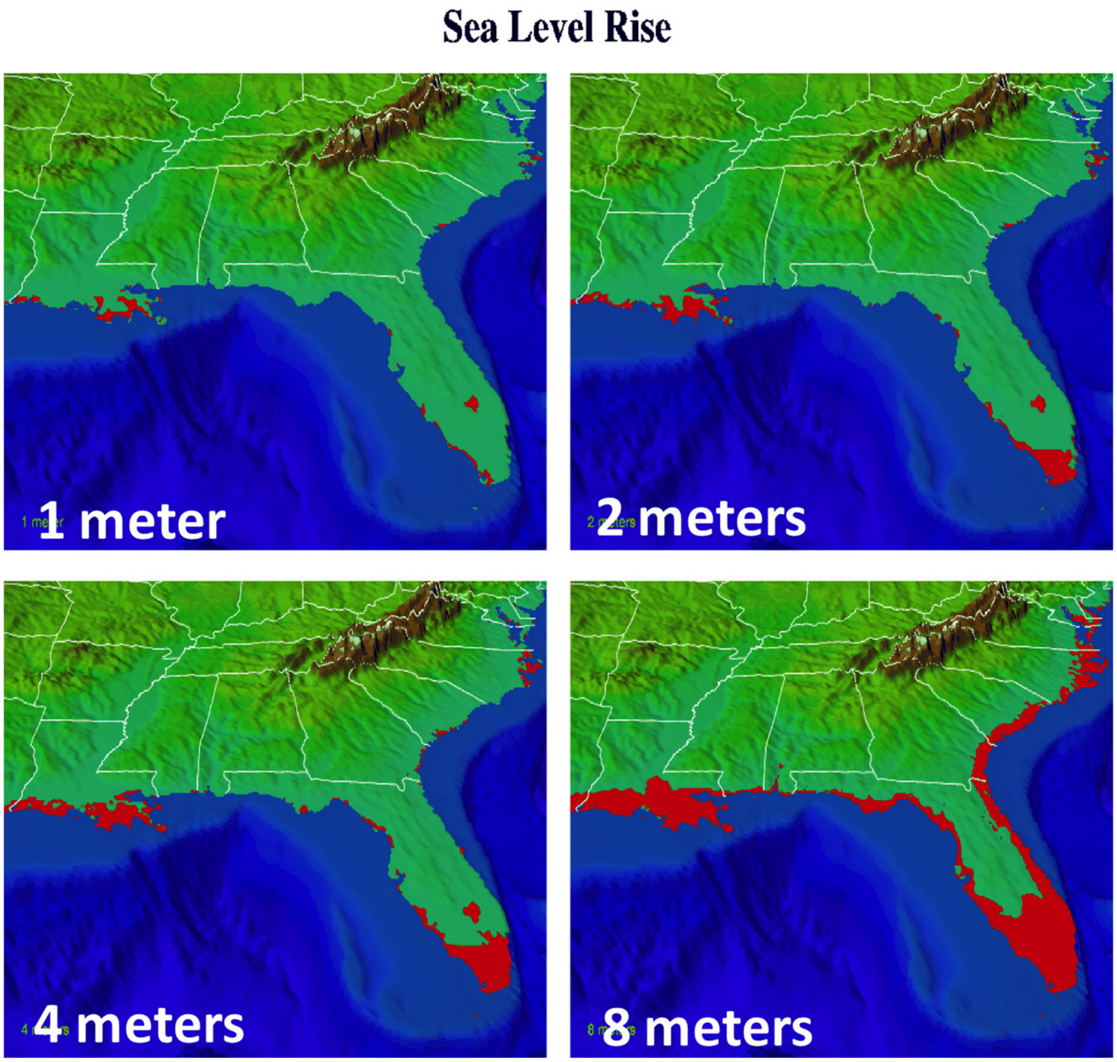

Figure 3.3.1. Changes in the southeast US coastline with sea level rise. Source: T. Knutson, Geophysical Fluid Dynamics Laboratory, NOAA.

Public opinion is unlikely to allow a rollback of nuclear waste management standards. However, it is not too late to avoid excessive stringency in *new* areas. An important example is the emerging standards for the leakage of stored carbon dioxide (CO_2) associated with CO_2 capture and storage (CCS). Right now, the dominant view seems to be that the rate of leakage from these reservoirs must be fixed now so as to assure that if someday enormous volumes of CO_2 are stored, leakage will create negligible climate change. Rules so demanding may well lead to another stalemate. As with nuclear waste, the concepts of iteration with experience and progressive tightening are missing from the discourse.

Unburnable carbon is a third vexatious problem in need of help from Destiny Studies. Not long ago "Peak Oil" was promoted by academics, who asserted that nearly half of the world's conventional oil had already been produced and that a slow, steady decline in production inevitably lay ahead. A public hungry for reassuring news about climate change inferred that the end was near for all fossil fuel, and that the world would be rescued from climate change by physical depletion. The recent commercialization of shale gas and shale oil has largely brought this wishful thinking to a close, as it becomes more widely understood that commercially attractive fossil fuels are abundant, rather than scarce. To address climate change, successive generations of human beings will need to leave most of these hydrocarbons underground.

Hans-Holger Rogner estimates that 80,000 billion tons of CO_2 would be created by burning all of the world's oil, natural gas, and coal resources, both conventional and unconventional—an amount equal to 2,000 years of emissions at today's rate and also more than 25 times larger than the 3,000 billion tons of CO_2 in the atmosphere right now.[1] Methane hydrates, also known as "clathrates" (ice crystals with methane molecules in their interstices), account for more than half of Rogner's estimate. Clathrates can exist within only narrow ranges of temperatures and pressures, but such ranges are found in the Arctic onshore beneath the permafrost and on the boundaries of continents just below the sea floor. Pilot projects to extract clathrates are already underway in Japan and India.

The carbon budget measures the total quantity of carbon in fossil fuel that will be extracted, ever. The latest Intergovernmental Panel on Climate Change (IPCC) reports connect the carbon budget to the rise in the ultimate rise in the Earth's average surface temperature. They find an approximately linear relationship and associate each 1,600 billion tons of CO_2 emissions with each Celsius degree of warming, out to 3°C. The 1,600 billion tons of CO_2 already emitted will bring one degree of warming, and budgets of 3,200 and 4,800 billion tons of CO_2 of total emissions (past and future) will bring two and three degrees of warming, respectively. The two panels in Figure 3.3.2 show examples of these budgets. The future emissions of the two-degree trajectory are 2% of Rogner's 80,000 billion tons of CO_2; for three-degrees, these emissions are 4%.

The emissions scenario in Panel A —which depicts cutting global CO_2 emissions in half in 40 years—is representative of what is required to meet the demanding two-degree target promoted at the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change in Paris last December. The extra four decades in Panel B relative to Panel A produce an additional whole degree of surface temperature rise in exchange for a calmer transition out of fossil fuels. Even the Panel B trajectory, however, affects exploration for new fossil fuels, because the strategic decisions by governments and companies, such as whether to develop resources in the Arctic—and whether to develop clathrates—entail commitments to emissions many decades from now.

Some of the questions implicit in carbon budgets are profound and nasty: From which countries should fuels be extracted and in which countries should they be consumed? When? For what purposes? In each case, who judges? Over the next 50 years, constraining "unburnable" fossil fuel will occupy center-stage.

Our endowment of plentiful fossil fuel is just one of a class of temptations that could lead human beings to burst our planet's seams by producing and consuming too much of a good thing. More kids, more meat, more leisure travel—all are problematic. Problems of abundance will be grist for the mill of Destiny Studies.

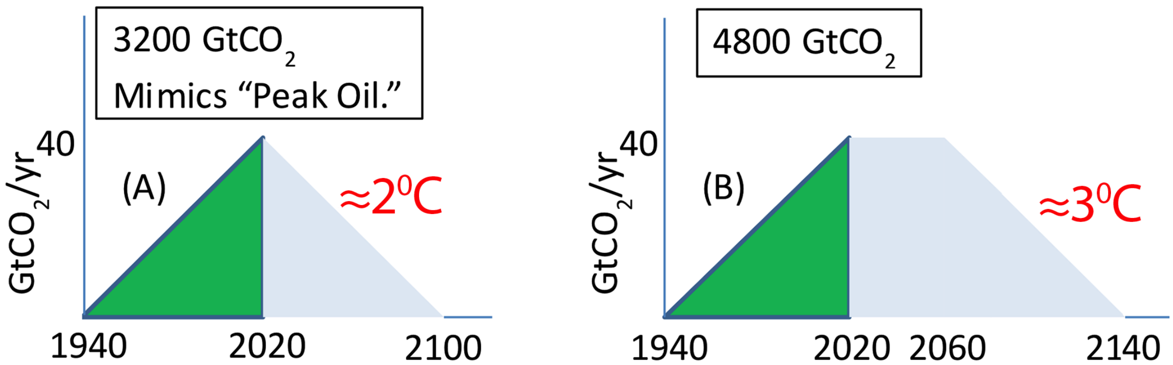

Figure 3.3.2. Representative CO_2 emissions trajectories consistent with two-degree and three-degree temperature targets. The dark triangles are an adequate abstraction of emissions to date. Panel A models the two-degree rise; it has no plateau at all and it mimics Peak Oil—we're halfway done. Panel B ("three degrees") adds a brief, 40-year plateau at today's emissions rate.

Iteration is a likely theme of Destiny Studies. How scared human beings will become of climate change will depend on what the Earth tells us about itself, decade by decade. Right now, the best and the worst outcomes 50 years from now that are consistent with climate science are very different. Gradually, during the coming 50 years, the Earth will give us clues about its variability and its feedback loops, such as those involving clouds, ice, and forests—provided that climate science flourishes. How can iteration be built into human institutions that govern future behavior so that new knowledge is taken into account?

Our collective afterlife is yet another problem suited for Destiny Studies. Sam Scheffler, a professor of philosophy at New York University and the author of *Death and the Afterlife,* asks how important it is for humanity to continue and answers that it is very important. He observes that human life derives much of its meaning from being embedded in a "thriving ongoing exercise," and that "humanity itself as an ongoing project provides the implicit frame of reference for most of our judgments about what matters." Our connectedness to future generations "staves off nihilism." We do not want to live forever; but we want the human project of which we are a part to endure.[2] Scheffler's book plowed new ground in philosophy—evidence that Destiny Studies is a project that has hardly begun.

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