Introduction

The Carbon Mitigation Initiative (CMI), based at Princeton University, is an independent academic program sponsored by BP. The goal of the program is to bring together scientists, engineers, and policy experts to design carbon mitigation strategies that are safe, effective and affordable. Since its inception in 2000, CMI has been committed to the dissemination of its research findings so they may benefit the larger scientific community, government, industry, and the general public.

In July 2017, the administering entity for CMI, the Princeton Environmental Institute (PEI), underwent a leadership transition. Michael Celia, the Theodora Shelton Pitney Professor of Environmental Studies Professor of Civil and Environmental Engineering and a CMI principal investigator (PI), became the Institute’s new director, succeeding François Morel, the Albert G. Blanke, Jr. Professor of Geosciences and also a CMI PI. Morel served two terms as PEI’s director: first, from 1998 to 2005, which included CMI’s early years and again from 2014 to 2017.

CMI is currently comprised of 18 lead faculty and more than 50 Princeton research staff and students. The program identifies both risks and opportunities posed by the carbon problem. Research teams are organized into three groups: science, technology, and integration.

**CMI Science** features close collaboration with Princeton’s neighbor, the Geophysical Fluid Dynamics Laboratory (GFDL) of the US Department of Commerce. Together, CMI and GFDL are improving the understanding of atmospheric, oceanic and terrestrial carbon dioxide (CO₂) and other greenhouse gases. The role of oceans as carbon and heat sinks is under investigation, with an emphasis on the relatively unexplored Southern Ocean. A growing effort is focused upon developing a better understanding of past tropical cyclone activity and intensity in order to improve the ability to predict future activity in response to changing climatic conditions. The study of surface waves at the interface between the atmosphere and ocean waters has important implications for improved understanding of climate and weather. Modeling of ice flows reveals new information about ocean mixing with implications for ocean ecology. Research on the role of terrestrial vegetation in the carbon cycle continues with additional focus on the hydrological cycle. An initiative launched in late 2017 investigates the physics of soil carbon dynamics to inform practical strategies for enhancing carbon storage in soils. In addition, a new supplementary award was announced to study methane sources and sinks in the atmosphere and on land.

**CMI Technology** studies CO₂ storage in geological formations with a focus on understanding leakage risks associated with old oil and gas wells, and on modelling injection in unconventional reservoirs. A program on advanced batteries is developing new diagnostic methods. Other research focuses on incentivizing the decarbonisation of the transportation sector, with an emphasis on biofuel production combined with CO₂ capture and storage.
CMI Integration introduces new conceptual frameworks that are useful to governments and citizen groups considering climate change policies. One current effort seeks to make the emerging statistical analyses of extreme events, such as urban heat waves, more accessible. Another initiative involves the study of renewable energy intermittency, lulls in windpower in particular, and examines potential implications for power management.

The 16th annual meeting of CMI, held at Princeton University from April 4-5, 2017, gathered over 100 people to hear presentations and take part in discussions about terrestrial and ocean carbon sinks, modeling of tropical cyclones, energy innovations and disruptive technologies, US climate policy including the regulatory and tax outlook, and climate change perspectives in the era of the Trump administration.

During a celebratory reception at the meeting, BP’s chief scientist and head of technology, Angela Strank, presented the 2017 CMI Best Paper Award to Princeton University postdoctoral research fellow Bhargav Rallabandi. Rallabandi, who works in PI Howard Stone’s lab, was selected for his paper, “Wind-Driven Formation of Ice Bridges in Straits.” The paper was published in Physical Review Letters in March 2017.

The day before the commencement of the CMI annual meeting, a symposium entitled “Energy for a Carbon-Constrained World,” honored Robert Williams on the occasion of his retirement after more than 40 years at Princeton. Williams, former head of the Energy Systems Analysis Group, had participated in CMI since its inception. The all-day celebration featured renowned international
experts from academia, industry, and government speaking on a variety of solutions and technologies that can provide sustainable energy and mitigate the impact of climate change on the environment.

Stephen Pacala, the Frederick D. Petrie Professor in Ecology and Evolutionary Biology and CMI co-director, was appointed as chair of a new National Academies of Sciences, Engineering, and Medicine’s Committee on Developing a Research Agenda for Carbon Dioxide Removal and Reliable Sequestration. The committee’s objective is to assess the benefits, risks, and sustainable scale potential for CO₂ removal and sequestration approaches; and to increase their commercial viability.

CMI is pleased to announce the addition of three new PIs: Amilcare Porporato, Xinning Zhang, and Vaishali Naik. Porporato is a professor in the Department of Civil and Environmental Engineering and PEI; he is known widely for his work in soils and hydrology. Zhang is a biogeochemist who began her assistant professorship in the Department of Geosciences and PEI in 2017. Naik is a physical scientist at GFDL; she is an expert in atmospheric chemistry and global modelling.

Also in 2017, BP assigned Michelle Horsfield, the BP Climate Science and Sustainability Manager, to work closely with Gardiner Hill and Cindy Yeilding in managing BP’s CMI relationship.

In this report, each of the PIs or teams of PIs selected one research highlight from 2017 to feature and 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 - cmi.princeton.edu - or email us at cmi@princeton.edu.
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Research Highlights – At a Glance

**Jorge Sarmiento:** Previous research using ocean observations and model results has suggested that the ocean around Antarctica acts as a key sink for atmospheric CO$_2$, mitigating global temperature increases caused by increasing anthropogenic carbon emissions. However, ship-based observations to test these findings have been scarce and mostly limited to summertime measurements. New data from robotic floats that measure biogeochemistry year-round suggest that previous studies may have missed important wintertime outgassing in certain regions, resulting in overestimates of the size of the Southern Ocean sink. The Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) researchers are working to extend such observations throughout the global ocean.

**Gabriel Vecchi:** Models project an increase in the rate of “rapid intensification” for tropical cyclones globally by the end of the 21st century. However, projections of changes in hurricane frequency in the Atlantic remain more uncertain, and model simulations and potential undercounts prior to available satellite data suggest observed long-term trends in hurricane counts are data artifact. The
goal of this work is to reconcile these potential discrepancies and to improve the understanding of
the mechanisms behind and limits to the predictability of tropical cyclone (TC) activity over the past
few and next centuries. The work connects to broad questions in the climate science community,
such as uncertainty over what TC changes are likely to occur over the coming century, and the extent
to which intrinsic climate variability may be dominant over the impact of greenhouse forcing.

**Brandon Reichl:** Surface waves at the atmosphere-ocean interface have important implications for
climate and weather modeling. This research focuses on two topics related to surface waves. The
first is improved coupled model performance through explicit consideration of physical processes
related to surface gravity waves, including upper ocean turbulent mixing and interfacial fluxes of
heat, momentum, and gases. The second is the investigation of changing surface wave characteristics
in an evolving climate.

**François Morel:** The fixation of nitrogen gas by specialized organisms such as *Trichodesmium* is
key to controlling photosynthetic production in marine ecosystems and may be impaired by ocean
acidification. Recent studies sought to untangle the separate effects of high CO$_2$ and low pH on
*Trichodesmium* and found that the former accelerates photosynthesis and N$_2$-fixation whereas the
latter impairs these functions. Low ambient pH results in low intracellular pH, which decreases the
efficiency of the nitrogenase enzyme.

**Howard Stone:** Climate changes involve atmospheric motions, ocean flows, and evolution of ice on
land and in the sea. These dynamics are closely 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 and distribution of ice during the formation of polynyas, which refer to localized
regions of water surrounded by ice, and through narrow straits, which can affect flow, mixing and
ecology in the ocean. The approach seeks to draw generalizations valid for various geometric and
climate conditions.

**Stephen Pacala:** The Pacala group’s work has continued to improve the representation of the carbon
cycle in climate models, including empirical support for a new theory of evaporative water loss in
plants and an explanation of tree behavior in response to drought. Additional work on the warming
impacts of methane, including a collaboration with the Environmental Defense Fund, analyzed the
methane budget of the US oil and gas infrastructure and provided new estimates for US emissions.

**Elena Shevliakova:** Human water management practices have a noticeable impact on the hydrological
cycle. These include diverting water for irrigation, abstraction of groundwater, and construction of
reservoirs. Hydrologic extremes, in particular, are heavily affected by water management practices,
due to the existing stress on the system during droughts and floods. To prepare adaptation plans
for hydrological extremes in the future, it is essential to account for water management and other
human influences in state-of-the-art climate models.

**Ian Bourg:** An objective of the Bourg group is to resolve the physics of soil carbon storage. Field
experiments indicate that the carbon storage capacity of soils increases significantly with their
content in smectite clay minerals, but the cause of this relationship is unknown. The Bourg group is
using atomistic-level simulations to predict the energetics of clay-organic interaction, the hydrology of clayey soils and sediments, and their dependence on aqueous chemistry. These results will enable more accurate Earth System Model predictions of soil carbon dynamics and inform practical strategies for enhancing the soil carbon sink.

François Morel (lead), Vaishali Naik, Elena Shevliakova, and Xinning Zhang: The CMI methane project, initiated in spring 2017, consists of three interconnected subprojects: an experimental project dealing with the critical issue of methane releases from wetlands, and two modeling projects aimed at quantifying the sources, sinks, and variations of methane in the atmosphere and on land. All three projects are now in full swing, following the hiring of postdoctoral researchers during the second half of 2017.
CMI Technology

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Research Highlights – At a Glance

Michael Celia: In earlier work, the Celia group studied CO₂ injection into depleted shale-gas systems and concluded that it was not feasible for most situations. That modeling work has now been extended to study the fate of fracking fluids in shale-gas systems. Modeling results indicate that the large amount of fracking fluids left underground is unlikely to pose any significant environmental risk.

Daniel Steingart: The misbehavior of batteries shows up in many ways and from a variety of root causes. The challenge is determining the where and what of the root causes. In 2017, the Princeton Lab for Electrochemical Engineering Systems Research made advances toward this understanding by studying the most fundamental electrochemical behaviors with novel electron microscopy.

Eric Larson: The US transportation sector emits about a quarter of total US greenhouse gases. It may be the most challenging sector to decarbonize, given its heavy reliance on petroleum and millions of small emission sources. Biofuels are one of the few decarbonization options, especially for difficult-to-electrify modes. Moreover, deployment of biofuel production systems that incorporate CO₂ capture and storage may be essential for achieving mid-century greenhouse gas emission reductions that limit global warming to 2°C. The required speed and scale of deployment of biomass supply infrastructure and conversion facilities to meet future biofuels targets that could mitigate significant transportation sector emissions have no historical precedents. Incentives stronger than those that drove the expansion of the US corn-ethanol industry will be needed for an advanced biofuel industry to contribute significant carbon mitigation by mid-century.
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**Research Highlights – At a Glance**

**Michael Oppenheimer:** Heat waves (HWs) are among the most damaging climate extremes to human society. For urban residents, the urban heat island (UHI) effect further exacerbates the heat stress resulting from HWs, and these risks are even greater if HWs interact synergistically with UHIs. Combining climate model simulations and a new analytical framework, the Oppenheimer group has investigated the synergistic effects, sometimes positive and sometimes negative, between UHIs and HWs at a large scale under climate change. The study also uncovered the physical mechanisms underpinning these synergistic effects.

**Robert Socolow:** Intermittency—variability in output—bedevils wind and solar energy. Presented here is a fresh approach to intermittency that focuses on the statistics of lulls (periods of low output), especially the longest lulls. Long lulls are extreme events and should be at the center of attention in grid management. The longest lulls are unlikely to elicit the same strategies as shorter lulls. In particular, batteries (and other storage strategies that have costs roughly proportional to the energy they store) will be ill-suited to compensate for the rare, longest lulls.
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