GLOBAL CHANGES

MIT JOINT PROGRAM ON THE SCIENCE & POLICY OF GLOBAL CHANGE
SPRING 2016

GLOBAL CHANGE

OUR RESEARCH MISSION

At the Joint Program, our integrated team of natural and social scientists studies the interactions among human and Earth systems to provide a sound foundation of scientific knowledge. Such a foundation will aid decision-makers in confronting the interwoven challenges of future food, energy, water, climate and air pollution issues, among others.

Our mission is accomplished through:

- *Quantitative analyses of global changes and their social and environmental implications, achieved by employing and constantly improving an Integrated Global System Modeling (IGSM) framework;*
- *Independent assessments of potential responses to global risks through mitigation and adaptation measures;*
- *Outreach efforts to analysis groups, policymaking communities, and the public; and*
- *Cultivating a new generation of researchers with the skills to tackle complex global challenges in the future.*

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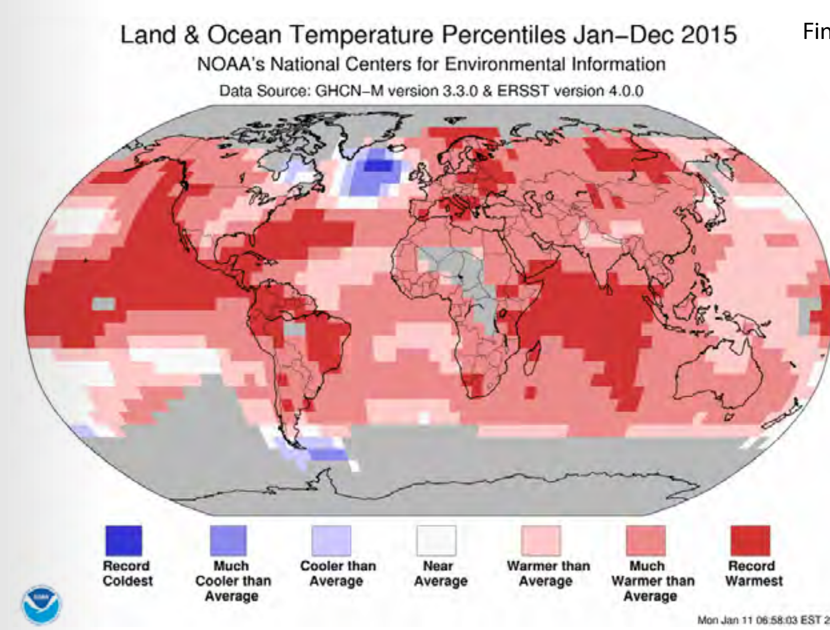
2015 Ranked Warmest Year on Record

COP21, Joint Program advancing global cooldown effort

The year 2015 saw a number of climate change records being broken once again. Global average carbon dioxide levels passed 400 ppm and total greenhouse gas levels passed 490 ppm of CO_2 equivalent; global average temperatures broke the previous record high set in 2014; and the 2015 El Niño challenged the 1997–1998 El Niño as the most intense ever observed (and also helped propel the record high temperature). Now the ten warmest years recorded with thermometers since records began in 1880 have all occurred in the last 18 years (in order: 2015, 2014, 2010, 2005, 1998, 2013, 2003, 2002, 2006 and 2009). And the apparent post-1998 slow-down in warming, the so-called "hiatus," has ended.

There are several ideas about the origin of this slowdown. Two linked natural climatic cycles, the El Niño Southern Oscillation and the Inter-decadal Pacific Oscillation, can lead to a prolonged cooling influence on global climate. No very large El Niños occurred after 1998 and before 2015 and, as a result, the upward mixing of cold water and downward mixing of warm water in the tropics was enhanced, leading to less surface warming and greater ocean warming. Meanwhile, medium-scale volcanic eruptions may have increased reflection of sunlight, further slowing the warming.

The 2015 Pacific category 5 Severe Tropical Cyclone Pam, with sustained winds of 155 mph and gusts up to 165 mph, joined the 2013 category 5 Typhoon Haiyan in the same region, as the two strongest tropical cyclones to hit land anywhere in recorded history. In the record warm year 2015, there were vastly more new hot temperature records broken than new cold temperature records (see figure). Observations clearly show the probability distribution for temperature is shifting to higher values, but be aware that global average record highs do not imply highs everywhere; there is one lonely record low in the North Atlantic.



The end of 2015 also saw a significant global climate agreement reached by 196 nations at the 21st meeting of the Conference of the Parties (COP) to the UNFCCC in Paris. It is important to note that despite 21 COP meetings and 5 major climate assessments by the IPCC since the signing of the UNFCCC in 1992, global CO_2 emissions have climbed from 28 to 40 gigatons per year. So hopes were high that the Paris talks would finally move the world on a trajectory toward a slowdown and, ultimately, a turndown in these emissions over the next two decades.

The major achievements in Paris centered on Nationally Determined Contributions (NDCs) representing 188 of the signatory countries. The NDCs involved pledges on emissions reduction actions and targets and inclusion of all greenhouse gases and their sources (except ships and aircraft). Targets reflected a wide range of approaches, from decreasing emissions or emissions intensity within a certain period, to peaking emissions from a designated energy source by a particular year.

The Paris Agreement established that the first pledge phase will begin in 2020, followed by updates every 5 years, and provided for a review process for each NDC and for an emissions trading market. An important element for vulnerable developing countries was aid in the forms of financing for adaptation, technology transfers, capacity building and recovery from losses and damages. NDCs could use forestry credits that would involve long-term but not necessarily permanent sequestration.

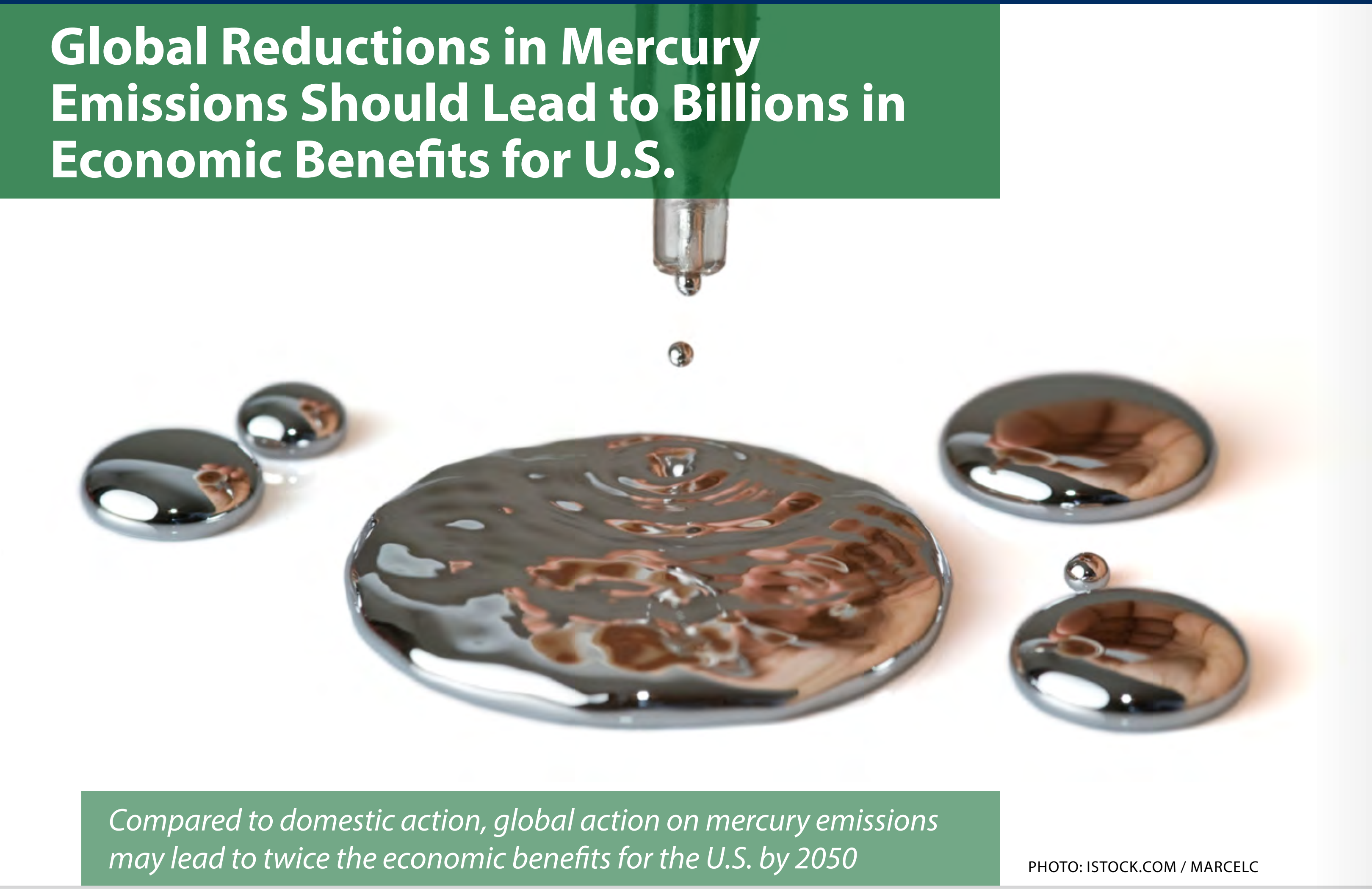
Much remains to be worked out in the next few years: the review process for NDCs, the sources and amount of financing for developing countries (a minimum of $100 billion per year is the initial target), and accounting rules and supervision of markets.

Finally, even if all NDC pledges made in Paris are honored, the planned emissions reductions still allow for a global temperature rise above preindustrial levels of more than 3°C (5.4°F), and well above the aspirational target of 2°C (3.6°F) widely discussed both before and during COP21. In a pre-Paris analysis by the Joint Program that contained the essence of what was finally agreed upon, the projected temperature rise was 3.7 (3.1–5.2) °C or 6.7 (5.6–9.4) °F (see *Joint Program Report 286*).

In support of the global effort to meet, and eventually exceed, targets set in the NDCs, the Joint Program is taking a leadership role in two initiatives—a conversation with allied MIT organizations on how to help developing countries fulfill their pledges, and a study (with the MIT Energy Initiative), *The 2°C Challenge*, aimed at determining viable research, development and policy pathways to achieving the 2°C target. ■

—Ronald Prinn, Joint Program Co-Director

Global Reductions in Mercury Emissions Should Lead to Billions in Economic Benefits for U.S.



Compared to domestic action, global action on mercury emissions may lead to twice the economic benefits for the U.S. by 2050

PHOTO: ISTOCK.COM / MARCELC

By Jennifer Chu, MIT News Office

Mercury pollution is a global problem with local consequences: Emissions from coal-fired power plants and other sources travel around the world through the atmosphere, eventually settling in oceans and waterways, where the pollutant gradually accumulates in fish. Consumption of mercury-contaminated seafood leads to increased risk for cardiovascular disease and cognitive impairments.

In the past several years, a global treaty and a domestic policy have been put in place to curb mercury emissions. But how will such policies directly benefit the U.S.?

In a new study published in December in the *Proceedings of the National Academy of Sciences*, MIT researchers report that global action on reducing mercury emissions will lead to twice the economic benefits for the U.S., compared with domestic action, by 2050. However, those in the U.S. who consume locally caught freshwater fish, rather than seafood from the global market, will benefit more from domestic rather than international mercury regulations.

The researchers calculated the projected U.S. economic benefits from the Minamata Convention on Mercury, a global treaty adopted in 2013 to reduce mercury emissions worldwide, compared with the Mercury and Air Toxics Standards (MATS), a national regulation set by the U.S. Environmental Protection Agency to reduce mercury pollution from the country's coal-fired power plants.

Overall, while both policies are projected to lead to roughly the same amount of reductions in mercury deposited on U.S. soil compared to a no-policy case, Americans' consumption of mercury by 2050 are estimated to be 91 percent lower under the global treaty, compared to 32 percent under U.S. policy alone. The researchers say these numbers reflect the U.S. commercial fish market, 90 percent of which is sourced from Pacific and Atlantic Ocean basins—regions that are heavily influenced by emissions from non-U.S. sources, including China.

From their projections of reduced mercury consumption, the researchers estimated health impacts to the U.S. population under both policies, then translated these impacts into economic benefits. They characterized these in two ways: projected lifetime benefits from an individual's reduced exposure to mercury, including willingness to pay for lowering the risk of a fatal heart attack, cost savings from avoided medical care, and increased earnings; and economy-wide benefits, or the associated productivity gains of a national labor force with improved IQ and fewer heart attacks, as a result of reduced exposure to mercury.

Based on these calculations, the team estimated that by 2050, emissions reductions under the Minamata Convention on Mercury would lead to $339 billion in lifetime benefits and $104 billion in economy-wide benefits in the U.S., compared to $147 billion and $43 billion, respectively, from MATS. The global treaty, then, should lead to more than twice the benefits projected from the domestic policy.

Selin and Giang used economic valuation methods to translate heath impacts into economic benefits to the U.S.

"Historically it's been hard to quantify benefits for global treaties," says Noelle Selin, the Esther and Harold E. Edgerton Career Development Associate Professor in MIT's Institute for Data, Systems and Society and in the Department of Earth, Atmospheric and Planetary Sciences. "Would we be able to see a U.S. benefit, given you're spreading reductions and benefits around the world? And we were."

Tracing the policy-to-impacts pathway

Determining how regulatory policies will ultimately lead to health and economic benefits is a complex and convoluted problem. To trace the pathway from policy to impacts, Selin and co-author Amanda Giang, a graduate student in MIT's Institute for Data, Systems and Society, began with estimates of mercury reductions set by both the Minamata Convention and MATS.

The team then used an atmospheric transport model to trace where emissions would settle over time, based on the reductions proposed by each policy scenario. From regional depositions of mercury, they then estimated the resulting mercury concentrations in fish and mapped these concentrations to seafood sources throughout the world.

Next, the team correlated seafood sources to fish consumption in the U.S., and calculated changes in human exposure to mercury through time. They used epidemiological models to estimate how changes in mercury exposure affect incidence of health impacts, such as heart attacks and IQ deficits. From there, Selin and Giang used economic valuation methods to translate heath impacts into economic benefits—namely, lifetime and economy-wide benefits to the U.S.

Understanding the drivers

While the researchers were able to come up with benefits in the billions for both the global and domestic policies, they acknowledge that these numbers come with a significant amount of uncertainty, which they also explored.

"We're trying to understand different drivers in the variability of these numbers," Giang says. "There's a lot of uncertainty in this system, and we want to understand what shifts these numbers up and down."

For example, scientists are unsure how far different forms of mercury will travel through the atmosphere, as well as how long it will take for mercury to accumulate in fish. In their analysis, Giang found that, even taking into account most of these uncertainties, the economic benefits from the global treaty outweighed those from the domestic policy, except when it came to one key uncertainty: where people's seafood originates.

"We do find that in our scenario where everyone is eating local fish, the benefits of domestic policy are going to be larger than the Minamata convention," Giang says. "Our study points to the importance of domestic policy in terms of protecting vulnerable populations such as subsistence fishers or other communities that do rely on U.S. freshwater fish."

"There are a ton of uncertainties here, but we know that mercury is a dangerous pollutant," Selin adds. "When you put in a policy, how do you think about its ultimate environmental and human effects? We think this method is really a way to try and move that forward." ■

This research was funded, in part, by the National Science Foundation.

Related Publication:

Giang, A. and N. Selin, 2015: Benefits of mercury controls for the United States, *PNAS* 113(2): 286–291.

In the News:

Selin, N. and A. Giang, 2016: Are Tighter EPA controls on mercury emissions worth it? *The Conversation*, Feb. 9, 2016.

Driving the Rain

Aerosols shown to exert strong influence on the geography of precipitation

While the effects of power plant emissions, vehicle exhaust and other manmade aerosols on air quality and public health are well-known, their impact on the climate is not completely understood. Scientists have shown that aerosols can lower surface temperatures either directly, by reflecting sunlight skyward, or indirectly, by increasing the reflectivity of clouds, but until now have not figured out the role these airborne particles play in shaping the distribution of rain and snowfall around the world.

According to a new MIT study in *Geophysical Research Letters*, the effects of anthropogenic aerosols exert a strong influence in determining where precipitation increases and decreases take place across the globe. Running historical simulations with models that represent aerosol–cloud interactions with far greater precision than in previous analyses, the MIT study indicates that the distribution of precipitation in the second half of the 20th century is dominated by the effects of anthropogenic aerosols over the tropics, and also substantially influenced in non-tropical regions of the Northern Hemisphere.

"While it is true that *total* precipitation change is controlled by average global temperature change, which, in turn, is largely based on greenhouse gas emissions, our research shows that aerosols have significantly impacted the *distribution* of precipitation change around the world since preindustrial times," says Chien Wang, a senior research scientist at the MIT Joint Program on the Science and Policy of Global Change.

Using historical simulations running from 1850 to 2005, the MIT study compared results of an ensemble of 10 models from the recent Coupled Model Intercomparison Project Phase 5 (CMIP5), which explicitly represent aerosol–cloud interactions, with those of a set of seven older models that oversimplified these interactions. The new models showed that aerosol-driven precipitation changes occurred not only where aerosol concentrations were high (e.g., the Indian summer monsoon region) but also in a number of far-off locations.

"We compared results with and without aerosols from preindustrial times to 2005, and found that aerosols alone can force a pattern change in precipitation," says Wang. "Because of the sophistication of the new, physically-based models, we can now see that aerosols have a larger impact on precipitation distribution than previously established."

"Because of the sophistication of the new, physically-based models, we can now see that aerosols have a larger impact on precipitation distribution than previously established."

Aerosol concentrations may rise or fall as nations grow their economies, implement clean air policies or develop in other ways, leading to changes in the distribution of precipitation around the world that could adversely impact economic, agricultural and other activities. These results suggest that anyone formulating a climate mitigation or adaptation strategy will be wise to consider the potential impact of aerosols on both local and global precipitation patterns. ■

This research was supported by the U.S. National Science Foundation, Department of Energy, and Environmental Protection Agency; and the National Research Foundation of Singapore.

Related Publication:

Wang, C., 2015: Anthropogenic aerosols and the distribution of past large-scale precipitation change, *Geophysical Research Letters* 42(24): 10,876–10,884.

PHOTO: NASA

Aerosols can lower surface temperatures either directly, by reflecting sunlight skyward, or indirectly, by increasing the reflectivity of clouds.

UPCOMING: XXXIX (39TH) MIT GLOBAL CHANGE FORUM

15–17 June 2016 • Cambridge, MA USA

At the 39th MIT Global Change Forum, representatives of industry, government, NGOs and research groups will discuss the evolving science and policy of the climate issue. The Forum is designed to promote interaction among disparate stakeholders and provides an informal, "off-the-record" setting for independent assessment of studies and policy proposals.

General Theme:
Corporate Strategy and Climate Change

Sponsors Meeting to convene:
Wednesday 15 June
2:00 PM–5:00 PM EDT

Individual sessions:
1. Land & Agriculture
2. Finance
3. Future Directions in Energy
4. Supply Chain Risk
5. Water Resources & Adaptation Strategies
6. Panel: Monitoring, Reporting, & Verification of Paris Agreement

By invitation only. For more information, please contact Frances Goldstein: fkg@mit.edu

Nature's Carbon Sinks

Study assesses role of rainforests, other protected areas in mitigating climate change

PHOTO: GREG ASNER, CARNEGIE INSTITUTION FOR SCIENCE

Manu National Park, a large (15,328km^2) protected area in southeastern Peru, includes several ecological zones and spans an elevation range of 150–4200 meters above sea level. Manu's vast tracks of Amazonian rainforest are part of the global tropical forest carbon sink that is slowing the rate of increase in atmospheric carbon dioxide, a primary driver of climate change.

By Mark Dwortzan (MIT Joint Program) and Diana Kenney (Marine Biological Laboratory)

Protected areas such as rainforests occupy more than a tenth of the Earth's landscape, and provide invaluable ecosystem services, from erosion control to pollination to biodiversity preservation. They also draw heat-trapping carbon dioxide (CO_2) from the atmosphere and store it in plants and soil through photosynthesis, yielding a net cooling effect on the planet.

Determining the role protected areas play as carbon sinks—now and in decades to come— is a topic of intense interest to the climate-policy community as it seeks science-based strategies to mitigate climate change. Toward that end, a study in the journal *Ambio* estimates for the first time the amount of CO_2 sequestered by protected areas, both at present and throughout the 21st century as projected under various climate and land-use scenarios.

Based on their models and assuming a business-as-usual climate scenario, the researchers projected that the annual carbon sequestration rate in protected areas will decline by about 40 percent between now and 2100. Moreover, if about a third of protected land is converted to other uses by that time, due to population and economic pressures, carbon sequestration in the remaining protected areas will become negligible.

"Our study highlights the importance of protected areas in slowing the rate of climate change by pulling carbon dioxide out of the atmosphere and sequestering it in plants and soils, especially in forested areas. Maintaining existing protected areas, enlarging them and adding new ones over this century are important ways we can manage the global landscape to help mitigate climate change," said Jerry Melillo, the study's lead author. Melillo is a Distinguished Scientist at the Marine Biological Laboratory (MBL) in Woods Hole, Mass., former director of the MBL's Ecosystems Center and a research affiliate of the MIT Joint Program on the Science and Policy of Global Change.

Based on a global database of protected areas, a reconstruction of global land-use history, and a global biogeochemistry model, the researchers estimated that protected areas currently sequester 0.5 petagrams (500 billion kilograms) of carbon each year, or about 20 percent of the carbon sequestered by all land ecosystems annually. Using an integrated modeling framework developed by the MIT Joint Program, they projected that under a rapid climate-change scenario that extends existing climate policies, keeps protected areas off-limits to development, and assumes continued economic growth and a 1 percent annual increase in agricultural productivity, the annual carbon sequestration rate in protected areas would fall to about 0.3 petagrams of carbon by 2100.

When they ran the same scenario but allowed for possible development of protected areas, they projected that more than a third of today's protected areas would be converted to other uses. This would reduce carbon sequestration in the remaining protected areas to near zero by the end of the century. (The protected areas that are not converted would be the more marginal systems that have low productivity, and thus low capacity to sequester carbon.)

Based on this analysis, the researchers concluded that unless current protected areas are preserved and expanded, their capacity to sequester carbon will decline. The need for expansion is driven by climate change: As the average global temperature rises, so, too, will plant and soil respiration in protected and unprotected areas alike, thereby reducing their ability to store carbon and cool the planet.

Unless current protected areas are preserved and expanded, their capacity to sequester carbon will decline.

"This work shows the need for sufficient resources dedicated to actually prevent encroachment of human activity into protected areas," said John Reilly, one of the study's coauthors, and co-director of the MIT Joint Program. ■

This study was supported by the David and Lucille Packard Foundation, the National Science Foundation, the U.S. Environmental Protection Agency and the U.S. Department of Energy.

Related Publication:

Melillo, J., X. Lu, D. Kicklighter, J. Reilly, Y. Cai and A. Sokolov, 2016: Protected areas' role in climate-change mitigation, *Ambio* 45(2): 133–145.

Paving the Way for Policy

MIT–Tsinghua University project, publications advance U.S.–China climate cooperation

In the global effort to mitigate climate change, China has taken center stage. The world's leading carbon dioxide emitter (the U.S. is second), China emits 30 percent of global CO_2 emissions and is home to some of the planet's worst air pollution, both largely due to its reliance on coal for energy. More than a year before the Paris climate talks in December 2015, many watched closely to see what China and the U.S. would put on the table. In November 2014 at the Asia-Pacific Economic Cooperation (APEC) Summit in Beijing, Presidents Obama and Xi jointly unveiled landmark pledges for post-2030 action that represented a new level of ambition for both nations.

Specifically, China pledged to achieve two energy-related goals by 2030: to increase the share of non-fossil fuels (nuclear power and renewables) in its energy mix to about 20 percent, and to reach its peak in CO_2 emissions. In support of those goals, it announced a national cap-and-trade system that will put a price on carbon emissions starting in 2017.

China did not arrive at these major policy decisions overnight; they represent a three-year effort to develop a comprehensive plan to balance environmental, public health and economic concerns on the home front with growing international pressure to mitigate its rising greenhouse gas emissions. To formulate that plan, Chinese government officials consulted with leading experts in climate science, energy and economics, including those at the Tsinghua–MIT China Energy & Climate Project (CECP), an initiative of the MIT Joint Program on the Science and Policy of Global Change that provides analyses of the impact of existing and proposed energy and climate policies in China on its technology, energy mix, environment and economy.

In its signature study—released in October 2014 as *Joint Program Report 267* and presented over the course of a year to nearly 100 policymakers, academics and industry representatives in Beijing—CECP researchers showed that by combining carbon taxes with ongoing investment in increasingly cost-competitive renewable energy technologies, China could achieve peak CO_2 emissions by 2030 without undermining long-term economic growth. Known as the *China Energy Outlook*, the CECP study now appears in the journal *Energy Economics*.

Influencing U.S.–China cooperation on climate change

Since its initial release in 2014, the study has made a substantial contribution to U.S.–China cooperation on climate change and global efforts at the recent Paris climate talks.

> *"CECP's research has helped inform both the U.S. and China about China's climate change mitigation potential and what targets and policies China could adopt."*

"Both the U.S. and Chinese governments relied significantly on a number of studies of China's future energy and emissions trajectories that were conducted over the past two years to inform them on the details behind China's proposed climate goals," says Lynn Price, senior staff scientist and leader of the China Energy Group of the Energy Analysis and Environmental Impacts Division at Lawrence Berkeley National Laboratory. "These goals were announced in November 2014 in the U.S.–China Joint Announcement on Climate Change, submitted as part of China's Intended Nationally Determined Contributions, and ultimately included in the Paris Agreement in December 2015. The *China Energy Outlook* was a key study that helped positively shape the U.S.–China climate cooperation that has been credited with providing the momentum for the successful outcome in Paris."

Paul Joffe, senior foreign policy counsel at the World Resources Institute in Washington, DC, concurs.

"CECP's research has helped inform both the U.S. and China about China's climate change mitigation potential and what targets and policies China could adopt," says Joffe. "This was important as the U.S. and China reached a breakthrough understanding on their climate action goals, embodied in their climate action plans for the Paris climate conference. Understanding of China's climate action helped build momentum among other countries, resulting in the successful conclusion at Paris."

Projecting economically viable climate solutions

The *Outlook* used an analytical framework developed by CECP—the China-in-Global Energy Model (C-GEM)—to test what might happen under three policy scenarios between 2010 and 2050: a *No Policy* (baseline) scenario in which no energy or climate policies are implemented from 2010 onwards, resulting in steady CO_2 emissions growth through 2050, endangering prospects for global climate stabilization; a *Continued Effort* scenario that assumes that China remains on its pre-COP21 path of reducing carbon intensity by around 40 percent every 15 years; and an *Accelerated Effort* scenario that assumes increases in both the resource tax applied to coal, crude oil and natural gas, and in tax incentives to promote renewable energy.

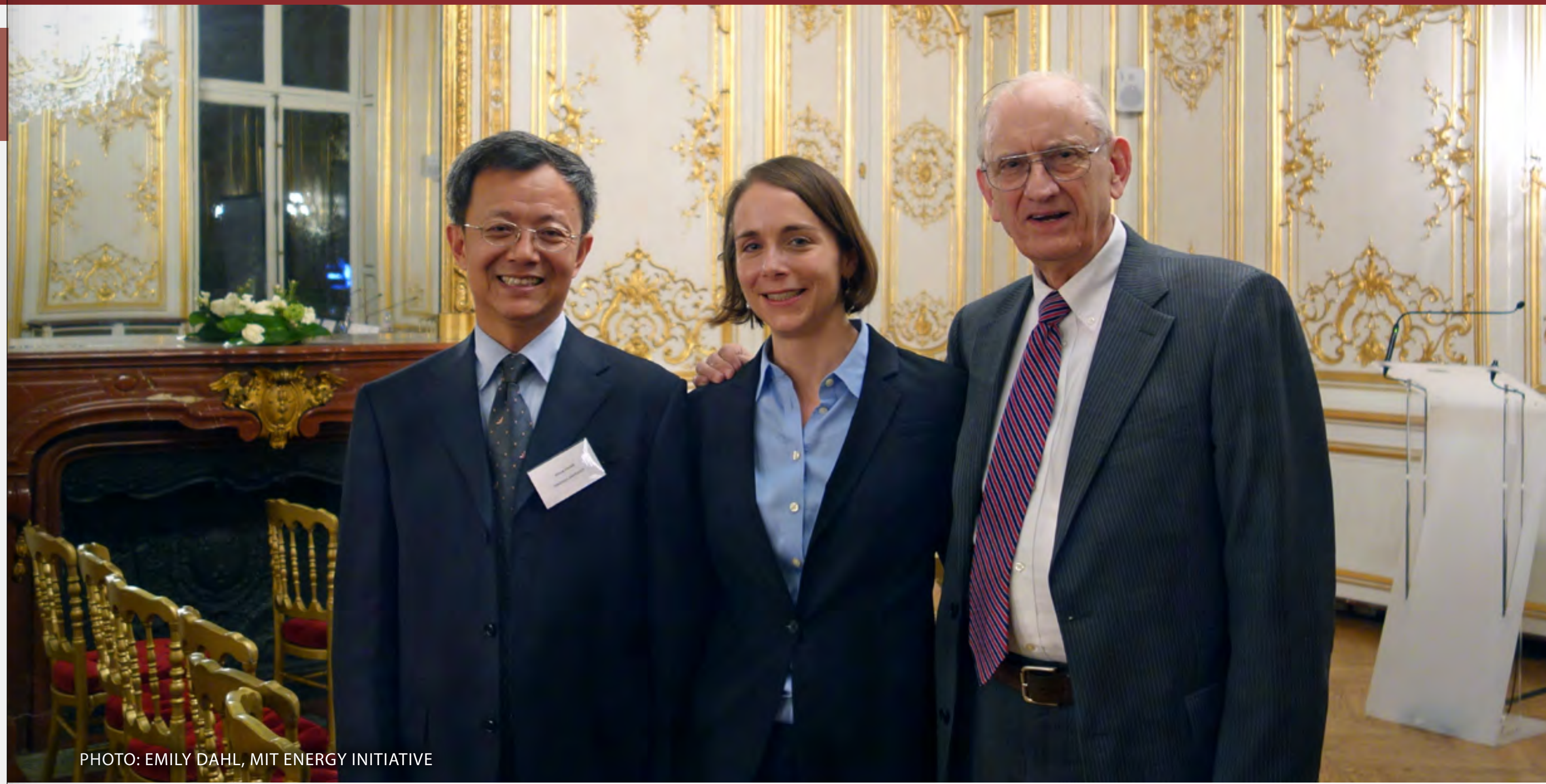


PHOTO: EMILY DAHL, MIT ENERGY INITIATIVE

On Dec. 4, 2015, MIT Sloan School of Management professors Henry Jacoby (right) and Valerie Karplus (center) and their collaborator, Professor Xiliang Zhang (left) of Tsinghua University and the MIT–Tsinghua CECP, gave presentations at the MIT Club of France in the historic France-Amériques building. Addressing COP21 attendees, MIT alumni, current students and others, they discussed how China's actions coming out of COP21 could help shape the future global energy system.

Enabled by a carbon price that rises to \$26/ton CO_2 in 2030 and \$58/ton CO_2 in 2050, the *Continued Effort* scenario would lead to carbon emissions peaking around 2040 and the non-fossil energy share rising to 15 percent in 2020 and around 26 percent in 2050. In the *Accelerated Effort* scenario, which approximates China's COP21 pledge, CO_2 emissions peak around 2030 (with coal consumption peaking around 2020) and the non-fossil energy share rises to 26 percent in 2030. In this scenario, the carbon tax rises from \$38/ton CO_2 in 2030 to \$115/ton CO_2 in 2050. Meeting the 2030 targets would exact an added cost to the economy that rises to 2.6 percent of the value of China's domestic consumption in 2050.

The CECP team's analysis indicates that a commitment to a significant energy system transition—one that includes broad market reforms and a price on carbon emissions—can reduce environmental impact while maintaining economic growth over the longer term. While the study does not explicitly calculate avoided air pollution and health damages, the researchers note that reductions in coal under both policy scenarios will reduce adverse impacts on these fronts as well.

"The CECP *China Energy Outlook* demonstrated the value of co-creating policy-relevant analysis through international academic collaboration," says study co-author Valerie Karplus, an assistant professor of Global Economics and Management at the MIT Sloan School of Management and Director of CECP in the MIT Joint Program from 2011 to 2015. "When it comes to the impact of our work, the mutual understanding and trust built in the course of model development has proven to be as important to its impact as the numbers themselves." ■

At MIT, the CECP is supported by founding sponsors AFD, Eni, ICF International, and Shell, and receives sustaining sponsorship from the Energy Information Administration at the U.S. Department of Energy. At Tsinghua University, the program is supported by the Ministry of Science and Technology, National Development and Reform Commission, and the National Energy Administration as well as Rio Tinto. Both groups also received support from the U.S. Energy Foundation.

Related Publication:

Zhang, X., V. Karplus, T. Qi, D. Zhang and J. He, 2016: Carbon emissions in China: How far can new efforts bend the curve?, *Energy Economics* 54(Feb 2016): 388–395. (See also: MIT Joint Program Report 267).

MIT JOINT PROGRAM ON THE SCIENCE AND POLICY OF GLOBAL CHANGE

Symposium Calls for Science-Based Climate Action

Experts examine how MIT can be most effective in addressing climate-change issues

By David L. Chandler (MIT News Office)

The following is an abridged version of the original article:

In a daylong symposium at the Stata Center in January, called "MIT on Climate: Science + Action," a series of presentations described the severity of the global climate change threat, the wide variety of related impacts on human society and economies, and actions that might be most effective in minimizing the damage.

"There will always be more to learn, but we have to act on what we already know," said Robert van der Hilst, head of MIT's Department of Earth, Atmospheric and Planetary Sciences (EAPS), which sponsored the event.

Keynote speaker Marcia McNutt, editor-in-chief of *Science*, began by addressing the question of whether or not climate change is a case of "settled" science. "It depends on the kind of question you ask," she said. "Is the climate changing due to human activity? Yes. We know enough about that question to know that we should be taking action to limit emissions. But, from a scientific standpoint, there are a lot of questions that remain to be answered."

Ronald Prinn, director of MIT's Center for Global Change Science.

Such remaining questions, she said, include just how fast the effects of climate change are occurring, especially those effects that may have the greatest impacts on human society, such as how fast (and how far) sea level may rise. Other open questions, McNutt said, concern the detailed effects of ocean acidification as a result of carbon dioxide absorption, the impact of warming on droughts and flooding events, increases in the prevalence and intensity of storms, and the effect of increases in lightning strikes. "We need better predictions" of all the effects that impact human activities, she said, and "better information can guide better decisions."

A series of talks by present and former MIT faculty members outlined the state of present knowledge about climate systems, from studying the atmospheres of distant planets to understanding the links between climate and the evolution of life, including major extinction events and swings between hothouse eras and "snowball Earth" epochs, when the planet was frozen from pole to pole. Such research aims, among other things, to resolve some of the many complex interactions triggered by changing climates and to assess their likely impacts on human activities.

Laying odds on the "climate gamble"

Ronald Prinn, director of MIT's Center for Global Change Science, summarized the need for making major policy decisions in the face of remaining uncertainties, by showing a pair of roulette wheels. These were designed to show, based on the best available global climate and economic models, the relative likelihoods of temperature rise under a "business as usual" scenario, versus a scenario in which strict emissions controls are put into place.

Without such action, he showed, there is about a 25 percent chance that the average global temperature increase by the end of this century will be more than 6 degrees Celsius—an amount that would be catastrophic for many regions of the world. And, there is an 80 percent chance of exceeding a 2-degree increase, which is the amount the world's leaders have agreed is an upper limit on what can be accepted without major disruptions to global economies and populations. Those increases are calculated relative to 1990 levels, the baseline used in the recent Paris agreements, but a more relevant measure, he said, was the increase from pre-industrial levels. By that measure, "business as usual" leads to a staggering 97 percent chance of exceeding a 2-degree increase.

But that is not an inevitability, Prinn stressed. If strict emissions standards are put in place over the next few years, the chances of exceeding the 2-degree threshold would drop dramatically, as shown in the second wheel. "That's the future we would rather live in," he said.

A series of speakers then addressed the questions of what kinds of actions could and should be taken to combat the climate-change risks. They described the non-carbon energy technologies that are available; the economic and health benefits of pursuing those options; the psychological, social and political obstacles to taking action; and processes that can aid in negotiating agreements on mitigation measures and harnessing "collective intelligence" through the Internet to find, evaluate and disseminate solutions.

A major task for researchers is to see who can produce renewable energy at the least cost.

Healthy side-benefits

While most studies of alternative energy sources focus on the costs and direct climate impacts, Noelle Selin, the Esther and Harold Edgerton Career Development Associate Professor in EAPS and an associate professor in the Institute for Data, Systems and Society, pointed out that switching to non-carbon energy sources can also have very significant near-term effects on health, because particulate matter associated with disease goes hand-in-hand with fossil fuel use. Particle emissions are believed to be responsible for 3 to 7 million premature deaths per year worldwide, she said, but the emissions reductions agreed to in Paris last fall could significantly improve that situation. "That's potentially a real motivator for action," she said.

A final panel discussion focused on what could and should be MIT's role in the issue of climate change, as related to fundamental research on the science and technology; educating the next generation of researchers and the public; and the potential for leading by example.

Valerie Karplus, an MIT alumna and assistant professor at the MIT Sloan School of Management, said one of the most important things MIT students and faculty can do is "to talk to skeptics. We need to build bridges rather than create divisions." John Fernandez, newly appointed head of MIT's Environmental Solutions Initiative, suggested holding a series of several events each year on environmental change, "in which people from the multitude of disciplines in MIT's five schools play out scenarios" to find practical approaches to addressing problems.

Dennis Whyte, head of the Plasma Science and Fusion Center, said one important lesson is "don't do what hasn't worked." Specifically, many researchers have found ingenious new ideas for energy production "that no one will ever use" because of economic, manufacturing or materials supply issues, he said. But technologies that do have commercial potential "are new opportunities for action" for the scientific and technical community. "You have to be ambitious and realistic at the same time," he said.

Prinn said that given the clear evidence of human-caused climate change, "renewables need to be the major source of energy for the world, regardless of whether we're on a high, low or medium path" in terms of the speed of global warming. So now a major task for researchers is "to see who can produce renewable energy at the least cost," he said, adding that such solutions may differ depending on location. "It's not one solution for the world." ■

Dispatches from the Paris Climate Talks

MIT attendees of COP21 share experiences, perspectives on outcomes

Amanda Giang (left) moderates a panel of MIT students and staff who attended the Paris climate talks in December.

By Francesca McCaffrey (MIT Energy Initiative)

Since the successful conclusion of the Paris climate talks, known as COP21, in December with a unanimous multinational agreement to address the causes and impacts of climate change, members of MIT's delegation to COP21 have been engaging with others throughout the Institute to provide analysis and perspectives on the process and outcomes from Paris.

On January 25, four participants spoke at "Dispatches from Paris: Reflecting on the Climate Talks with COP21 attendees," an evening event co-hosted by the MIT Energy Initiative (MITEI) and the MIT Joint Program on the Science and Policy of Global Change, to give the MIT community a taste of what it was like to be at the talks.

Amanda Giang, a graduate student in engineering systems who moderated the panel, set the stage for audience members unfamiliar with the climate talks, describing formal meetings filled with people from countries around the world listening to simultaneous translations of the proceedings, happening alongside "informal negotiations in the corridors." She added, "There are long hours spent poring over very dense legal language, negotiating words like 'shall' or 'should,' or 'must' or 'may.'"

Panelists noted the collective sense of urgency to reach a strong agreement, describing it as one of the vital aspects of COP21. Michael Davidson, a PhD candidate in the Institute for Data, Systems and Society who also works with the Joint Program, said that there was "an air of cordiality in Paris, an atmosphere of cooperativeness" compared with previous climate negotiations he has attended, that helped move the Paris negotiations along.

From civil society organizations to world leaders, everyone was going into the proceedings at COP21 with dedication.

From civil society organizations to world leaders, "everyone was going into the proceedings at COP21 with dedication," said MITEI communications director Emily Dahl. "This is the time it had to be done."

Another key element of success in Paris was establishing a common framework of accountability. This new structure allows countries to determine their own emissions reductions levels and strategies, through nationally determined contributions (NDCs), with transparency in reporting to hold nations accountable for their pledges. This will be coupled with a periodic review against long-term goals to encourage ratcheting up of pledges.

CLIMATE AT MIT

The focus on resilience in the face of climate change already impacting nations and communities was also important throughout the negotiations, panelists said.

In Paris, "climate change adaptation was for the first time placed on an equal footing with climate change mitigation," said Jessica Gordon, a PhD candidate in Environmental Policy and Planning in the Department of Urban Studies and Planning. Gordon added that both of these issues must be addressed together: "We really can't deal with them separately."

In Paris, climate change adaptation was for the first time placed on an equal footing with climate change mitigation.

Gordon and the other panelists discussed the prominence at COP21 of climate adaptation financing: monetary contributions to help the countries that stand to suffer most from climate change—many of which are among the least-developed nations—build resiliency. France, for example, expressed a desire to contribute to financing plans for the first time at this conference, while U.S. Secretary of State John Kerry stated that the U.S. plans to double its contributions.

International cooperation was also evident in the marked change in the relationship between the U.S. and China. After years of stalemate, both countries are now working together to solve climate issues, due in large part to meetings between the two countries leading up to Paris. Davidson, who is also a researcher with the MIT–Tsinghua China Energy and Climate Project, called U.S.–China collaboration "the defining partnership on the international scene."

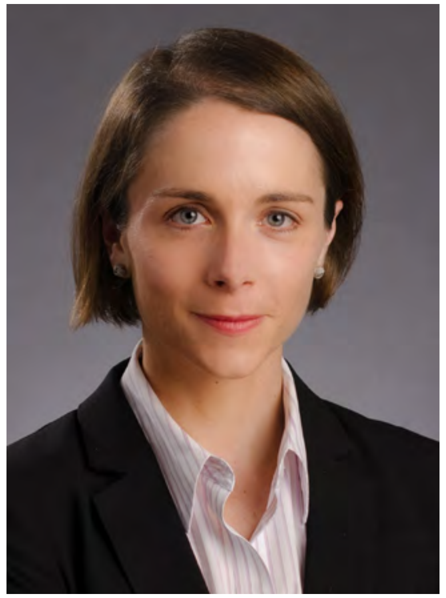
For Joseff Kolman, an MIT undergraduate in political science and physics, COP21 was a first-time foray behind the scenes of international negotiations. "One of the big reasons I wanted to go was to see what the climate negotiations looked like," says Kolman, who won a grant from MITEI to attend the talks as a part of an undergraduate Energy Studies Minor competition.

Learning in class about how the negotiations should theoretically work, Kolman says, was very different from being there in person: "Actually being there was eye-opening." One unexpected discovery, he says, was "the entire infrastructure of individuals who come from around the world" with diverse missions and engage each other in climate discussion and planning outside of the main conference framework.

Dahl discussed the role of MIT faculty, including professors John Sterman, Jessika Trancik, Jake Jacoby, Tom Malone and Valerie Karplus, in providing analysis for policymakers leading up to and during COP21 and helping to inform public understanding of the events unfolding at the talks.

This commitment to fostering public discourse and spurring action, informed by science, is a hallmark of MIT's recently unveiled climate plan.

Another notable aspect of MIT's climate plan is its call for engagement across all disciplines and sectors on climate solutions, which it shares with the Paris talks. The spirit of COP21 is alive and well on campus, as MIT community members continue researching, discussing, and collaborating—with each other and with government, industry, and society—on climate solutions. ■



Joint Program researchers Henry "Jake" Jacoby and Valerie Karplus provided analysis for policymakers leading up to and during COP21, and helped to inform public understanding of the events unfolding at the talks.

Nourishing People

Challenges of feeding the world

PHOTO: ISTOCK.COM / MARILYNA

By John Reilly

According to United Nations experts, enough food is produced around the globe to enable everyone to be adequately nourished and lead healthy and productive lives. And yet, approximately 926 million people continue to go hungry, especially the rural poor in developing countries. The reasons for this are manifold, ranging from natural disasters and extreme storms to war and poverty. Identifying and implementing viable solutions to the problem will become even more urgent over the next 35 years, as the global population soars from today's 7.3 billion to an estimated 9–10 billion, and the demand for food is expected to more than double.

Agriculture faces the challenge of meeting that demand even as it must reduce its environmental footprint and adapt to a changing environment. As it stands now, the Earth's atmosphere and waterways are on the front line, and climate change, tropospheric ozone, and water availability are threats to continued growth in yields.

Land use and agriculture (including forestry) account for an estimated 24 percent of planet-warming greenhouse gas emissions (land sequestration offsets an estimated 1/5

Agriculture contributes a majority of the emissions from human activities for both nitrous oxide (85%) and methane (50%).

of that total). Land-use change is an important source of carbon dioxide, although when properly managed, it could be a sink. The agriculture sector is the biggest contributor of nitrous oxide (largely from fertilizers) and methane (primarily from rice cultivation, ruminants and manure management), accounting for an estimated 85 percent and 50 percent, respectively, of emissions of these gases from human activities.

In addition, soil erosion resulting from crop cultivation, along with the nutrients carried with it, has degraded water quality in streams, lakes and coastal waters. In the U.S., the Gulf of Mexico and Chesapeake Bay are among the most seriously impacted coastal ecosystems. Nitrate contamination of groundwater from fertilizer use is also a concern. As efforts proceed to reduce these impacts, agricultural practices will need to adapt.

On the other side of the ledger, climate change and increasing levels of tropospheric ozone will continue to threaten future yields unless global emissions are brought under control. While warming may advantage areas limited by cold temperatures, extreme heat and drought are likely to increase the frequency of major crop failures. Tropospheric ozone damages the leaves of crops, especially at early stages of growth, and is already estimated to reduce yields by 10–12 percent in China, and somewhat less in the U.S. and Europe. Increasing competition for water resources as population and economic activity expand, combined with changing precipitation and snowpack, will affect water availability for irrigation, even as higher temperatures increase crop water needs. While warming speeds up the hydrological cycle—meaning more rainfall—computer model simulations show increased water stress in most important agricultural regions of the world.

While warming may advantage areas limited by cold temperatures, extreme heat and drought are likely to increase the frequency of major crop failures.

Evaluation of land resources by the U.N.'s Food and Agriculture Organization suggest availability of arable land itself is not a major constraint on food production at least through mid-century, assuming continued yield improvements. There are, however, some wild cards that could vastly impact agriculture in the coming decades. Among these are more ambitious policies to stabilize the climate, large-scale production of biomass energy, and major incentives for carbon sequestration in forests.

Since energy is an important input to agriculture, a global shift away from fossil fuels is likely to boost energy costs and thus make agricultural production more expensive. In addition, the space requirements for biomass energy and re-growing forests to sequester carbon could cut into the amount of land available for crops and livestock production.

Agriculture will need to continue to intensify use of available land, getting more output from less land, while at the same time reducing environmental impacts of the more intensive land-use practices.

Other long-term forces affecting agriculture include the industrialization of agriculture; technological advances; specialization or diversification of farming systems; reliance on a global or local food supply; and the use of land and waterways for urbanization, recreation and ecosystem protection. While some of these forces may make the job of feeding the world more difficult, technology that improves yields and limits vulnerability to environmental change, delivers nutrients efficiently and reduces food waste can hopefully overcome the challenges. At the same time, successful efforts to control climate change and ozone pollution will lessen the adaptation agriculture will need to make. More diversification of farming systems and well-developed international markets can further limit vulnerabilities to local droughts and disasters. And while new technology is certainly welcome, if not essential, adopting today's best practices worldwide can take us a long way. ■

A version of this essay was presented at Cargill's Minneapolis headquarters on Dec 16, 2015 to invited agriculture industry, university and NGO participants. A global producer of food, agriculture, financial & industrial products, Cargill is a signatory to the 2014 United Nations' New York Declaration on Forests, in which the company committed to helping cut natural forest loss in half by 2020, and end it by 2030.

See video of the presentation, *Nourishing People*, in the News/Speeches section of our website.

PHOTO: ISTOCK.COM / MATAUW

Contrails, Carbon and Climate

Steven Barrett probes the environmental impact of aviation and options for reducing it

One round-trip flight between New York and San Francisco generates two to three tons of carbon dioxide emissions per passenger, more than 10 percent of the annual carbon footprint of the typical American. The aircraft further heats up the climate through the cloudlike contrails (condensation trails) that form in its wake, and by cruising at an altitude where the warming effect of greenhouse gases is magnified. Air travel is now responsible for about five percent of global warming, but that number is expected to rise as demand—expected to triple by 2050—outpaces efficiency improvements in airliners.

Concerned about this trend, MIT's Steven Barrett aims to better understand the impact of aviation on the environment, from local air pollution to global climate change, and to explore technological, operational and regulatory options to reduce that impact. An associate professor of Aeronautics and Astronautics, director of the Laboratory for Aviation and the Environment, and Joint Program faculty member, Barrett has published around 50 papers covering aviation and its impact on the environment and public health.

Barrett's research in this field stems from an early interest in airplanes and environmental science while growing up in London and the Scottish Highlands. At Cambridge University, he earned his bachelor's degree and PhD in aerospace engineering—both involving stints at MIT as an exchange and visiting student. After completing his doctoral thesis on public health impacts of aviation in 2009, he spent a year on the Cambridge University faculty before assuming his current position at MIT, where he is part of the Joint Program, the MIT Center for Environmental Health Sciences, and the SMART Center for Environmental Sensing and Modeling. The associate director of the Partnership for Air Transportation Noise and Emissions Reduction from 2012 to 2015, he has served as an independent expert on green aviation, and on advisory committees on aviation and the environment and emissions mitigation.

Reducing aircraft emissions enough to make a dent in the local and global environment is a daunting challenge. The fastest growing mode of transport, aviation is expanding at about five percent a year. At the current rate, aviation CO_2 emissions—90 percent of which are produced at cruise altitude—are expected to double or triple by 2050. Unlike in the automotive industry, in which emissions can be cut by shifting to smaller cars or electric vehicles, obvious substitutes don't exist for today's aircraft, and even if they did, it can take decades to deploy them.

"Even if we took a recent MIT design for an aircraft with 70 percent reduction in fuel consumption, that might take 10 or

MIT Joint Program researcher Steven Barrett.

Barrett aims to better understand the impact of aviation on the environment, from local air pollution to global climate change, and to explore technological, operational and regulatory options to reduce that impact.

15 years to complete, well into the 2020s," Barrett explains. "To penetrate the market, it might take 30 years, to the 2050s. Even with the most aggressive technological scenario, we might hold CO_2 emissions constant. The problem is hugely challenging due to the expected growth rate of CO_2, the lack of substitution options and the technological inertia of the system."

Nonetheless, Barrett is among perhaps less than a dozen academicians whose primary focus is the environmental impact of aviation—research that's largely supported by the Federal Aviation Administration, NASA and the Environmental Protection Agency. Much of his work centers on evaluating the economic and environmental viability of replacing conventional jet fuel with biofuel.

FACULTY FOCUS

On first glance, using biofuels seems like a no-brainer. Producing a biofuel entails growing biomass, which through photosynthesis, extracts CO_2 from the atmosphere, and then converting the biomass to fuel, which when burned in flight, releases CO_2 back into the atmosphere. But the process is not exactly a zero-sum game. Converting biomass into liquid jet fuel requires a lot of energy, far more than it takes to process biomass as a coal substitute in power plants, where—since jet fuel burns much cleaner than coal—it could offset twice the CO_2 emissions at a much lower cost.

"That tells us that biofuels for aviation might make sense in the long run, but in the short run, there is more to gain by offsetting coal-fired power generation," says Barrett.

Another potential emissions reduction strategy that Barrett is pursuing is to minimize the impact of contrails. According to a recent study in *Nature Climate Change*, the radiative forcing, or warming, from aircraft contrails exceeds that of all CO_2 emissions produced by the entire 113-year history of aviation. One way to reduce the impact of contrails is to alter flight paths so that aircraft avoid very cold or wet regions of the atmosphere where they typically form, or fly at altitudes where they are less likely to emerge.

"The typical commercial jetliner altitude today is close to the most efficient altitude to create contrails, so higher or lower-flying aircraft could reduce their incidence," says Barrett, who has also determined that a switch from conventional, petroleum-based jet fuels to alternative fuels may result in thinner contrails. "If you could figure out a way to significantly mitigate contrails, you could perhaps reduce aviation's climate footprint by one-third or more."

Barrett is also evaluating strategies to reduce aviation's impact on air pollution and public health through new technologies, flight operations rules and/or cleaner jet fuels. Delivered primarily at cruise altitude, health-hazardous emissions from aircraft include sulfur dioxide, oxides of nitrogen, and particulate matter.

In a study published in 2012, he determined that removing sulfur from jet fuel would avert about 2,000 deaths per year

Much of Barrett's work centers on evaluating the economic and environmental viability of replacing conventional jet fuel with biofuel.

in the U.S. for just three cents a gallon, but it would also increase the warming effect of aviation by about 10 percent. That's because sulfur in airplane exhaust is emitted in the form of reflective sulfate particles, which cool the planet by reducing the amount of sunlight that reaches the surface. Barrett is currently analyzing the effects of aircraft-borne lead emissions in a joint EPA-funded study with MIT Associate Professor Noelle Selin. ■

In February 2016, the aviation industry agreed to the first global carbon emissions standards for commercial aircraft. Established by the U.N. and applicable to new aircraft starting in 2028, the standards could lower carbon emissions by more than 650 million metric tons between 2020 and 2040.

For more information about Steven Barrett's research, visit http://lae.mit.edu/barrett.

Related Publications:

Winchester, N., R. Malina, M.D. Staples and S.R.H. Barrett, 2015: The impact of advanced biofuels on aviation emissions and operations in the United States. *Energy Economics* 49 (2015), 482–491.

Trivedi, P., H. Olcay, M.D. Staples, M.R. Withers, R. Malina and S.R.H. Barrett, 2015: Energy return on investment for alternative jet fuels. *Applied Energy* 141 (2015), 167–174.

PHOTO: ISTOCK.COM / SIERRARAT

MIT JOINT PROGRAM ON THE SCIENCE AND POLICY OF GLOBAL CHANGE

Technology-Driven?

MIT graduate student Tochukwu Akobi investigates the impact of technological innovation on the price of oil

As the world strives for a low-carbon future, the search is on for fuels that are both emissions-free and cost-competitive with fossil fuels. One way to estimate how low alternative fuels must be priced to go head-to-head with fossil fuels is to run the Joint Program's Economic Projection and Policy Analysis (EPPA) model, which estimates the evolving costs of coal, oil and natural gas. By default, EPPA projects a long-term rise in the price of oil as producers gradually exhaust low-cost extraction opportunities and increasingly turn to higher-cost resources. This suggests that it's only a matter of time before zero-emissions fuels represent a better bargain. Just how accurate is this assessment?

With the exception of 2007–2008, the price of oil rose steadily between 2000 and 2014, but drastic reductions followed. The main drivers of this steep decline may be a combination of geopolitics, increased production of unconventional oil resources such as shale and tar sands, a faster rate of improvement in oil production technology, and other factors. One hypothesis is that technological advances—by enabling access to more reserves, reducing operating costs and increasing production volumes per investment dollar—have played a critical role in driving down oil prices, but it's unclear how fast the technology has been improving over the years.

Enter MIT graduate student and BP Fellow Tochukwu (Tox) Akobi, who since September has been systematically investigating that question as a Joint Program research assistant.

"I'm trying to define a relationship between technological improvement, capital investment and the price of oil, to see if this relationship can be used to inform the EPPA model."

"I'm trying to define a relationship between technological improvement, capital investment and the price of oil, to see if this relationship can be used to inform the EPPA model," says Akobi, whose work is funded by BP through the MIT Energy Initiative. His ultimate goal is to estimate the overall annual rate of technological improvement among leading oil companies, and incorporate that value in the EPPA model so as to better represent oil extraction costs and depletion rates in the coming decades.

Toward that end, he's analyzing data in annual reports and other public records—primarily over the past 15 years, but in some cases since the 1970s—from about a dozen leading oil and gas companies in order to infer the rate of technological improvement across the industry. Such improvement can be measured by evaluating how quickly these companies have upgraded their capability to extract more barrels of oil per invested dollar. In addition, Akobi is aggregating this data at the country level, with a focus on the U.S. and Canada. Finally, he is estimating the impact of unconventional oil production on U.S. oil prices by determining the number of active oil rigs in the U.S. that extract oil from unconventional sources.

Through this three-pronged approach, Akobi aims to uncover insights into the key drivers of technological improvement and how they influence price, and share those insights in his master's thesis.

"Tox has done a tremendous job of getting all the data—capital, number of workers, cost of production, etc.—from a dozen of the major oil companies," says Joint Program Deputy Director Sergey Paltsev, who is advising Akobi on the project. "His historically-based analysis should significantly improve our understanding of current fossil fuel price dynamics." Once Akobi determines a range for the annual rate of technological improvement, more rigorous research will be needed to see how it can be incorporated in EPPA's projections of the future energy mix.

By quantifying the oil industry's rate of technological improvement and the key drivers behind it, Akobi's research may also help industry leaders to optimize the amounts and timing of capital investments.

"Using this analysis, they might better determine where the current balance lies between productivity and profitability," he explains, "so that every dollar spent produces a reasonable return on investment."

Akobi's preparation for this work came both from the classroom—MIT courses in energy economics and policy sharpened his understanding of the factors that drive fossil fuel prices—and several years of experience in the oil and gas industry.

Tochukwu (Tox) Akobi at his workstation in the Joint Program office.

While balancing multiple academic and extracurricular commitments, Akobi found time to spearhead and implement a new approach to gauge the rate of technology improvement in the oil industry.

After earning a bachelor's degree in metallurgical engineering with honors from Ahmadu Bello University in his native Nigeria, Akobi served as a management consultant with Hay Group in South Africa and then returned to Nigeria to work for ExxonMobil over the next six years. His duties included field operations, project management, strategic planning and capital investment analysis. A student in MIT's System Design & Management (SDM) program since Fall 2014, Akobi has pursued a full plate of extracurricular activities. He chaired the SDM Student Leadership Council, helped organize the 2015 MIT Global Startup Workshop in Guatemala, and serves as a member of MIT's Energy Club, Society of Energy Fellows, Sloan Africa Business Club and Product Management Club. While balancing multiple academic and extracurricular commitments, Akobi found time to spearhead and implement a new approach to gauge the rate of technology improvement in the oil industry.

"In five months, I've been able to develop a method of pursuing this research in a space where this kind of analysis hasn't been done before at the global industry level," says Akobi, who, upon completing a master's degree in engineering and management in June, plans to work as a consultant with the Boston Consulting Group in Houston.

Reflecting on his time in MIT and with the Joint Program, he adds, "It's a privilege to be part of an organization that's working at the frontier of research that feeds directly into the global conversation." ■

AMERICAN GEOPHYSICAL UNION: SHOWCASING GLOBAL CHANGE

JOINT PROGRAM RESEARCH PRESENTED AT THE AGU'S ANNUAL FALL MEETING

In December, several Joint Program researchers and affiliates shared recent findings at the American Geophysical Union's (AGU) 2015 Fall Meeting in San Francisco, the largest Earth and space science conference in the world. They presented their research to nearly 24,000 attendees who gathered to learn about the latest discoveries, trends and challenges in the field.

Research Scientist Andrei Sokolov presented a poster, *Climate Stabilization at 2°C and 'Net Zero' Emissions*, exploring potential greenhouse gas emissions reduction scenarios aimed at ensuring that the global average surface temperature does not exceed 2°C above pre-industrial levels, a key target in the recent COP21 climate negotiations in Paris.

In their study, Sokolov and his coauthors put to the test a claim that's appeared in a number of recent publications—that to achieve the 2°C goal, net anthropogenic carbon dioxide (CO_2) emissions must be reduced to zero between 2050 and 2100. Running several emissions-driven climate simulations from 1861 to 2500 using the MIT Integrated Global System Modeling (IGSM) framework, they produced findings suggesting that anthropogenic emissions need not zero out by 2050 or 2100 because of carbon sinks in oceans and terrestrial ecosystems. Assuming a median value of climate sensitivity, they showed that the desired result could be achieved by reducing annual CO_2 emissions to about 50 percent of today's levels by 2050, and 20 percent by 2100. Collaborators on Sokolov's poster included three Joint Program researchers (Co-Director Ronald Prinn, Deputy Director and Senior Research Scientist Sergey Paltsev, and Research Scientist Y.-H. Henry Chen), and Shell International researcher Martin Haigh.

Noelle Selin, Esther and Harold E. Edgerton Career Development Associate Professor, Institute for Data, Systems and Society and Department of Earth, Atmospheric and Planetary Sciences, delivered a talk, *An Assessment of Uncertainty in Projections of Climate-Induced Changes to U.S. O_3 Pollution*, on the use of models of 21st-century climate change and air quality to explore major sources of uncertainty in projections of climate-induced change to surface ozone (O_3) over the U.S. Coupling the Community Atmosphere Model with Chemistry (CAM-Chem) to the IGSM framework, Selin and her coauthors evaluated and compared how the three main drivers of uncertainty in climate simulations—emissions scenario, model response and natural variability—propagate to estimates of O_3 concentrations.

PHOTO: AGU

Their simulations of atmospheric chemistry in 2050 and 2100 suggest that climate change may increase U.S. O_3 pollution substantially (to >5 parts per billion) under a business-as-usual case. Greenhouse gas mitigation policies can significantly lessen these impacts. To quantify this effect given the variability in climate responses, however, this work showed that large ensemble simulations are required (>15 years of simulations).

Coauthored by postdoctoral associate Fernando Garcia Menendez and Research Scientist Erwan Monier, the study showed that projected impacts of climate change on O_3 are largely dependent on uncertainties associated with natural variability and climate model response.

Monier was also a coauthor on two presentations by Joint Program affiliates: a talk delivered by Chris Forest (Pennsylvania State University), *Towards Quantifying Robust Uncertainty Information for Climate Change Decision-making*, and a poster presented by David Kicklighter (Marine Biological Laboratory), *Importance of Nitrogen Availability on Land Carbon Sequestration in Northern Eurasia during the 21st Century*.

Joint Program Deputy Director Adam Schlosser displayed a poster, *Quantifying Climate Impacts of Urban Surface Albedo Using the WRF Model*, on research for MIT's Concrete Sustainability Hub project, focused on the impact of albedo—the proportion of incident light or radiation reflected by a surface—from buildings and paved surfaces in urban areas on surface-air temperature. An important part of the energy budget in shaping local and regional climate, surface albedo could also be a potential tool to mitigate the anthropogenic effect on climate. The study showed that the impact of elevating surface albedo has a cooling effect that's robust at both local and regional scales.

"We ran the WRF model in a series of numerical experiments that modify the urban albedo over major metropolitan areas," said Schlosser. "The effect is mainly local due to the coarse resolution of the model (50 km), but experiments planned in the coming year will increase the spatial resolution (10 km) to see if we find downstream effects."

Joint Program Co-Director Ronald Prinn was also a coauthor on eight other posters or presentations related to the Advanced Global Atmospheric Gases Experiment (AGAGE), which has been measuring the composition of the global atmosphere continuously since 1978. Of those, four of the lead authors are current Joint Program postdoctoral fellows and graduate students (Langley DeWitt, Xuekun Fang, Jimmy Gasore and Michael McClellan), and two of the lead authors were formerly affiliated with the Joint Program and are now based at the University of Bristol (Anita Ganesan and Matthew Rigby). ■

JOINT PROGRAM IAP COURSES HIGHLIGHT FUNDAMENTALS OF CLIMATE SCIENCE AND POLICY

In January during the 2016 MIT Independent Activities Period (IAP), Joint Program graduate students and postdoctoral fellows presented the Introduction to Climate Science and Policy program, a fast-paced but accessible introduction to the Earth's climate system and the links between scientific and societal aspects of climate change. The program consisted of eight sessions on climate science and global and local climate policy, six of which are available on our website, in the News/Education section.

PHOTOS: DIMONIKA BRAY

Samantha Houston, a graduate student in the Technology and Policy Program (TPP), reviewed options for climate mitigation, adaptation and geoengineering.

TPP graduate student Katie Mulvaney presented a session on international, national and subnational climate governance.

JANOS PASZTOR LECTURE: A VIRTUOUS CIRCLE

U.N. INITIATIVE EXPANDING CLIMATE ACTION BEYOND NATIONAL LEVEL, SAYS TOP U.N. CLIMATE ADVISOR

At the recent U.N. climate talks in Paris, national governments weren't the only entities asked to do their part to help cap the rise in average global temperature since preindustrial times at 2 degrees Celsius. So, too, were so-called "non-state actors" such as NGOs and industry leaders, who along with national representatives, were urged to form partnerships and increase climate action in a process called the Action Agenda. The goal: to launch a virtuous cycle of climate action, where demonstration of action on the ground encourages negotiators to make more ambitious pledges, which, in turn, generate even more action.

In a lecture hosted by the MIT Joint Program on the Science and Policy of Global Change on March 2, Janos Pasztor, Senior Advisor to the U.N. Secretary-General on Climate Change, described the U.N.'s Action Agenda from its origins to its emergence at COP21 to its next steps. Pasztor '79 SM '79, who received his M.S. and B.S. degrees at MIT, has spent the past 35 years working for various U.N. and non-governmental organizations on issues of energy and environment, with an increasing focus on climate change. His previous U.N. appointments include Assistant Secretary-General on Climate Change, and Director of the Secretary-General's Climate Change Support Team.

Origins

Pasztor noted that until recently, U.N. climate negotiations—starting with the UN Framework Convention on Climate Change (UNFCCC) in 1992 and continuing with the annual Conference of the Parties (COP)—were largely limited to U.N. officials and national government representatives.

"It's all the same people. They talk to each other, some of them get promoted, they go into the [U.N.] Secretariat, some of them go from the Secretariat back to countries and they become delegates," he observed. "There [was] this sense that climate change links to everything, everything impacts climate change, and the negotiations are isolated."

Recognizing that much of the action that was necessary to stabilize the global climate was beneath the national government level, U.N. Secretary-General Ban Ki-moon invited heads of state as well as business, finance, civil society and local leaders to a Climate Summit in New York City in September 2014. Its objective was to identify shining examples of concrete actions in climate mitigation, adaptation, finance and other domains, and then import those examples into the negotiation process.

"The hope was that this would create a kind of virtuous circle," Pasztor explained, "because if there is recognition by the negotiators that there is action already on the

Janos Pasztor, Senior Advisor to the U.N. Secretary-General on Climate Change.

Pasztor described the U.N.'s Action Agenda from its origins to its emergence at COP21 to its next steps.

ground, then it would be easier for them to come to more ambitious agreements, and if they come to more ambitious agreements, then there will be even more action on the ground."

The summit resulted in many new initiatives, including the New York Declaration on Forests, a pledge by more than 150 partners from government, industry and civil society to halve the rate of deforestation by 2020 and to end it by 2030; a commitment by the world's largest food retailers to change their supply chains to reduce emissions and increase resilience; and promises from firms in the finance sector to shift billions of dollars of assets from high to low-carbon investments.

SAVE THE DATE: 14–15 APRIL, 2016

MIT Earth System Modeling (MESM) Workshop Retreat

MIT Endicott House Conference Center, Dedham, MA USA (Boston suburb 30–45 minutes from Boston Logan Airport)

The first annual MIT Earth System Model (MESM) retreat is designed to bring together the climate scientists who have developed and run the MESM framework, as well as students, postdoctoral fellows and sponsors of the MIT Joint Program on the Science and Policy of Global Change.

Participants will get a general introduction to MESM and its various components: the land, energy and water biogeophysics (CLM); the land biogeochemistry (TEM); the ocean dynamics and sea-ice; the ocean biogeochemistry and biology; the atmosphere dynamics and physics; and the atmospheric chemistry. We will highlight ongoing research projects focusing on each component of the model and present how the MESM framework will help advance the Joint Program's research agenda.

The retreat will also provide an ideal setting for an overview of Svante, the high-performance computer cluster on which MESM is run. We will demonstrate how to download, compile and run MESM code. An overriding objective of the retreat will be to elicit participant feedback and broad discussion about MESM.

By invitation only. For more information, please contact Frances Goldstein: fkg@mit.edu

"It was amazing to see the mixture of private sector and NGO delegates all sitting there and exchanging about action, and you could really feel that isolation was no longer the reality."

Bringing the Action Agenda to COP21

The summit also led to the first COP-level discussion of the Action Agenda at COP20 in Lima in December 2014, and a commitment to bring that agenda to the COP21 Paris climate talks one year later. Coordinated by the U.N. Secretary-General, the Executive Secretary of the UNFCCC and the presidents of Peru and France, this pledge became known as the Lima-to-Paris Action Agenda.

Each of the four parties, in collaboration with multiple stakeholders from the private sector and civil society, oversaw one or more of 12 work streams on energy efficiency, renewable energy, agriculture, transport, short-lived climate pollutants, forestry, resilience, cities and regions, innovation, buildings, business and private finance. They agreed that actions in these domains must be ambitious (consistent with capping the rise in average global temperature since pre-industrial times at 2°C); collaborative (preferably involving multiple stakeholders); aligned with the U.N.'s sustainable development goals; and transparent.

At the Paris Climate talks in December 2015, developments in all 12 work streams of the Lima-to-Paris Action Agenda were presented and discussed in full or half-day meetings that drew delegates from civil society and the private sector, as well as the U.N. Secretary General and French President Hollande. The meetings not only demonstrated specific actions on the ground but also produced many new commitments—all integrated into the 188 Nationally Determined Contributions to the Paris Agreement.

"It was amazing to see the mixture of private sector and NGO delegates all sitting there and exchanging about action, and you could really feel that isolation was no longer the reality," said Pasztor. "We have collectively managed to achieve a situation where all this incredible action and development that is taking place outside of the negotiation process has now found a way into the negotiation process. I think that's a very positive development, and we will really see the positive results of this over time."

As climate negotiators anticipate the 22nd Conference of the Parties (COP22) in Marrakesh, Morocco in November, the Action Agenda continues to grow, as more non-state actors join in. ■

This event was cosponsored by the MIT Joint Program, MIT Center for Collective Intelligence/MIT Climate CoLab, MIT Energy Initiative, MIT Environmental Solutions Initiative, MIT Office of the Vice President for Research, and MIT Sloan School of Management/MIT Sloan Sustainability Initiative.

See video, *The Action Agenda*, in the News/Speeches section of our website.

Milestones

SELIN NAMED LESHNER LEADERSHIP INSTITUTE FELLOW

Associate Professor Noelle Eckley Selin (Earth, Atmospheric and Planetary Sciences and Institute for Data, Systems and Society) was named as one of the first 15 fellows of the Leshner Leadership Institute for Public Engagement with Science, all climate scientists seeking to promote dialogue between science and society. The new fellows were recognized during the American Geophysical Union's Fall Meeting in San Francisco on December 16, 2015.

Selin's research focuses on using atmospheric chemistry modeling to inform decision-making strategies on air pollution, climate change and toxic substances including mercury and persistent organic pollutants. She has also published articles and book chapters on the interactions between science and policy in international environmental negotiations, in particular focusing on global efforts to regulate hazardous chemicals and persistent organic pollutants. Prior to joining the MIT faculty in 2010, Selin spent two years as a postdoctoral associate and research scientist with the MIT Joint Program on the Science and Policy of Global Change. She received her PhD in 2007 from Harvard University in Earth and Planetary Sciences. Previously, she was a research associate with the Initiative on Science and Technology for Sustainability at Harvard's Kennedy School of Government, a visiting Fulbright fellow at the European Environment Agency in Copenhagen, Denmark, and worked on chemicals issues at the U.S. Environmental Protection Agency.

STRZEPEK CO-EDITOR OF BOOK IN AFRICA DEVELOPMENT FORUM SERIES

Research Scientist Kenneth Strzepek co-edited *Enhancing the Climate Resilience of Africa's Infrastructure: The Power and Water Sectors*, in the Africa Development Forum Series.

Related Publication:

Cervigni, R., R. Liden, J.E. Neumann and K.M. Strzepek, 2015: *Enhancing the Climate Resilience of Africa's Infrastructure: The Power and Water Sectors.* Africa Development Forum; Washington, DC: World Bank. © World Bank. https://openknowledge.worldbank.org/handle/10986/21875 License: CC BY 3.0 IGO

MONIER AND WINCHESTER: PRINCIPAL RESEARCH SCIENTISTS

Two Joint Program researchers were promoted to Principal Research Scientist: Erwan Monier and Niven Winchester.

Erwan Monier's research focuses on quantifying the uncertainty in future regional climate projections and estimating the contributions from various sources of uncertainty, including the uncertainty in the global climate system response, emissions of greenhouse gases and aerosols, natural variability, future land use change as well as climate model structural uncertainty. He is a contributor to the intercomparison project with Earth System Models of Intermediate Complexity (EMICs) undertaken in support of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5). He is also a leading climate scientist for the US EPA Climate Change Impacts and Risk Analysis (CIRA) project. Within this project, he has been involved in various climate impact assessments including the impacts of climate on agriculture and water resources, on wildfires and terrestrial ecosystem carbon storage, and on air quality and health. He completed his PhD in Atmospheric Science at the University of California, Davis, and holds a Master's degree in Hydraulics and Fluid Dynamics Engineering from the National Polytechnic Institute of Toulouse (ENSEEIHT, University of Toulouse).

Niven Winchester's research focuses on analyses of climate, energy and trade policies using applied general equilibrium analysis. Recent studies assess the effectiveness of border carbon adjustments, China's trade-embodied CO_2 emissions, the feasibility, costs, and environmental implications of large-scale biomass energy, and the economic and emissions impacts of US aviation biofuel goals. Prior to joining MIT, Dr. Winchester held a faculty position at the University of Otago and earned a PhD from the University of Nottingham. Dr. Winchester's research has informed several organizations on trade and energy issues, including the OECD, the Federal Aviation Administration, and the New Zealand Ministry of Foreign Affairs and Trade. In 2013, Dr. Winchester was awarded a Global Trade Analysis Project Research Fellowship for outstanding research. He is currently co-editor of the *Journal of Global Economic Analysis*.

US Environmental Protection Agency CIRA Project
http://www.epa.gov/cira

Journal of Global Economic Analysis
https://www.jgea.org/resources/jgea/ojs/index.php/jgea

COMINGS & GOINGS

Alyson Kenword completed a visit as a Postdoctoral Affiliate working with Climate Central.

Thomas Geissman completed a visit as a PhD student and returned to ETH Zurich.

Gunther Glenk arrived as a visiting PhD student with CEEPR from Technical University of Munich.

Nina Rajpurkar was appointed as a research associate with CECP.

Bhargavi Ramanathan began an undergraduate research project as a senior at Wellesley College.

David Ramberg PhD '15 accepted a position at Amazon in Seattle.

Xingyao Shen joined as a Master's student.

Arun Sign joined as a Master's student.

Christian Stoll completed a visit as a PhD student with CEEPR and returned to Technical University of Munich.

Cicero Zanetti de Lima arrived as a visiting a PhD student from the Federal University of Vicosa, Brazil.

Danwei Zhang departed after completing a Master's degree.

IN THE NEWS

Nov 9 - *World Resources Institute* - INSIDER: Why Are INDC Studies Reaching Different Temperature Estimates?

Nov 12 - *AP* - CLIMATE COUNTDOWN: When's a warming treaty not a treaty?

Nov 12 - *Greentech Lead* - COP21: Climate scientists to debate on decarbonizing the world economy

Nov 24 - *Nature* - Is the 2°C world a fantasy?

Nov 30 - *CNN* - COP21: Can we avoid climate apocalypse? (Opinion)

Dec 4 - *World Nuclear News* - Academics at Paris talks make plea for nuclear power

Dec 7 - *PR Newswire* - MIT-China team offers approach for addressing distributional equity alongside economic efficiency in a national emissions trading system

Dec 9 - *Scientific American* - CO_2 Pollution Holds Steady as China's Economy Cools

Dec 11 - *ChinaFAQs* - Where Wai (outer) meets Nei (inner): How China's international and domestic policy positions reinforce each other

Dec 11 - *Dallas Morning News* - Climate proposal's goals on target, action lacking, scientists say

Dec 11 - *Portland Press Herald* - Goals for global warming clash with reality

Dec 14 - *Carbon Pulse* - COMMENT: For carbon pricing in China, the question is not "if" but "how" – with lessons for the U.S.

Dec 15 - *The Conversation* - Engaging civil society will help ensure transparent and credible review of climate pledges

Dec 20 - *NY Magazine* - People Who Were Certain Climate Change Is Fake Are Now Certain That Paris Can't Stop It

Dec 28 - *Energy Collective* - Caldeira, Emanuel, Wigley, and Hansen Statement at COP 21

Jan 13 - *The Australian* - Rusal's Deripaska calls for worldwide carbon tax

Jan 16 - *The Economist* - Sharing the Nile

Jan 22 - *Scientific American* - The Future of Epic Blizzards in a Warming World

Jan 22 - *PRI* - Can a Norwegian company with 'oil' in its name transform into a wind company?

Jan 29 - *Politifact* - Rubio says he has 'never supported cap and trade,' despite energy deal as Florida speaker

Feb 4 - *National Geographic* - Has the U.S. Really Reached an Epic Turning Point in Energy?

Feb 8 - *Washington Post* - What Earth will be like in 10,000 years, according to scientists

Feb 9 - *The Conversation* - Are tighter EPA controls on mercury pollution worth it?

Feb 19 - *CLP Group blog* - Building a more sustainable future in a world where energy production, water resources, land use and environmental concerns intersect

Feb 22 - *NY Post* - The Paris climate deal won't even dent global warming

Feb 24 - *Nature* - Global warming 'hiatus' debate flares up again

Feb 27 - *NY Times* - Scientists Protest Cuts and Commercialization at Australian Climate Center

Mar 9 - *Carnegie Science* - Greenhouse gas 'bookkeeping' turned on its head

Mar 11 - *DecodedScience.org* - Melting Permafrost in the Arctic: A Tale of Two Feedbacks

Mar 18 - *WilsonCenter.org* - Putting the Brakes on Carbon: China After Paris [webcast]

Mar 22 - *ChinaFAQs* - China's Thirteenth Five-Year Plan Paves the Way for a CO_2 Emissions Peak

Mar 23 - *Boston Globe (Opinion)* - Pricing solar so it doesn't raise everyone's energy rates

JOINT PROGRAM REPORTS

293. Uncertainty in Future Agro-Climate Projections in the United States and Benefits of Greenhouse Gas Mitigation

292. Costs of Climate Mitigation Policies

291. Scenarios of Global Change: Integrated Assessment of Climate Impacts

290. Modeling Uncertainty in Climate Change: A Multi-Model Comparison

289. The Impact of Climate Policy on Carbon Capture and Storage Deployment in China

288. The Influence of Gas-to-Liquids and Natural Gas Production Technology Penetration on the Crude Oil-Natural Gas Price Relationship

287. Impact of Canopy Representations on Regional Modeling of Evapotranspiration using the WRF-ACASA Coupled Model

JOINT PROGRAM REPRINTS

2015-30. Consumption-Based Adjustment of Emissions-Intensity Targets: An Economic Analysis for China's Provinces (*Environ. Resour. Econ.*)

2015-29. Emulating maize yields from global gridded crop models using statistical estimates (*Agricultural & Forest Meteorology*)

2015-28. Reconciling reported and unreported HFC emissions with atmospheric observations (*PNAS*)

2015-27. The Observed State of the Energy Budget in the Early 21st Century (*J. Climate*)

2015-26. US major crops' uncertain climate change risks and greenhouse gas mitigation benefits (*Environmental Research Letters*)

2015-25. Benefits of mercury controls for the United States (*PNAS*)

2015-24. Electricity generation costs of concentrated solar power technologies in China based on operational plants (*Energy*)

2015-23. An analysis of China's climate policy using the China-in-Global Energy Model (*Economic Modelling*)

2015-22. Protected areas' role in climate-change mitigation (*Ambio*)

2015-21. The impact of climate change on wind and solar resources in southern Africa (*Applied Energy*)

2015-20. Enhanced marine sulphur emissions offset global warming and impact rainfall (*Nature Scientific Reports*)

2015-19. Climate change impacts and greenhouse gas mitigation effects on U.S. water quality (*J. Adv. Model. Earth Sys.*)

2015-18. Quantitative Assessment of Parametric Uncertainty in Northern Hemisphere PAH Concentrations (*Environ. Sci. Technol.*)

PEER-REVIEWED STUDIES & PENDING REPRINTS

Determinants of Family Farms Efficiency: Evidence from the Senegal River Valley (*Experimental Agriculture*)

Global and regional emissions estimates of 1,1-difluoroethane [HFC-152a, CH_3CHF_2] from in situ and air archive observations (*Atmos. Chem. Phys.*)

Extreme precipitation drives groundwater recharge: the northern High Plains Aquifer, Central United States, 1950–2010 (*Hydro. Proc.*)

How well do global ocean biogeochemistry models simulate dissolved iron distributions? (*Global Biogeochem. Cycles*)

Climate extremes and ozone pollution: a growing threat to China's food security (*Ecological Soc. Of America*)

Long-term economic modeling for climate change assessment (*Economic Modelling*)

Anthropogenic Aerosols and the Distribution of Past Large-Scale Precipitation Change (*Geophys. Res. Lett.*)

Metamodeling of Droplet Activation for Global Climate Models (*J. Atmos. Sci.*)

The terrestrial biosphere as a net source of greenhouse gases to the atmosphere (*Nature*)

Carbon emissions in China: How far can new efforts bend the curve? (*Energy Economics*)

Equity and emissions trading in China (*Climatic Change*)

The Observed State of the Water Cycle in the Early Twenty-First Century (*J. Climate*)

The Response of the South Asian Summer Monsoon to Temporal and Spatial Variations in Absorbing Aerosol Radiative Forcing (*J. Climate*)

Increase in HFC-134a emissions in response to the success of the Montreal Protocol (*Journal of Geophysical Research: Atmospheres*)

The dynamical landscape of marine phytoplankton diversity (*Journal of the Royal Society Interface*)

Using Green's Functions to initialize and adjust a global, eddying ocean biogeochemistry general circulation model (*Ocean Modelling*)

Simulation of atmospheric N_2O with GEOS-Chem and its adjoint: evaluation of observational constraints (*Geosci. Model Dev.*)

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