MIT JOINT PROGRAM · SCIENCE · POLICY · GLOBAL CHANGE

GLOBAL CHANGES

MIT JOINT PROGRAM ON THE SCIENCE & POLICY OF GLOBAL CHANGE
SPRING 2017

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- *Future of forests under climate change*
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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.*

In This Issue:

MIT JOINT PROGRAM ON THE SCIENCE AND POLICY OF GLOBAL CHANGE

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Climate policy and bioenergy: A tree-hugger's guide

One of the most controversial issues in establishing miti-gation policy for climate change is the role of bioenergy. Nine years ago a paper by Timothy Searchinger in the journal *Science* laid down a gauntlet, suggesting that bioenergy would be a far-from-carbon-neutral source of energy because of land-use emissions. If virgin forests are harvested for bioenergy, argued Searchinger, the carbon implications are obvious: a large initial carbon debt from lost carbon in standing forests and soils. Less obvious are possible indirect emissions; even if biomass is harvested sustainably, it could induce land-use change and deforestation elsewhere in the world.

The gauntlet was picked up, with significant follow-on work, including several papers from the Joint Program. A basic issue with Searchinger's paper is that it did not account for behavioral response on the intensive margin. That is, are landowners more likely to increase production on existing crop and pasture land (the intensive margin) rather than cut down carbon-rich virgin forests (the extensive margin)? Some movement on both margins is likely, but how much in either direction will determine the importance of indirect emissions, or the possibility of net carbon uptake on land from bioenergy expansion.

The issue of bioenergy and carbon accounting has been in the news again lately. A recent Chatham House report called out the climate risks of bioenergy. The report maintained that carbon neutralilty of bioenergy "in reality cannot be assumed," that international greenhouse gas accounting rules risk never accounting for "a proportion of the emissions from biomass," and that the "the current criteria in use in some EU member states and under development in the EU" do not meet the intended sustainability goals.

The report drew a letter of objection by experts at the International Energy Agency and further response supporting the Chatham House view. The IEA letter claimed that the Chatham House report had a "misplaced focus on emissions at the point of combustion," ignoring regrowth; an "inaccurate interpretation of impact of harvest on forest carbon stock;" and an "unrealistic counterfactual scenario" in which the land, if not used for biomass energy, would remain undisturbed.

The Environmental Protection Agency convened a Science Advisory Board (SAB) a few years ago (I'm on it) to look at the carbon implications of bioenergy, with a final report due soon. I am not at liberty to share details from the SAB Report. Public comment versions of the report rejected the simple assumption of carbon neutrality of bioenergy. The work of the SAB was limited by the constraints of the guidance it received to consider biomass energy narrowly, and focused on approaches that would rely on model projections requiring simulation several decades into the future. This is a heavy demand on the predictive power of models.

To quote our president, "Who could have known it could be so complex?"

Actually, the solution is fairly simple if we step back and look at the problem broadly: it's forest protection. This follows standard economic theory of focusing directly on the problem of concern. Deforestation can be addressed through conventional land protection policies such as creating protected areas, or more unconventionally by pricing changes in land-based carbon stocks.


John Reilly, Joint Program Co-Director

The folly of focusing only on bioenergy and its impact on land use is that bioenergy only accounts for a small fraction of land use—about two percent of cropland, much less than one percent of all agricultural land (including pasture). It follows that most of land-use change is occurring due to other factors—expanding other agricultural areas, urbanization, road construction, etc. No matter how detailed (and even accurate) estimates of bioenergy's impact on land use, rules focused only on bioenergy would do nothing to prevent deforestation due to other causes.

The indirect emissions dilemma is impossible to crack with "sustainability" criteria on bioenergy sourcing. It is essentially impossible to track down indirect emissions that result from shuffling and shifting what was produced where, as "sustainable" production of biomass squeezes out existing activities on that land that must be made up somewhere else. Onerous sustainability rules would most likely kill bioenergy as an option altogether.

Forest protection policy would guard against land-use change from all sources. While negotiators work to make forest protection the norm everywhere, sourcing bioenergy from countries with records of forest protection makes sense. Rather than complex criteria, it is a simple go/no-go decision. And, if a country wants to get on the bioenergy export bandwagon, such a strategy would give them an incentive to improve protection of forests so they met that basic criteria. This won't protect against indirect leakage out of the certified bioenergy export countries, but I believe it can lead us in the right direction. ■

—John Reilly, Joint Program Co-Director

Related Publications

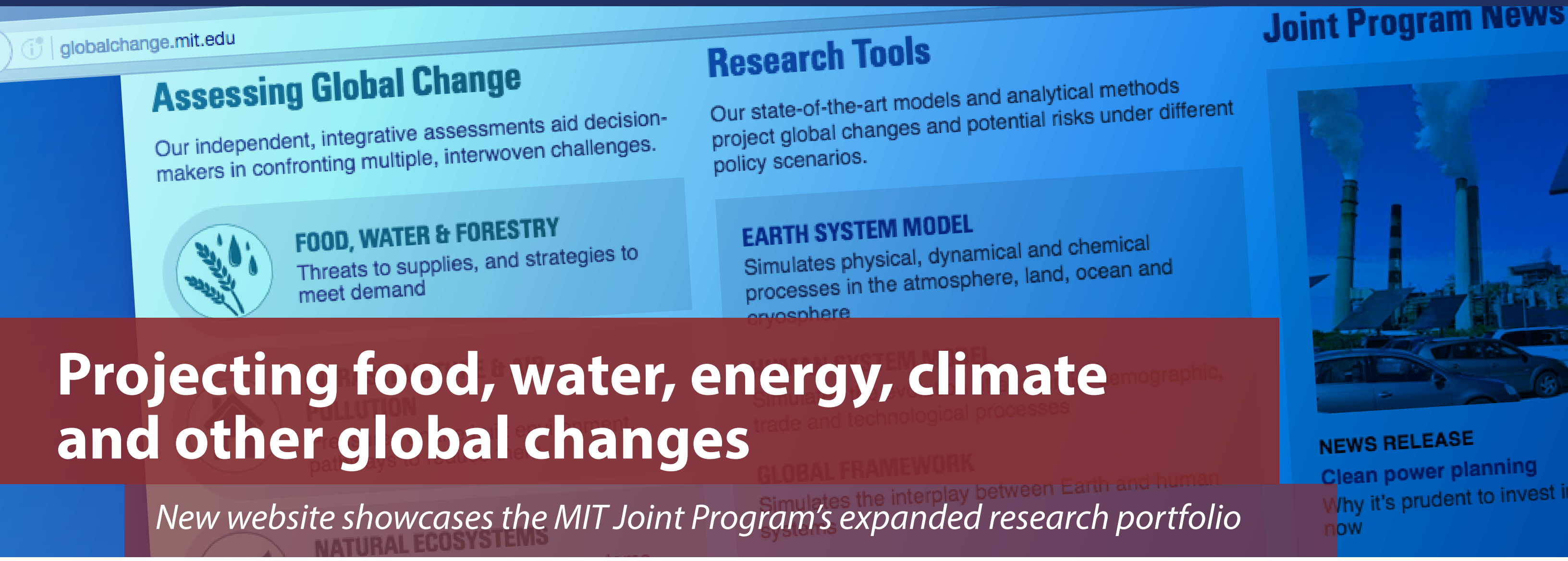
Searchinger, T. *et al.* (2008): Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. *Science* 319(5867): 1238–1240.

Winchester, N. *et al.* (2016): The impact of water scarcity on food, bioenergy and deforestation. *Joint Program **Report 300***.

Winchester, N. & J. Reilly (2015): The feasibility, costs, and environmental implications of large-scale biomass energy. *Energy Economics* 51, 188–203.

Reilly, J.M. *et al.* (2012): Using land to mitigate climate change: Hitting the target, recognizing the tradeoffs. *Environ. Sci. Technol.*, 46(11): 5672–5679.

Melillo, J.M. *et al.* (2009): Indirect Emissions from Biofuels: How Important? *Science* 326(5958): 1397–1399.



Projecting food, water, energy, climate and other global changes

New website showcases the MIT Joint Program's expanded research portfolio

Phytoplankton bloom off Denmark in 2004

Mapping out a low-carbon future

Water scarcity, air pollution and climate change

Projecting the impacts of land-use change

These recent headlines reflect the breadth of the MIT Joint Program on the Science and Policy of Global Change. They draw attention not only to climate change, a topic with which the Joint Program has been associated for more than 25 years, but also to changes in energy consumption, water availability, air quality and land use. In recent years the Joint Program's research portfolio has expanded considerably, leading the Program to redefine its work in terms of seven research focus areas and four research tools.

The seven research focus areas include food, water and forestry; infrastructure and air pollution; natural ecosystems; energy; Earth system science; climate policy; and regional analysis for the Americas, Asia, Europe and Africa. The four research tools consist of analytical methods to quantify risk at global and regional scales, and three Joint Program models covering the Earth system (the MIT Earth System Model (MESM)), human system (the MIT Economic Projection and Policy Analysis (EPPA) model) and a global framework (the Integrated Global System Modeling (IGSM) framework) that simulates the interplay between Earth and human systems.

"Most of our work will fall in more than one of these broad categories, and likely several of them," says Joint Program Co-Director John Reilly. "As we accept the reality of global environmental change and the Earth as a system that's continuously impacted by human activity, our research must become more granular. This granularity is intended to enable decision-makers to more easily develop effective strategies to limit our impact on the environment and adapt to unavoidable changes."

Toward that end, the Joint Program has developed a new website that places these categories front and center. Launched in January, the new site (http://globalchange.mit.edu/) enables visitors to learn about advances the Program is making in its seven core research focus areas and in the development of four main research tools used to project changes in those seven areas.

While the homepage highlights the breadth of the Program's research portfolio, the landing pages for the seven research focus areas and four research tools showcase the depth of the Program's work. Each landing page includes an introduction to the topic; the latest publications, news and media coverage; active research projects; and researchers associated with the research focus area or tool.

Visitors may also access reverse-chronological-order displays of all of our research publications; signature publications—our *Global Changes* newsletter and annual *Food, Water, Energy and Climate Outlook*; and other news, media and event coverage.

Program sponsors also have exclusive access to a section of the website that provides pre-release publications and early access to our *Global Changes* newsletter; our Annual Report; and information on past and upcoming Global Change Forums, conferences, webinars and lectures. A sponsors' dashboard will soon be added that will provide sponsors with rapid access to latest and upcoming publications, news and events.

"We believe this new website will allow both the public and our research sponsors to find what they are looking for more quickly, and to better recognize the variety of studies undertaken by our researchers," says Reilly. ■

Projecting the impacts of land-use change

New book chapter highlights the Joint Program's approach to representing land use in global computable general equilibrium models

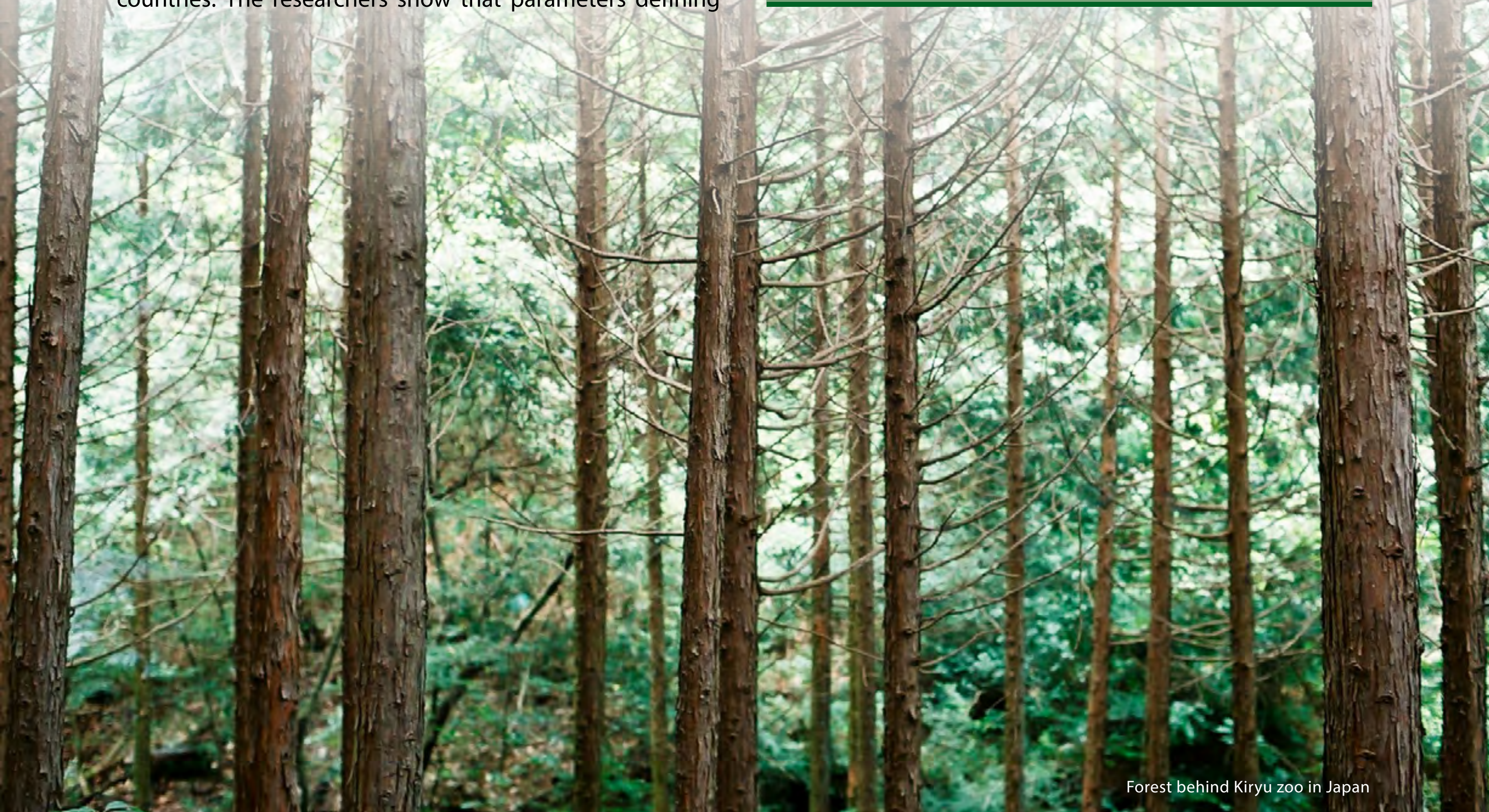
The incorporation of natural resources has been a growing area of focus in the evolution of computable general equilibrium (CGE) models, which use actual data to estimate the economic impacts of changes in technology, consumption patterns and other factors. A case in point is the explicit representation of land use and land-use conversion in global CGE models in order to project land-use impacts on food prices, international trade, climate change mitigation strategies and other critical global and regional concerns.

In a new book chapter, researchers at the Joint Program highlight the advantages of their approach to including land use in a global CGE model—the MIT Economic Projection and Policy Analysis (EPPA) model—and representing its connection to the broader economy through agriculture and forestry production. In simulations produced by the EPPA model, they find important linkages between environmental services and economic development as well as differences in land-use trajectories among developed and developing countries. The researchers show that parameters defining agricultural yields and population growth, far more than GDP growth rates, are particularly important in projecting future services from land use.

Co-authored by Joint Program Research Associate Angelo Gurgel, Research Scientist Henry Chen, Deputy Director Sergey Paltsev and Co-Director John Reilly, the chapter, "CGE models: Linking natural resources to the CGE framework," appears in *Computable General Equilibrium Models*, Volume 3 in the World Scientific Publishing Company's (WSPC) four-volume *World Scientific Reference on Natural Resources and Environmental Policy in the Era of Global Change*. ■

Related Publication

Gurgel, A., H. Chen, S. Paltsev and J. Reilly (2016): CGE Models: Linking natural resources to the CGE framework. *The WSPC Reference on Natural Resources and Environmental Policy in the Era of Global Change: Volume 3: Computable General Equilibrium Models*, T. Bryant and A. Dinar (eds.), World Scientific.



Forest behind Kiryu zoo in Japan

Study finds more extreme storms ahead for California

New technique predicts frequency of heavy precipitation with global warming

MIT scientists have found that extreme precipitation events in California should become more frequent as the Earth's climate warms over this century.

By Jennifer Chu | MIT News Office

On Dec. 11, 2014, a freight train of a storm steamed through much of California, deluging the San Francisco Bay Area with three inches of rain in just one hour. The storm was fueled by what meteorologists refer to as the "Pineapple Express"—an atmospheric river of moisture that is whipped up over the Pacific's tropical waters and swept north with the jet stream.

By evening, record rainfall had set off mudslides, floods and power outages across the state. The storm, which has been called California's "storm of the decade," is among the state's most extreme precipitation events in recent history.

Now MIT scientists have found that such extreme precipitation events in California are expected to become more frequent as the Earth's climate warms over this century. The researchers developed a new technique that predicts the frequency of local, extreme rainfall events by identifying telltale large-scale patterns in atmospheric data. For California, they calculated that, if the world's average temperatures rise by four degrees Celsius by the year 2100, the state will experience three more extreme precipitation events than the current average, per year.

The researchers, who have published their results in the *Journal of Climate*, say their technique significantly reduces the uncertainty of extreme storm predictions made by standard climate models.

"One of the struggles is that coarse climate models produce a wide range of outcomes. [Rainfall] can increase or decrease," says Adam Schlosser, senior research scientist in MIT's Joint Program on the Science and Policy of Global Change. "What our method tells you is, for California, we're very confident that [heavy precipitation] will increase by the end of the century."

The research was led by Xiang Gao, a research scientist in the Joint Program. The paper's co-authors include Paul O'Gorman, associate professor of earth, atmospheric, and planetary sciences; Erwan Monier, principal research scientist in the Joint Program; and Dara Entekhabi, the Bacardi Stockholm Water Foundations Professor of Civil and Environmental Engineering.

"Regardless of the combination of atmospheric variables we used, the new schemes were much closer to observations."

Large-scale connection

Currently, researchers estimate the frequency of local heavy precipitation events mainly by using precipitation information simulated from global climate models. But such models typically carry out complex computations to simulate climate processes [at a resolution of] hundreds and even thousands of kilometers. At such coarse resolution, it's extremely difficult for such models to adequately represent small-scale features such as moisture convection and topography, which are essential to making accurate predictions of precipitation.

To get a better picture of how future precipitation events might change region by region, Gao decided to focus not on simulated precipitation but rather on large-scale atmospheric patterns, which climate models are able to simulate much more reliably.

"We've actually found there's a connection between what climate models do really well, which is to simulate large-scale motions of the atmosphere, and local, heavy precipitation events," Schlosser says. "We can use this association to tell how frequently these events are occurring now, and how they will change locally, like in New England, or the West Coast."

Weather snapshots

While definitions vary for what is considered an extreme precipitation event, in this case the researchers defined such an event as being within the top five percent of a region's precipitation amounts in a particular season, over periods of almost three decades. They focused their analysis on two areas: California and the Midwest, regions which generally experience relatively high amounts of precipitation in the winter and summer, respectively.

For both regions, the team analyzed large-scale atmospheric features such as wind currents and moisture content, from 1979 to 2005, and noted their patterns each day that extreme precipitation occurred. Using statistical analysis, the researchers identified telltale patterns in the atmospheric data that were associated with heavy storms.

"We essentially take snapshots of all the relevant weather information, and we find a common picture, which is used as our red flag," Schlosser explains. "When we examine historical simulations from a suite of state-of-the-art climate models, we peg every time we see that pattern."

Using the new scheme, the team was able to reproduce collectively the frequency of extreme events that were observed over the 27-year period. More importantly, the results are much more accurate than those based on simulated precipitation from the same climate models.

"None of the models are even close to the observations," Gao says. "And regardless of the combination of atmospheric variables we used, the new schemes were much closer to observations."

"Actionable information"

Bolstered by their results, the team applied their technique to large-scale atmospheric patterns from climate models to predict how the frequency of heavy storms may change in a warming climate in California and the Midwest over the next century. They analyzed each region under two climate scenarios: a "business as usual" case, in which the world is projected to warm by four degrees Celsius by 2100, and a policy-driven case, in which global environmental policies that regulate greenhouse gases should keep the temperature increase to two degrees Celsius.

For each scenario, the team flagged those modeled large-scale atmospheric patterns that they had determined to be associated with heavy storms. In the Midwest, yearly instances of summer extreme precipitation decreased slightly under both warming scenarios, although the researchers say the results are not without uncertainty.

For California, the picture is much clearer: under the more intense scenario of global warming, the state will experience three more extreme precipitation events per year, on the order of the December 2014 storm. Under the policy-driven scenario, Schlosser says "that trend is cut in half."

The team is now applying its technique to predict changes in heat waves from a globally warming climate. The researchers are looking for patterns in atmospheric data that correlate with past heat waves. If they can more reliably predict the frequency of heat waves in the future, Schlosser says that can be extremely helpful for the long-term maintenance of power grids and transformers, which are vulnerable to overheating.

"That is actionable information," Schlosser says. ■

This research was supported, in part, by the National Science Foundation, NASA and the Department of Energy. This article has been updated since its appearance in MIT News.

Related Publication

Gao, X. *et al.* (2017): Twenty-First-Century Changes in U.S. Regional Heavy Precipitation Frequency Based on Resolved Atmospheric Patterns. *J. Climate* 30, 2501–2521.

What's the best way for Europe to curb greenhouse emissions from cars?

Emissions trading would be more effective than mileage standards, new study shows

David L. Chandler | MIT News Office

As the European Union contemplates new policies aimed at meeting its emissions-reduction commitments under the Paris Agreement on climate change, a new study by MIT and European researchers could provide some valuable guidance on the most effective strategy.

Instead of a grams-of-carbon-dioxide-per-kilometer standard for automotive emissions—analogous to the United States' CAFE (corporate average fuel economy) standards—the EU could achieve the same results for CO_2 emission reduction, at far lower cost to the economy, by simply extending their existing emissions-trading system to encompass transportation rather than just electricity generation and energy intensive industry, the researchers found.

Switching from the automotive standards to the trading scheme could save as much as 63 billion Euros, says the study's lead author Sergey Paltsev, deputy director at MIT's Joint Program on the Science and Policy of Global Change and senior research scientist at the MIT Energy Initiative. The results were published in the journal Transportation, in a paper co-authored by Joint Program researchers Valerie Karplus, Henry Chen, Paul Kishimoto, and John Reilly, and three others.

"There are many ways to do policies" to try to reduce greenhouse gas emissions, Paltsev says, "and sometimes political reality doesn't allow you to do things the best way." But as the EU seeks ways to implement the 40 percent emissions reduction by 2030 that it agreed to at the 21st Conference of the Parties (COP21) meeting in Paris, policymakers may be well-positioned to use this agreement as an impetus to adopt such an expansion of their emissions trading system.

"I'm an economist, and if I see 63 billion [Euros] lying on the floor, I say pick it up!"

A chance for a fix

The existing emissions trading system in Europe has not worked well, Paltsev says, partly because its price on carbon is quite low, and partly because it does not encompass enough different emissions-producing sectors of the economy. However, "the system can be fixed, and this is a great opportunity to fix it," he says.

The new analysis, Paltsev says, clearly shows that instead of imposing mileage efficiency standards, "there is a much better way to achieve the relevant targets" for cutting emissions from the transportation sector. He points out that because of high fuel taxes and the resulting high cost of gasoline in Europe, the existing fleet of passenger cars there is already more efficient than the U.S. fleet, so implementing stringent fuel efficiency standards would be more costly for Europe.

From an economic point of view, "emissions trading or a carbon tax is going to achieve their emissions goals at the lowest possible cost to society," says Paltsev, who is an economist and an engineer by training. And the emissions trading system is already established in the EU, he says, even though in its present form the system is flawed because of over-allocation of emission permits and interaction with renewable energy requirements. In addition, it only addresses the most energy-intensive sectors, primarily power generation. However, the trading system could easily be expanded to encompass private vehicles as well, according to Paltsev.

Since the goal is to achieve a given amount of reduction in the EU's overall greenhouse gas emissions, expanding the program to include transportation could achieve the same amount of reduction, according to the new study, "and save money for taxpayers and the European economy—and those savings can be quite substantial," Paltsev says.

Detailed computer modeling

The team used a computer model developed at the Joint Program that encompasses the scenarios' interactive effects on all aspects of the economy, rather than just the transportation sector as most analyses do. For example, the interactive model includes secondary effects such as how manufacturing or service industries may respond to policy changes that affect transportation costs, which can in turn influence the cost of goods. Using this model, the study found that using the emissions trading system instead of a mileage standard could save between 24 and 63 billion Euros in 2025, he says, and "achieve exactly the same goal." He adds, "I'm an economist, and if I see 63 billion lying on the floor, I say pick it up!"

The modeling team also benefited from having access to detailed data from the U.S. Environmental Protection Agency about the costs of meeting fuel standards in this country, whereas analysts in Europe who studied these tradeoffs "didn't have that luxury," he says. As a result, their studies were much simpler and "didn't provide the richness of data the EPA has been able to achieve."

He says the team presented their findings to EU officials in Brussels, and the initial response there was "very receptive, and that's a good sign." The approach used by this team is one that they hope will be replicated in analyzing other proposed policy measures and other regions of the world. "It shows you need to have this kind of overarching view, to look at all sectors at the same time," in order to derive useful policy recommendations.

Andreas Schafer, professor of energy and transport at University College London, who was not involved in the analysis, noted that "this study, for the first time, quantifies the vast economic costs of that policy using a general equilibrium framework. Although the figures should be considered with caution (as also suggested by the authors), the extra costs of separate emission standards between 2015 and 2020 compare to roughly half the EU Framework Programme for Research and Innovation Horizon 2020 [spending] of around 80 billion Euros over nearly the same period."

The research team also included Andreas Löschel of the University of Münster, in Germany; Kathrine von Graevenitz of the Center for European Economic Research, in Germany; and Simon Koesler of the Center for Energy Policy at the University of Strathclyde, in Glasgow, U.K. The research was supported by the U.S. Department of Energy, Office of Science, the U.S. Environmental Protection Agency and other sponsors from government, industry and foundations through the Joint Program on the Science and Policy of Global Change. ■

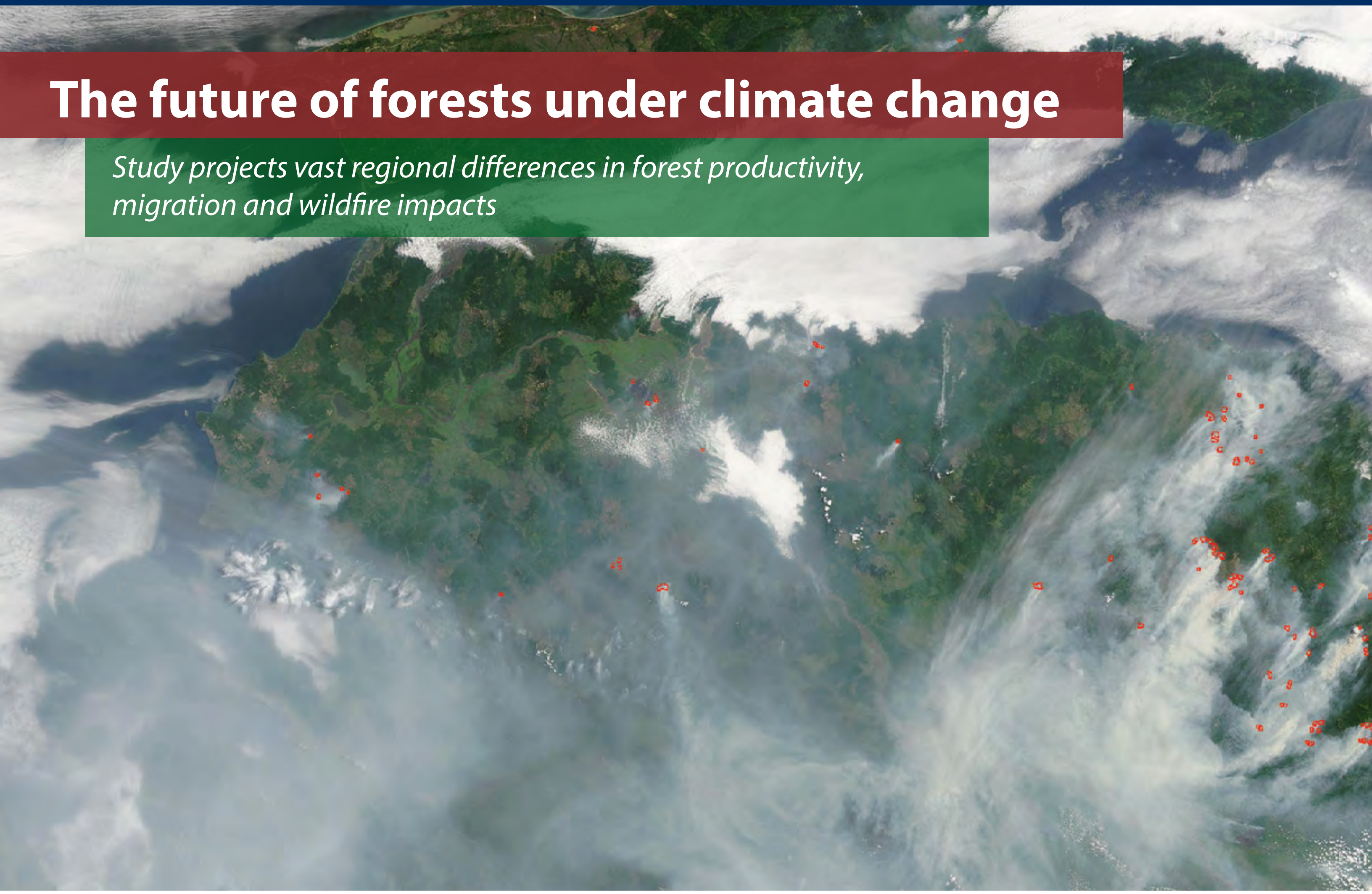
This article has been updated since its appearance in MIT News.

Related Publication

Paltsev, S., YH-H. Chen, V. Karplus *et al*. (2016): Reducing CO_2 from cars in the European Union. T*ransportation*, online first (doi: 10.1007/s11116-016-9741-3).

The future of forests under climate change

Study projects vast regional differences in forest productivity, migration and wildfire impacts



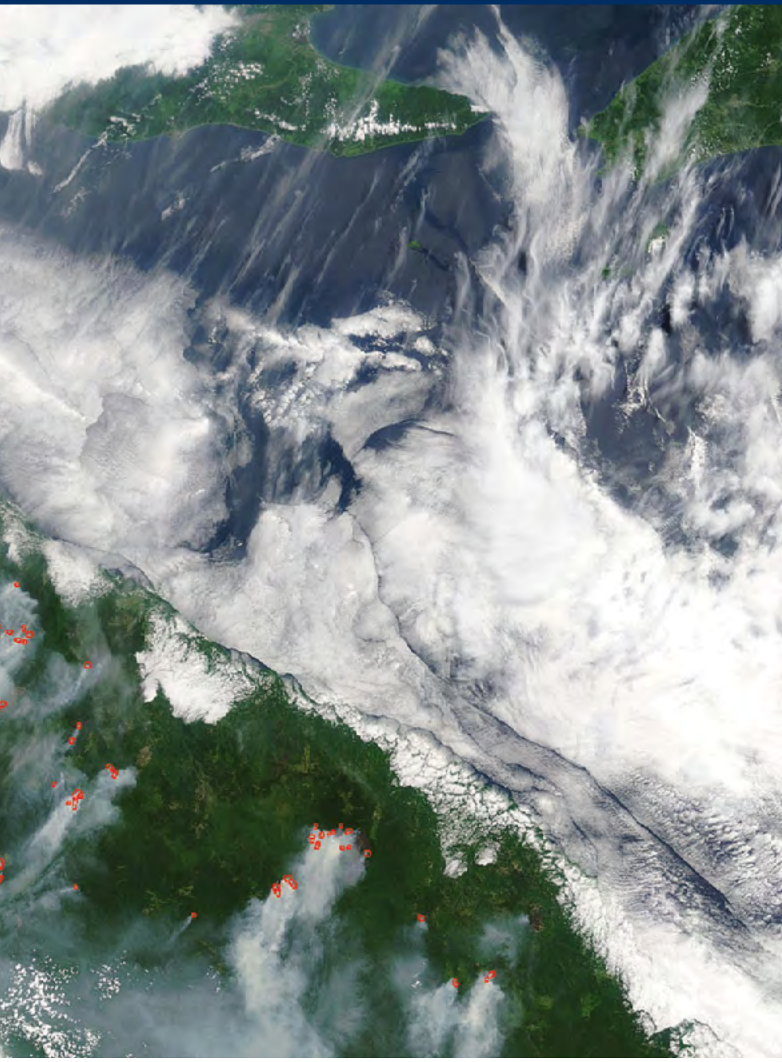
Scores of fires (marked in red) were choking the skies above far eastern Russia (left) and Sakhalin Island (right) on July 24, 2003.

Accounting for nearly one-third of the global land surface, forests help regulate the climate and protect watersheds while providing consumer products and outdoor experiences that enhance the quality of life. Climate change will inevitably influence forests' ability to deliver these services, but past studies have provided a limited picture of what changes may come this century. Now researchers from the Corvallis Forestry Sciences Laboratory, MIT, Ohio State University and the U.S. Environmental Protection Agency have sharpened that picture by assessing the impact of climate change on three key factors: forest productivity (capacity to extract, store and transform atmospheric carbon dioxide into forest products), migration (geographical shifts of vegetation) and wildfire-induced depletion and regrowth.

Using a combined global vegetation and climate model to compare two climate policy scenarios—a "business-as-usual" scenario in which greenhouse gas emissions are unconstrained, and a "2°C" scenario representing an emissions pathway that would limit the rise in global mean temperature since preindustrial times to two degrees Celsius by 2100—the researchers determined that the impact of climate change on forests in the coming decades is decidedly mixed.

While unconstrained climate change would likely benefit forests at the global level and in some regions, it would decrease forested areas in many others, particularly in Russia, Canada and China.

Both scenarios project a net increase in forest carbon stocks across the globe, with most of the gains occurring in tropical forests. The business-as-usual scenario would raise concentrations of atmospheric carbon dioxide substantially, increasing the fertilization effect of CO_2, leading to higher vegetation growth and carbon stocks. But because increased CO_2 leads to higher surface temperatures, some



of these gains would be counteracted by a higher incidence of wildfires, particularly in temperate zones, which release CO_2 into the atmosphere as they consume trees and other forest plants. The 2°C climate mitigation scenario, which significantly decreases atmospheric CO_2, would, in turn, reduce these forest carbon stock gains, especially in the southern hemisphere.

While unconstrained climate change would likely benefit forests at the global level and in some regions, it would decrease forested areas in many others, particularly in Russia, Canada and China. Wildfires would multiply with increasing temperatures, especially in Russia and Central America. In Russia, climate change would significantly decrease carbon stocks and forest areas while increasing burnt forest areas.

"While climate mitigation would reduce carbon stocks globally, it would also reduce wildfire damages to forests and the adaptation costs associated with those damages," says Erwan Monier, a co-author of the study and principal research scientist at the MIT Joint Program on the Science and Policy of Global Change. "By minimizing uncertainty about future forest health and productivity, climate mitigation would lower the complexity and expense of future forestry sector management and planning."

The study, which was primarily funded by the EPA, appears in the journal *Environmental Research Letters*. (A companion paper published in the same journal used this study's results to evaluate the economic impacts of climate change on the forestry sector.)

To assess the impact of climate change on forests under different climate scenarios, the researchers used a dynamic global vegetation model under multiple climate simulations from a version of the MIT Integrated Global Systems Modeling (IGSM) framework that incorporates the Community Atmosphere Model. They arrived at their "business-as-usual" and "2°C" scenario projections by tracking changes in forest carbon stocks, total forest area and burnt forest area in 16 geographical regions over the course of the 21st century.

As lead climate scientist of the study, Monier sought to examine the precision of these projections. Recognizing three key sources of uncertainty in climate change impacts on the world's forests—emissions scenarios, the global system climate response (climate sensitivity) and natural variability (year-to-year and longer-term variations in the climate), the researchers ran large numbers of simulations of each scenario to understand the impact of these sources of uncertainty on their estimates. ■

"By minimizing uncertainty about future forest health and productivity, climate mitigation would lower the complexity and expense of future forestry sector management and planning."

Related Publications

Kim, J.B., E. Monier *et al*. (2017): Assessing climate change impacts, benefits of mitigation, and uncertainties on major global forest regions under multiple socioeconomic and emissions scenarios. *Environmental Research Letters*, 12(4): 045001 (doi: 10.1088/1748-9326/aa63fc).

Tian, X. *et al*. (2016): Global climate change impacts on forests and markets. *Environmental Research Letters*, 11(3): 035011 (doi: 10.1088/1748-9326/11/3/035011).

John Kerry: Climate drive an urgent "race against time"

At MIT, U.S. Secretary of State highlights peril of climate change, economic promise of clean energy

U.S. Secretary of State John Kerry said in an address at MIT on January 9 that the effort to limit climate change was a dire "race against time" but one that could be successful due to the economic promise of renewable energy.

Peter Dizikes | MIT News Office

Voicing both concern and confidence, U.S. Secretary of State John Kerry said in an address at MIT on January 9 that the effort to limit climate change was a dire "race against time," but one that could be successful due to the economic promise of renewable energy.

Amid record temperatures and rising sea levels that stem in large part from carbon emissions, Kerry stated, we must act quickly "to avoid the catastrophe we will inevitably see if we allow carbon emissions to go up, and up, and up." Moreover, he added, "We need to speed it up dramatically because we are in a race against time."

However, speaking before a capacity audience of about 250 people in MIT's Samberg Conference Center, Kerry talked at greater length about the upsides of a prospective clean-energy revolution, referencing the falling prices of wind and solar power and observing that by making renewable energy a major growth industry, "we can put millions of people to work."

"We can put millions of people to work."

The speech constituted one of the last major public statements Kerry made on climate change as Secretary of State before leaving office. Climate change efforts have been a key part of Kerry's portfolio, and he highlighted the State Department's recent work on the topic.

Kerry hailed the 2015 Paris Agreement, in which over 190 countries agreed to limit greenhouse gas emissions, and contended that the extensive bilateral U.S.–China climate negotiations, leading to a 2014 announcement of climate cooperation, "changed the whole playing field" by showing how committed the two countries were to an evolving approach on energy.

The Paris Agreement also signaled to entrepreneurs, innovators and investors that the renewable energy sector would remain a growth industry, Kerry said, and he called on his audience to participate in the transformation of energy.

"Brilliant minds trained at MIT are behind some of the most transformative innovations in history," Kerry said, suggesting the Institute's students and entrepreneurs could help mitigate climate change while developing "the greatest economic opportunity the world has ever known."

"As Secretary Kerry knows well, acting against climate change is not only about avoiding potential catastrophe: It is also an economic imperative, and an incredible opportunity."

Maria Zuber, MIT's vice president for research, introduced Kerry before his speech by noting that environmental protection has been a priority of his throughout his time in the Senate and at the State Department. "Today, it is starkly obvious that society must act quickly and boldly to minimize our emissions of greenhouse gases into the atmosphere," Zuber said. "Yet as Secretary Kerry knows well, acting against climate change is not only about avoiding potential catastrophe: It is also an economic imperative, and an incredible opportunity."

"We know how to do these things"

As Kerry noted in his remarks, 2016 produced the highest average global temperatures ever recorded, while each of the last three decades have been, consecutively, the warmest ever recorded.

He also recounted a recent visit he made to the scientific stations of Antarctica, where he was given a vial of air containing over 401 parts per million of carbon dioxide. Many scientists have stated that limiting the carbon dioxide in the atmosphere to 350 parts per million is a necessity in order to prevent climate change from having its most drastic potential effects.

"The natural world is changing in obvious and deeply troubling ways," Kerry said.

Making the climate change problem all the more frustrating, Kerry added, is that we understand what will solve the problem: developing inexpensive, carbon-free sources of energy.

"We know how to do these things," Kerry observed. As he detailed, the prices of large-scale wind and solar projects have in some places become competitive with coal, which is the least expensive form of fossil fuel energy in many regions. In some recent cases, contracts for large-scale renewables have been signed for prices as low as three cents per kilowatt-hour.

Solar energy costs have dropped by 62 percent since 2009, Kerry noted, while the number of solar-industry jobs has grown by over 20 percent in the U.S. in each of the last three years.

He cited a World Bank study stating that every $1 million of investment in renewable energy yields as many jobs as the same amount of investment in fossil fuels.

This means that "market-based forces are already beginning to shift" in the direction of clean energy, Kerry said, while adding that as a matter of governance, "very few public policy choices present as much upside."

MIT meetings

Before his speech, Kerry met with MIT President L. Rafael Reif; as Kerry related in his talk, the two discussed MIT initiatives on climate matters. After his speech, Kerry and Deputy Secretary of State Anthony Blinken then met for a roundtable discussion with a group of about 20 MIT faculty and industry and government experts.

The roundtable dialogue, chaired by Zuber, focused on the future of employment in light of ongoing innovation and automation, areas of concern to the State Department given large-scale trends in employment and globalization. The MIT faculty and other business leaders discussed recent developments in artificial intelligence; ways in which employees can benefit from automation and technology rather than being displaced by them; and the prospects for job growth in advanced manufacturing.

Kerry served as U.S. Secretary of State since early 2013, a time period spanning President Barack Obama's second term in office. Previously, Kerry served nearly five full terms as a U.S. senator from Massachusetts, starting in 1984; he was previously elected as the state's lieutenant governor, in 1982. In 2004, Kerry was the Democratic Party's nominee for president.

In his public remarks, Kerry, the son of a diplomat, called the position of Secretary of State "about the best job anybody could imagine" and said he would remain engaged and active as a private citizen on many civic matters, including climate change.

"What we do right now, today, matters," Kerry told the audience. "We don't get a second chance on this one." ■

WATCH VIDEO OF SECRETARY KERRY'S SPEECH: https://youtu.be/vXK1gMln-6M

To get ahead, corporate America must account for climate change

"An innovative corporate America, along with the rest of the nation, can benefit from developing low-carbon technologies and other greenhouse gas-reducing options," says MIT Joint Program Co-Director John Reilly.

The following commentary appeared in The Hill *on February 24:*

By John Reilly

Scott Pruitt's confirmation last week as chief of the Environmental Protection Agency was a setback for environmentalists and scientists who waged a fierce campaign against the nominee.

As Oklahoma's attorney general, Pruitt led or took part in 14 lawsuits that sought to block EPA regulations and policies intended to tackle climate change. In addition, his views on global warming put him at odds with both the stated positions of many companies and their current policies toward climate change.

Pruitt is one of many announced appointees who is hostile to efforts aimed at reducing emissions linked to global warming. Many in the administration are skeptical that climate change is caused by human activity or doubt its consequences will be significant. President Trump has expressed extreme skepticism about climate change, calling it a hoax created by China.

Despite the skepticism from the administration, most industry leaders fully accept that climate change is real and is caused by humans. Crop production is shifting. Extreme events, such as heavy precipitation, droughts, and more powerful tropical storms, are more common or happening in places that normally wouldn't see them.

Extreme heat waves are imperiling people around the world and affecting the productivity of those who must work outdoors. Drought, heat and pests are damaging forests and setting the stage for wildfires. Moreover, global sea levels are rising.

Solar engineer Joshua Stein works on one of several photovoltaic systems being evaluated for industry partners at Sandia National Laboratories in the U.S. Regional Test Centers program. Sandia won a three-year renewal of a Department of Energy contract to manage the RTCs, a network of five sites across the country where industry can assess the performance, reliability and economic viability of solar photovoltaic (PV) technologies.

Thinking ahead is a competitive advantage—companies that adapt to changing markets will survive and prosper.

No matter what the White House says, corporate America cannot escape the effects of climate change. These changes can threaten supply chains; affect location decisions should key resources become scarce; damage important infrastructure, such as electricity, transportation and communication systems; threaten workers' health; or shut down local economies for extended time periods during extreme weather events.

Most nations, including key U.S. trading partners (Canada, Mexico, Europe), are proceeding with policies designed to mitigate greenhouse gases. Exported U.S. products from a revamped U.S. manufacturing sector will need to meet these standards and compete in places with carbon pricing or other regulations that favor low-carbon technologies.

An innovative corporate America, along with the rest of the nation, can benefit from developing low-carbon technologies and other greenhouse gas-reducing options. China has aggressively moved to develop its manufacturing capability for wind turbines, photovoltaics and nuclear power.

Is this altruism on the part of the Chinese, with these technologies aimed at its domestic market, or a realistic evaluation of the global demand for clean energy that can create new export markets? My guess is the latter, not the former.

Thinking ahead is a competitive advantage—companies that adapt to changing markets will survive and prosper. Of course, many of America's top companies have global reach, producing and selling around the world. A U.S. presidential administration that ignores climate change will be a short-term blip.

I recommend corporate America mostly ignore that blip and continue to develop low-carbon technologies and production processes. They will be competitive in the emerging clean energy market that is taking hold globally. Eventually, American companies will prosper domestically when science-based evidence undergirds policy initiatives again.

For the U.S. to be a haven for forward-looking companies, it needs to lead on climate change, not deny that it is happening. Corporate America will need to continue to grapple with climate change, regardless of the direction of the new administration. The future of corporate America would be better served if the administration embraces scientific evidence and gets down to the business of deciding what to do about it. ■

John Reilly *is senior lecturer at the Massachusetts Institute of Technology Sloan School of Management and co-director of the Joint Program on the Science and Policy of Global Change.*

Charting a better future for Africa

Kenneth Strzepek applies models to help decision-makers advance food security and sustainable development in a climate-compromised continent

Almost 25 percent of the world's malnourished popula-tion lives in sub-Saharan Africa (SSA), where more than 300 million people depend on maize (corn) for much of their diet. The most widely produced crop by harvested area in SSA, maize is also highly sensitive to drought. Because maize in this region is grown largely on rain-fed rather than irrigated land, any future changes in precipitation patterns due to climate change could significantly impact crop yields. Assessing the likely magnitude and locations of such yield changes in the coming decades will be critical for decision-makers seeking to help their nations and regions adapt to climate change and minimize threats to food security and rural economies that are heavily dependent on agriculture.

Toward that end, a team of five researchers at the MIT Joint Program on the Science and Policy of Global Change and Department of Earth, Atmospheric and Planetary Sciences (EAPS) has applied a broad range of multi- and individual climate model ensembles and crop models to project climate-related changes to maize yields in Africa throughout most of the 21st century. Accounting for uncertainty in climate model parameters—which is most pronounced in high-producing semiarid zones—the researchers project widespread yield losses in the Sahel region and Southern Africa, insignificant change in Central Africa, and sub-regional increases in East Africa and at the southern tip of the continent. The wide range of results highlights a need for risk management strategies that are adaptive and robust to uncertainty, such as the diversification of rural economies beyond the agricultural sector.

"In the wet regions you'd feel very secure in making large-scale, long-term agricultural decisions, knowing that the probability of error due to climate change is small," says Joint Program Research Scientist Kenneth Strzepek, one of the study's principal co-investigators (the other is Susan Solomon, Lee and Geraldine Martin Professor of Environmental Studies in the EAPS Department). "In the arid regions, where the magnitude of uncertainty is much higher, you'd need to proceed with caution. That means developing strategies that hedge on which crops are cultivated, learning more about how the climate is changing before making any major investments, and considering alternatives to agriculture for economic development."

The study, which was published on March 15 in the journal *AGU Earth's Future*, funded by the Abdul Latif Jameel World Water & Food Security Lab and supported-in-kind by the World Bank, is right in Strzepek's wheelhouse. For more than 40 years, he has cultivated expertise in environmental science and economics and applied it to promote sustainable development and poverty reduction, with an emphasis on optimizing the use of water resources in the developing world.

Kenneth Strzepek with Tefera Deribew, Minister of Agriculture, Ethiopia

Propelled by his experience and the tenets of his Christian faith, Strzepek resolved to help alleviate poverty and promote sustainable economic development in resource-limited countries.

Engineering sustainable development and poverty reduction

Inspired by the creation of the Environmental Protection Agency in 1972, Strzepek started out pursuing a bachelor's degree in environmental engineering at MIT, with the ultimate goal of working on U.S. environmental concerns. But during the summer of his sophomore year, after contracting a waterborne disease while participating in a water supply project in Mali, he felt called to shift his focus to the interplay of poverty, *Today Strzepek splits his time three ways: as a research scientist at MIT, as an educator at Harvard University and Denver Seminary, and as a U.S. government consultant.*

development and public health. Propelled by this experience and the tenets of his Christian faith, he resolved to apply his engineering skillset to help alleviate poverty and promote sustainable economic development in resource-limited countries.

To enhance his effectiveness in carrying out this mission, he spent the next eight years at MIT earning BS and MS degrees in civil engineering, and a PhD in water resources systems analysis; completed an MA in economics from the University of Colorado (where he also served as a professor of civil, environmental and architectural engineering); and, now, a true lifelong learner, is midway through a PhD program in economics at the University of Hamburg in Germany. Anchored by this interdisciplinary academic background, he has spent his career working at the intersection of water, agriculture, environmental and economic policy, modeling these systems to understand their linkages and implications for investment and policymaking in both developing and developed regions.

Today Strzepek splits his time three ways: as a research scientist at the MIT Joint Program churning out peer-reviewed papers, such as the *Earth's Future* study, that explore impacts of climate change on natural resources and economic development; an educator—he serves as an adjunct professor of public policy at Harvard University's John F. Kennedy School of Government focused on water and climate policy, and adjunct faculty member at Denver Seminary in Colorado where he teaches a course on development and poverty; and a consultant for U.S. government, World Bank and United Nations projects focused on sustainable development and poverty reduction.

For the U.S. Environmental Protection Agency, Strzepek has contributed to the 2015 Climate Change Impacts and Risk Analysis (CIRA) report, which estimated the environmental and economic benefits to the U.S. of reducing global greenhouse gas emissions. For the World Bank, he has helped develop a comprehensive framework agreement between all sovereign states in the Nile River basin to cooperatively manage their shared water resource. And as a nonresidential senior research fellow at the U.N. University World Institute for Development Economics Research (UNU-WIDER), he helps lead a research project Development under Climate Change (DUCC), which examines the impact of climate change on water resources, agriculture and other infrastructure systems, and the consequences for economic development in Africa and other developing regions. He is also a contributor to a Joint Program/UNU-WIDER project called Africa Energy Futures, which aims to explore the potential economic benefits of shifting the continent from fossil fuel-based to renewable energy systems.

"Ken Strzepek is never one to lose the forest for the trees," says Channing Arndt, another senior research fellow at UNU-WIDER. "Whether engaging in politically sensitive analysis of the Nile River or assessing the development implications of climate change, he has an uncanny ability to get to the crux of the issue. His many contributions include more realistic views of the implications of climate change in Southern Africa."

"Ken combines three traits that make him particularly effective in development work—world-class academic accomplishments, unbounded energy for Africans, and the right dose of humility," adds Raffaello Cervigni, a lead environmental economist with the World Bank's Environment and Natural Resources Global Practice who has led several World Bank assignments in Africa in which Strzepek served as a lead consultant or technical advisor. "This combination means he is almost uniquely able to fully engage his developing country counterparts."

Charting a better future for Africa under uncertainty

As he works to reduce poverty and expand sustainable economic development in Africa, Strzepek aims to ensure that nations in the region don't overreact or underreact to climate change. To assess the economic implications of such reactions, he considers the "opportunity costs" of policies designed to mitigate or adapt to climate change, i.e., what critical economic development projects, from new schools to housing, could have been funded if such policies were not implemented.

Of particular interest to Strzepek is to determine the role of agricultural development in ensuring food security and as a potential engine of economic growth across the continent, all while the magnitude, pace and impacts of temperature and precipitation change remain uncertain.

"Policymakers and investors are asking, how do we proceed with all of this uncertainty?" says Strzepek. "The *Earth's Future* paper is one of the first attempts to try to see if there are any regions of Africa where the level of uncertainty is lower than we might expect. Using different climate models and accounting for variables that range from temperature to soil nutrient levels, is there a consistent signal that can direct decision-makers on how to proceed in the near future? We believe that our findings, which quantify the level of uncertainty by region, can help guide that process now." ■

Related Publications

"Climate change to worsen drought, diminish corn yields in Africa," *MIT News,* March 16, 2017.

Dale, A., C. Fant, K. Strzepek, M. Lickley and S. Solomon (2017): Climate model uncertainty in impact assessments for agriculture: A multi-ensemble case study on maize in sub-Saharan Africa. *Earth's Future* 5.

Monitoring mercury

Amanda Giang models a pollutant's pathways and assesses mitigation policies

Dispersal of mercury into the air has risen substantially since the industrial revolution, leading to increased deposits in water and soil, where it gets transformed by bacteria into methylmercury, a highly toxic form of the naturally occurring heavy metal that can affect neurological and immune systems. Stored in the tissues of wildlife and humans, methylmercury concentrations are magnified with each step up the food chain. For example, the mercury levels of a large predator fish such as trout may be more than one million times that of ambient water, potentially incurring serious health problems and costs for human and wildlife consumers. Much of the mercury pollution attributable to human activity is produced by coal-fired power plants and small-scale gold mining, with fish-dependent and mining communities among the hardest hit. In recent years, rising concerns about adverse consequences of mercury emissions have led to a number of new emissions-reduction policies.

But just how effective are these policies? For the past six years, MIT Joint Program research assistant Amanda Giang has been working to assess the environmental, public health and economic impacts of mercury pollution and the efficacy of policies designed to reduce them. Toward that end, she has taken both a qualitative and quantitative approach. Drawing on input from stakeholders ranging from citizens in affected communities to domestic regulators and international negotiators, Giang has developed integrated assessment models that trace the path of mercury from emissions sources to polluted watersheds to impacted consumers. Using those models, she has estimated the amounts of future mercury emissions that various policies would likely avoid, and the environmental, health and economic gains that would result. Her ultimate goal is to use the models' projections—and efforts to account for uncertainty in the data upon which they're based—to empower local, regional and global decision-makers to design and monitor better policies to minimize impacts of mercury and other long-range, persistent pollutants.

Assessing effectiveness of mercury mitigation policies

With that goal in mind, Giang, who on May 10 earned a PhD in the Technology and Policy Program of the Institute for Data, Systems & Society (IDSS), has combined tools from atmospheric sciences, environmental and health economics, and other disciplines to advance a case study of global and regional mercury policy. Her most salient findings appear in a paper co-authored by her advisor, Associate Professor Noelle E. Selin (IDSS and Department of Earth, Atmospheric and Planetary Sciences) in the journal *PNAS*.

The paper evaluates benefits to the U.S. of the UN Minimata Convention, a global environmental treaty initiated in 2013 to significantly reduce mercury emissions. In collaboration with Selin, Giang developed an integrated framework that models chemical transport in the atmosphere; mercury exposure and health impacts; and economic impacts of the global Minimata Convention as well as of the domestic Mercury and Air Toxics Standard (MATS), which targets emissions from U.S. coal-fired power plants. The framework projected that by 2050, the U.S. is likely to benefit more than twice as much from the global policy than it will from the domestic policy, with one exception: MATS produces larger benefits for subsistence populations that depend on locally caught freshwater fish for much of their diet.

"The struggle isn't just to get policy made but to make sure it's effective at achieving its intended environmental and health goals. The Joint Program has been a great place to meet the latter challenge."

Giang cautions that the paper's results, while providing a good handle on the impact of mercury emissions reduction policy, come with a fair degree of uncertainty. Sources of uncertainty include how mercury-emissions policy will get implemented, the priorities of local stakeholders, how quickly emissions control technology will advance and clean energy technologies will be adopted, and where the global and regional climate are heading. These uncertainty sources pose significant challenges for policy design, monitoring and evaluation.

For her PhD dissertation, Giang is working to characterize and quantify different aspects of the uncertainty involved in mercury policymaking, with a focus on the Great Lakes region. Consulting with local stakeholders, she is developing models to evaluate the environmental, public health and economic impact of anthropogenic mercury emissions in the region, and the efficacy of regional and global policies designed to curb those emissions.

"This work comes at a critical time for mercury policy development, where decision-makers need to figure out how to determine if policies are working," says Giang. "The struggle isn't just to get policy made but to make sure it's effective at achieving its intended environmental and health goals. The Joint Program has been a great place to meet the latter challenge."

A passion for environmental health and justice

Giang was exposed to environmental issues early in life (her elementary school song focused on sustainability), but by the time she became a freshman at the University of Toronto, her primary focus was on human health and how to treat disease. It was as a biomedical engineering major that she found a way to combine these interests. Her first research experience, which involved the study of environmental contaminants, led her to shift her focus from disease treatment to prevention, and pay more attention to the environmental and social determinants of health. Meanwhile, courses in engineering and society impelled her to consider how environmental science could be used to empower communities to make better decisions about public health.

As she reached her senior year, Giang saw the MIT Technology and Policy Program as an ideal venue to explore how science-based policy can be designed to systematically protect environmental health and ensure environmental justice. Collaborating with Noelle Selin on mercury pollution policy studies provided the opportunity to address both concerns.

"Amanda's research has given us a better, more detailed understanding of the links between policy decision-making and mercury pollution," says Selin. "In her work, she has been able to connect complex regulatory proposals to mercury emissions and transport, projecting impacts to communities. A unique aspect of her research has been her ability to mobilize methods from social science and engineering research to answer these questions. This research has been influential in helping policymakers to better understand the impacts and economic benefits of mercury regulations; for example, it has been cited by the EPA and in testimony before Congress."

Giang's research has also garnered several accolades, including Best Environmental Policy Paper in the journal *Environmental Science & Technology* (2015 and 2016), and two best paper awards at the Technology Management Policy Graduate Consortium in Cambridge, England, and the Fall Meeting of the American Geophysical Union (both 2016).

Buoyed by her success at MIT, Giang plans to continue tackling environmental policy challenges for the foreseeable future. After defending her PhD thesis (currently scheduled for May), she will serve as a postdoctoral fellow in Selin's group and as a visiting fellow at Harvard University's Program on Science, Technology and Society. In January, 2018, she will begin work as an assistant professor at the University of British Columbia in Vancouver.

"My hope is to continue exploring questions of policymaking under uncertainty, and how communities can be more involved in policy design and evaluation," she says. "Thinking about how we proceed in the face of uncertainty involves not only a deep understanding of natural and social systems, but also value judgments, and so it's important to include both expert analysis and public deliberation." ■

Giang's research is funded by the National Science Foundation, Natural Sciences and Engineering Research Council of Canada, and MIT Martin Fellows program.

Related Publication

Giang, A. and N.E. Selin (2016): Benefits of mercury controls for the United States. *PNAS*, 113(2): 286–291.

XL (40th) MIT Global Change Forum

New challenges in global change research

The XL MIT Global Change Forum was convened on March 29-31 at Airlie House in Warrenton, Virginia. (Photos by Dimonika Bray)

The MIT Global Change Forum invites government, industry, NGO and research group representatives to discuss the evolving science and policy of global environmental change. The Forum is designed to promote interaction among disparate stakeholders and provide an informal, "off-the-record" setting for independent assessment of studies and policy proposals.

Today's rapidly changing global environment and policy landscape provided ample subject matter for the more than 80 stakeholders gathered at the XL (40th) MIT Global Change Forum on March 29–31 at Airlie House in Warrenton, Virginia. Presentations and discussions focused on key challenges in four research domains—Earth systems science, energy, transportation, and agriculture and water—and two policy areas—U.S. energy and environmental policy, and mitigation and adaptation under the Paris Agreement.

Science challenges

The Forum kicked off with an exploration of a core, near-term challenge in Earth systems science: to upgrade integrated Earth and human systems models (including the Joint Program's own Integrated Global System Modeling (IGSM) framework) to make more actionable projections of changes in natural resources such as food, water, bioenergy, forestry and ocean ecosystems. By providing science-based roadmaps for regional climate change, extreme events, water stress, air pollution, land use and other looming environmental changes, and interactions among them, these models can better equip decision-makers to formulate more effective policies and make more prudent investments that minimize risk under uncertainty.

To that end, the Joint Program is working to improve and expand the IGSM's representations of different natural resources, sharpen its focus on low- and zero-emission technologies at large scale, update global and regional climate uncertainty estimates, and implement a more computationally efficient 3D model of atmospheric chemistry. The latter upgrade should improve the Program's capability to assess environmental, health and economic benefits and risks of climate and air pollution policies.

The Forum highlighted several research challenges in the energy space, driven primarily by international climate policy targeting a two-degree-Celsius (2°C) cap on the rise in global mean surface temperature since pre-industrial times. Meeting that target will require a dramatic "decarbonization" of today's energy mix amid lingering uncertainty about future policies, technology costs and resulting technology mixes. To support decision-making in this highly uncertain space, researchers will need to improve models' representation of energy and climate policies and their impacts on the environment and economy. An important consideration is to accurately represent how national security vulnerabilities affect energy technology choices such as the expansion of multinational electric power grids.

Forum presenters also explored new and ongoing research challenges associated with mitigating carbon dioxide (CO_2) emissions in the transportation sector, which is becoming more energy-intensive, multi-modal and electrified. These include modeling the impact of emerging shifts in demand and supply of different modes of transportation on travel patterns, energy consumption and CO_2 emissions—and policies designed to incent less energy-intensive travel. One growing source of those emissions is aviation, where jet fuel consumption is expected to double or triple by 2050. While biofuels have been touted as a low-carbon alternative, no solution currently on the table appears cost-effective.

Other talks examined research challenges in projecting the future of agriculture and water supplies. One takeaway was the need to consider both "Global-to-Local" interactions (e.g., impact of the Paris Agreement on local precipitation and crop yields) and "Local-to-Global" interactions (e.g. the impact of building a dam that increases water available for irrigation on global crop prices and land use) in agricultural and water research. For instance, studies that ignore local irrigation responses to changes in water availability overestimate the impact of changes in water availability on food and land-use outcomes. To address such shortcomings requires embedding information from local-scale models in global models, and/or linking models with different spatial resolutions and time scales. Another challenge identified at the Forum is to expand agricultural monitoring and surveillance systems to improve crop model yield estimates in resource-limited countries, with the overarching goal of boosting productivity of smallholder farms and expanding economic opportunity for farmers.

Policy challenges

Against the backdrop of an executive order from the White House to review and roll back Obama-era climate policies including the Clean Power Plan (CPP), the Forum examined the economic and political viability of a market-driven alternative favored by environmentalists, a majority of U.S. citizens, and a number of Republican elder statesmen: a carbon tax. A recently released plan by the Climate Leadership Council proposed replacing nearly all Obama-era climate policies with a rising carbon tax starting at $40 per ton, where revenue would be returned to all taxpayers in the form of quarterly, Social Security Administration-issued checks. Analysis presented at the Forum showed that the plan would yield substantial long-term environmental and economic benefits, and be much more effective at reducing U.S. greenhouse gas emissions than the CPP. Despite support from high-level Republicans, the plan has not yet appeared to garner substantial support among Republican office-holders, and several participants suggested a carbon tax remains a tough sell politically.

A panel focusing on challenges in implementing the Paris Agreement stressed that meeting the 2°C target is becoming more difficult and expensive with each passing year; monitoring compliance with Nationally Determined Contributions (NDCs) is hampered by poor administrative coordination, inconsistent tracking methods and insufficient human and financial resources; significant research will be needed to guide adaptation and climate resilience policy design; and the current U.S. administration's efforts to unravel the CPP and other components of the U.S. mitigation efforts must overcome several complex legal hurdles. ■

Joint Program Co-Director Ronald Prinn delivering opening remarks at the XL MIT Global Change Forum

SAVE THE DATE:
XLI MIT GLOBAL CHANGE FORUM

The Joint Program will convene the XLI (41st) Global Change Forum in the Boston/Cambridge area in Spring 2018.

SEEKING TO INFORM INDIA'S CLIMATE POLICY CHOICES

MIT JOINT PROGRAM RESEARCH ASSISTANT ARUN SINGH SHARES ENERGY-ECONOMIC MODELING RESEARCH AT UN CLIMATE CHANGE CONFERENCE

Emily Dahl | MIT Energy Initiative

The MIT Energy Initiative publicized reports from the United Nations Climate Change Conference in Marrakech, Morocco, where MIT community members observed the climate negotiations and spoke at auxiliary events.

At a side event of COP22, the 2016 United Nations Climate Change Conference in Marrakech, Morocco, researchers and nongovernmental leaders from around the world discussed policy research that can support implementation of the 2015 Paris Agreement to limit global temperature rise. Among the nine panelists was a sole graduate student: MIT's Arun Singh.

On the panel, "New Directions in Climate Change Research and Implications for Policy," Singh and fellow representatives of the COP22 Research and Independent Nongovernmental Organizations (RINGO) constituency gave brief overviews of their research in various areas, from agro-industrial development policies to green social work.

Singh shared his research on clean development pathways for India, which applies an energy-economic model he is developing with advisors Valerie Karplus and Niven Winchester. The model simulates policy and technology choices India could make to fulfill its intended, nationally determined contributions under the Paris Agreement—and how each of those choices could impact emissions, energy use and the country's economy.

"For example," says Singh, "how would India's ambitious solar targets compare with, say, a price on carbon to achieve similar levels of emissions reductions? Who wins and loses under alternate policy choices? Those are the types of questions we're looking to answer."

In the global effort to address climate change, India's role as a major player is indisputable. The country is the third largest emitter of global greenhouse gas emissions, behind China and the U.S., yet nearly 19 percent of India's population, most of which lives in rural areas, still lacks reliable access to electricity—and the population is still growing rapidly.

"India is in a situation where it has to balance tradeoffs between increasing energy output and ensuring that additional generation does not add significantly to the country's carbon emissions," Singh explains. To make these tradeoffs, policymakers and regulators would benefit from having access to quantitative analysis of policy impacts, which Singh and his team hope to provide.

"Smart policies can be designed that encourage growth while limiting the impact on climate."

Arun Singh (Photo by Emily Dahl/MITEI)

"Arun's work stands out because it combines modeling of policies at the country level with an assessment of financial and operational barriers to clean energy investment at the micro level," says Karplus, an assistant professor of global economics and management at the MIT Sloan School of Management, who is also a faculty affiliate of the MIT Energy Initiative and the Joint Program on the Science and Policy of Global Change. "We hope to work with policymakers in India to identify strategies that are cost effective and politically workable. To do that, we need to analyze proposals in terms of both the cost and the distribution of impacts."

For Singh, researching solutions to climate and energy issues is personal: Having grown up in Ayodhya, India, he experienced the challenges firsthand. "Frequent power cuts were a norm while I was growing up. In peak summer months, we would not get power for eight to 10 hours a day. And this was still in a town," he says.

Following his undergraduate studies at India Institute of Technology Roorkee, Singh became more interested in understanding energy and environmental policymaking, while working at a petroleum refinery. Then, as a research associate at the Abdul Latif Jameel Poverty Action Lab (J-PAL) South Asia office in Mumbai, he worked on environmental regulation reform projects in India, including a pilot emissions trading scheme for industrial particulate matter emissions, conducted with India's Ministry of Environment and Forests. At J-PAL, he also carried out an impact evaluation of public disclosure of industrial air pollution ratings, for which he analyzed emissions data from more than 5,000 firms and worked closely with his team and with regulators to secure approval for a new disclosure program.

As he made field visits to some of the most polluted industrial clusters in India, he learned how nuanced the issues can be. "In India it is common to hold strong positions favoring or opposing development. But that's not helpful, as it's not an either-or question," he says. "Smart policies can be designed that encourage growth while limiting the impact on natural environment and climate. And India already has several forward-looking policies in place."

His work motivated him to come to MIT, where he arrived with a desire to focus on climate and energy policy research for developing countries, but he was not yet sure exactly where his studies would take him.

He started in 2015 as a graduate student in the Technology and Policy Program—which is now part of the Institute for Data Systems and Society—working with Karplus to study policies and regulation in the electricity sector in India, with funding from the MIT Energy Initiative. Then, an opportunity arose to help Karplus and Winchester develop the energy-economic model he now works on as a fellow of the Tata Center for Technology and Design and research assistant in the MIT Joint Program.

When Karplus learned of a call for researchers to present at COP22 with the RINGO constituency, she alerted Singh, who applied and was selected to present.

In Marrakech, Singh shared preliminary findings from his model, which offer initial insights into how carbon pricing and renewable energy support policies compare in terms of their impact on carbon dioxide emissions, the energy system and the economy. To finalize his research, he plans to expand the model's specifications to reflect policy priorities and physical constraints, especially on details in technology choices. He is also investigating the political and economic factors that drive these choices, and viable design options for increasing the political feasibility of cost-effective policies to reduce carbon dioxide emissions.

While at COP22, Singh also had the opportunity to interview developers, investors and aid organizations that are involved in the expansion of renewable energy in Morocco, supporting Karplus as she contributes to an upcoming book on the commercialization of renewable energy in several African countries.

"I am so pleased and proud that Arun had the opportunity to represent our group in Marrakech. By interacting with diverse stakeholders at the COP, Arun has been able to share his research on India with the world, and compare and contrast its insights with experiences in other countries," Karplus says.

At MIT, Singh co-leads a student group, Energy for Human Development (e4Dev), with fellow graduate student Turner Cotterman, bringing together members of the MIT community to advance understanding of issues facing the developing world, with guest lectures from notable experts, outreach programs and educational opportunities. He plans to share his COP22 experience with the group.

Singh's first experience with UN climate negotiations has been "overwhelming," he says, from the efforts that go into organizing the COP to how the complex negotiation process functions.

"It's very encouraging to see enthusiastic participation of all countries and the near unanimous recognition of climate change as a problem requiring strong collective efforts," he says. "There's no room for skepticism or delaying action."

Singh looks forward to continuing to play a role in informing energy and climate solutions for India with his research, as part of the MIT community dedicated to making a better world. ■

CLIMATE SCIENCE AND POLICY: NOW MORE THAN EVER!

AS NEW U.S. ADMINISTRATION TAKES OFFICE, JOINT PROGRAM IAP COURSES EXPLORE WHAT'S AT STAKE

On January 20 a new administration entered the White House determined to cut spending on climate change and environmental protection programs, and reduce restrictions on greenhouse gas emissions that contribute to global warming. To help the MIT community better understand what's at stake, graduate students with the MIT Joint Program on the Science and Policy of Global Change presented seven courses on climate science and policy during the 2017 MIT Independent Activities Period. Held January 30-February 2 and entitled **"Climate Science and Policy: Now more than ever!"** the series provided a fast-paced, accessible introduction to the Earth's climate system and the links between scientific and societal aspects of climate change.

Climate science

Justin Bandoro, a graduate student in the Department of Earth, Atmospheric and Planetary Sciences (EAPS) Program in Atmospheres, Oceans and Climate (PAOC), presented a two-part introduction to climate science. In **Climate Science 101: Fundamentals,** he reviewed the history of the field and provided a broad overview of the physics of the climate system. Topics included the structure and composition of the atmosphere; the Earth's energy budget; variability in the climate system; and the impact of greenhouse gas emissions on the climate. In **Climate Science 102: Modeling Systems,** Bandoro focused on how the global climate system responds to natural and human-caused forcings and feedbacks, and how models can detect and attribute observed changes in the climate system to human activity.

Christoph Tries, a master's student in the Technology and Policy Program (TPP), led a session on the role of uncertainty in climate projections and impacts. In **Embracing Uncertainty: How our society deals with not knowing, and what we can do to prepare for climate change**, he examined the substantial yet underestimated role which uncertainty plays in our economy, politics and science. In particular, he described the main sources of uncertainty in climate projections and how they translate into uncertainty in climate impacts. The course concluded with suggestions on how to adequately adapt to climate change and communicate uncertainty issues to the public.

"We have different conceptions and classifications of uncertainty," said Tries. "Even among the experts there's no agreement, and there is a push to have a coherent methodology for quantifying uncertainty."

Climate policy

Four Joint Program courses explored climate policy design, carbon pricing and global climate negotiations. In **Economics & Policy of Climate Change: How would you design a good climate policy?** Minghao Qiu, a graduate student at the Institute for Data, Systems and Society (IDSS), introduced basic concepts in environmental economics and policy, and defined and weighed the pros and cons of various climate change mitigation policy options, including government regulations, capandtrade and a carbon tax.

"We use cost-benefit analysis to evaluate whether a climate policy is good or not," said Qiu. "We calculate the benefit of a climate policy such as a carbon tax using the social cost of carbon; the cost of the policy can be captured using a carbon dioxide abatement cost curve."

Arun Singh and Michael Davidson presented **International Climate Governance & the U.S. Role: How do global climate negotiations work?** Singh, a master's student in the TPP, outlined the 25-year history of international climate negotiations under the U.N. Framework Convention on Climate Change, what the Paris Agreement achieved, and next steps in its implementation. Davidson, a PhD student in engineering systems at the IDSS, examined the role of the

TOP: Justin Bandoro, an EAPS graduate student, presented a two-part introduction to climate science. BOTTOM: The Joint Program IAP course series concluded with a mock international climate negotiation in which participating groups represented regions of the world with various goals for mitigation, adaptation and economic growth. (Photos by Dimonika Bray)

U.S, the world's second largest emitter of carbon dioxide, in shaping global climate policy; the successes and failures of U.S. climate policy; and what changes we might expect in the coming years.

In **Can Carbon Pricing Solve Climate Change? Lessons from climate policy efforts around the world**, Emil Dimantchev, a master's student in the TPP, unpacked one of the foremost proposed solutions to the problem of climate change: putting a price on carbon. Drawing on 20 years of government experiments with different forms of carbon pricing, from carbon taxes to cap-and-trade systems and other carbon markets, Dimantchev explained how a carbon price brought down a government, why politicians and economists are diametrically opposed on the idea, and what role carbon pricing could play in formulating effective climate policy.

"Carbon pricing is difficult, so we should think of it as a journey and be open to the idea of accepting concessions," said Dimantchev, who previously served as a senior carbon market analyst at Thomson Reuters. "It's going to be a slow and incremental process. If we want our research to be relevant and our strategies to be successful, we should account for political feasibility."

The Joint Program IAP course series concluded with an interactive group project, **World Climate Negotiations,** a mock international climate negotiation in which participating groups represented regions of the world with various goals for mitigation, adaptation and economic growth. The computer simulation C-ROADS (developed by MIT Sloan School of Management Professor John Sterman) was used to assess the outcomes of the mock negotiation in real-time. The project was based on Climate Interactive's World Climate Project. ■

Related Publication

"Forging ahead on climate action: At UN Climate Change Conference, MIT researchers share insights on implementing climate commitments," *MIT News*, November 22, 2016.

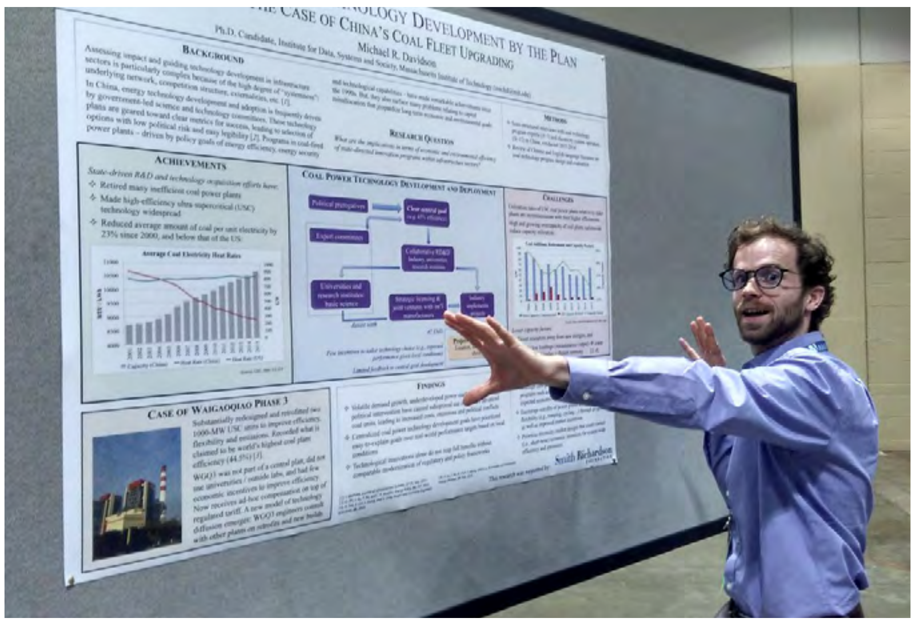
POWERPOINT SLIDES OF THE JOINT PROGRAM'S 2017 IAP COURSES

Available online: http://globalchange.mit.edu/IAP2017.

MICHAEL DAVIDSON SCORES WINNING POSTER IN SOCIAL SCIENCES CATEGORY IN 2017 AAAS STUDENT POSTER COMPETITION

POSTER HIGHLIGHTS HIDDEN COSTS IN CHINA'S COAL PLANT UPGRADE

Judges of the American Association for the Advancement of Science (AAAS) 2017 Student Poster Competition selected a poster by MIT Joint Program research assistant Michael Davidson as the winner in the Social Sciences category. Davidson's poster was one of 15 presented in that category at the AAAS Annual Meeting in Washington, D.C. in February. Winners receive a cash prize; their names and poster title printed in *Science*; a recognition certificate; and a year-long subscription to *Science*.



MIT Joint Program research assistant Michael Davidson with his poster at the AAAS 2017 Student Poster Competition (Photo courtesy of Michael Davidson)

In his poster, "Hidden Costs of Technology Development by the Plan: Case of China's Coal Fleet Upgrading," Davidson, a PhD student in Engineering Systems at the MIT Institute for Data, Systems, & Society, argues that system performance inefficiencies result when centralized technology target-setting does not consider local system conditions. This research is part of a broader project on Policy, Regulation and Innovation in Chinese Industry supported by the Smith Richardson Foundation.

Davidson maintains that while China's highly centralized technology development and deployment programs have led to massive reductions in deployment and manufacturing costs, they also produce inflexible, top-down and standardized technologies that can cause operational inefficiencies in electric power systems and other complex infrastructures. In China's electric power system, these inefficiencies include overcapacity and a limited ability to exploit renewable energy sources.

"Technological innovations alone do not reap full benefits without comparable modernization of regulatory and policy frameworks," says Davidson. To effect such modernization in China's coal technology programs, he recommends reengineering existing programs and introducing short-term price signals through electricity market reforms that incent better technology choice and more efficient systems operation. ■

Related Publication

Davidson, M. (2017): Hidden Costs of Technology Development by the Plan: Case of China's Coal Fleet Upgrading. AAAS 2017 Student Poster Competition, Washington, D.C.

Recent Research Project Grants

AN INTEGRATED FRAMEWORK FOR CLIMATE CHANGE ASSESSMENT

Project Leaders: Ronald Prinn and John Reilly

Under a renewed cooperative agreement with the DOE, the Joint Program is extending the effort that has developed a comprehensive analytical capability, the MIT Integrated Global System Modeling (IGSM) framework. In this renewed effort, the Program aims to: focus on energy–water–land–atmosphere interactions; characterize uncertain responses of the Earth system at scales relevant to decision-making under uncertainty; and develop understanding of U.S. vulnerability to global environmental change and tools that can assist in adaptation to these changes. A major focus of the work is the linkages between the Earth system and economic activity through water, crops, renewable energy resources and atmospheric chemistry. The focus is on enhancing these linkages in the global model, with increased fidelity on U.S. resource sectors using state-level data to better characterize trade-offs between renewable energy and other energy resources, along with linkages to water and land. A set of uncertainty studies will evaluate key uncertainties in the ocean that help explain decadal variability; examine predictability of hydrologic response to climate change, especially as it affects power generation (hydroelectricity, power plant cooling); and assess vulnerability of the grid to extreme events and links to decision-making under uncertainty. The enhanced modeling framework will be applied to U.S. energy-water-land-atmosphere interactions and to a more resolved look at the potential vulnerability and environmental implications of alternative renewable energy (wind, solar, biomass) systems at scale.

Sponsor: U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research (3 years)

MOBILITY OF THE FUTURE STUDY: GLOBAL ECONOMIC AND POLICY MODELING

Project Leader: Sergey Paltsev

Contributing to the MIT study Mobility of the Future, this project seeks to examine interactions among vehicle power train technologies, fuel options, refueling infrastructure, consumer choice, public transit, new transportation modalities and government policy. A major driver of future change is policy related to climate change and environmental concerns. The Joint Program's Economic Projection and Policy Analysis (EPPA) model provides a multi-region, multi-sector dynamic representation of the global economy. It has been successfully applied to study transportation-related issues such as the effect of economic development and energy policy on fuel mix, fuel prices, transportation demand, consumer choices and overall economic activity. The EPPA model will be used to integrate findings from other components of the Mobility study, provide projections of fuel prices and other variables for other modeling efforts in the study, and develop scenarios of future energy and transportation policy illustrating the impact on global and regional mobility trends.

Sponsor: MIT Energy Initiative (2 years)

RUSSIA IN THE POST-PARIS WORLD: NEW ENERGY LANDSCAPE

Project Leader: Sergey Paltsev

Achieving the Paris Agreement goals of climate stabilization requires a transformation of the energy system over the upcoming decades. As a fossil fuel producer, Russia will have to adjust its economy to reflect lower export earnings from oil, coal and natural gas. Using a global energy-economic modeling framework, this project will assess the impacts of energy transformation policies and the resulting global market dynamics on the Russian economy, including changes in its sectoral output, energy mix and GDP. The analysis will provide a basis for strategic decision-making to industry representatives, policymakers and academic researchers in Russia and other countries. Understanding sectoral and economy-wide impacts is crucial for assessing the magnitudes of the challenges that lie ahead. The project will be a tool to enhance discussions among government, industry and academia on the long-term strategy for the energy and economic transformation of Russia.

Sponsor: MIT Skoltech Seed Fund (1 year)

MILESTONES

Environmental Science & Technology's 2016 Best Policy Paper included three MIT Joint Program co-authors: MIT Aeronautics and Astronautics Associate Professor Steven Barrett, MIT Department of Earth, Atmospheric and Planetary Sciences (EAPS)/Institute for Data, Systems, and Society (IDSS) Associate Professor Noelle Selin, and IDSS PhD student Amanda Giang. The study showed long-lasting health, economic impacts of lead emissions from U.S. general aviation flights. ES&T's 2015 Best Policy Paper was also co-authored by Selin and Giang.

On April 30, Susan Solomon, the Lee and Geraldine Martin Professor of Environmental Studies in MIT's EAPS Department, will receive the 2017 National Academy of Sciences, Arthur L. Day Prize and Lectureship, awarded to a scientist making lasting contributions to the study of the physics of the Earth and whose lectures will provide solid, timely, and useful additions to the knowledge and literature in the field. A leader in the fields of atmospheric chemistry and climate change for three decades, Solomon will receive a $50,000 prize and funds to present a series of Day Lectures, supported by the Arthur L. Day Bequest. – Helen Hill, EAPS

Kerry A. Emanuel, the Cecil and Ida Green Professor of Earth and Planetary Sciences, was elected to the American Academy of Arts and Sciences.

On Februrary 8, Dara Entekhabi, the Bacardi and Stockholm Water Foundations Professor in MIT's Department of Civil and Environmental Engineering (CEE) and EAPS, was among 84 new members and 22 foreign members elected to the National Academy of Engineering (NAE). He was recognized for "leadership in the hydrologic sciences including the scientific underpinnings for satellite observation of the Earth's water cycle." Selection to the NAE is one of the highest distinctions bestowed upon an engineer and honors those who have made outstanding contributions to "engineering research, practice, or education." A formal induction ceremony will occur at the NAE's annual meeting in Washington, D.C., on October 8. – Helen Hill and Lauren Hinkel, EAPS

IN THE NEWS

Nov 10 - *The Verge* - What Does a Trump Presidency Mean for Climate Change?

Nov 21 - *CleanTechnica* - MIT: Emissions Trading for Transport = EU's Cheapest Means of Reducing Transport Emissions

Nov 21 - *Nature World News* - Is There No Future for Climate Change Researchers Under Trump?

Dec 9 - *BBC World Service* - Trump Raises Eyebrows over New Appointment

Dec 20 - *Climate Central* - New EU Wood Energy Rules Threaten Climate, Forests

Jan 3 - *UPI* - Study predicts more extreme storms for California in the future

Jan 3 - *Science Daily* - More extreme storms ahead for California

Jan 3 - *The Science Explorer* - MIT Scientists Predict More Extreme Storms Coming for California

Jan 5 - *CBS* - California To See More Major Storms In Coming Decades, MIT Scientists Say

Jan 10 - *International Business Times* - Climate Change: Even Short-Lived Greenhouse Gases Can Drive Sea-Level Rise For Centuries

Jan 11 - *Forbes* - Winter Weather Is Wild Right Now, And It's Just Starting

Jan 14 - *Salon* - Megastorms vs. mega-droughts: Climate change brings a potentially devastating "atmospheric river" to California

Jan 18 - *Popular Science* - 2016 was the hottest year on record

Jan 20 - *Scientific American* - U.S. Crop Harvests Could Suffer with Climate Change

Jan 23 - *E&E News: ClimateWire* - U.S. crop harvests to 'suffer' with climate change

Mar 7 - *Inside Climate News* - Climate Contrarian Gets Fact-Checked by MIT Colleagues in Open Letter to Trump

Mar 8 - *Boston Globe* - MIT professors are lobbying Trump — against their former colleague

Mar 24 - *The Atlantic* - How Climate Change Covered China in Smog

Mar 30 - *New Yorker* - Donald Trump and the Myth of the Coal Revival

Apr 7 - *Environmental Science & Technology* - Environmental Science & Technology's 2016 Best Policy Paper co-authored by Joint Program researchers

JOINT PROGRAM REPRINTS

2016-19. The Future of Natural Gas in China: Effects of Pricing Reform and Climate Policy (*Climate Change Economics*)

2016-20. Hydrofluorocarbon (HFC) Emissions in China: An Inventory for 2005–2013 and Projections to 2050 (*Environ Sci Technol*)

2016-21. Southern Ocean warming delayed by circumpolar upwelling and equatorward transport (*Nature Geoscience*)

2016-22. Teaching and Learning from Environmental Summits: COP-21 and Beyond (*Global Environmental Politics*)

2016-23. Splitting the South: Explaining China and India's Divergence in International Environmental Negotiations (*Global Environmental Politics*)

2016-24. Radiative effects of interannually varying vs. interannually invariant aerosol emissions from fires (*Atmospheric Chemistry & Physics*)

2016-25. Reducing CO_2 from Cars in the European Union (*Transportation*)

2017-1. Statistical Emulators of Maize, Rice, Soybean and Wheat Yields from Global Gridded Crop Models (*Agricultural & Forest Meteorology*)

2017-2. Biomass burning aerosols and the low-visibility events in Southeast Asia (*Atmospheric Chemistry & Physics*)

2017-3. Human Health and Economic Impacts of Ozone Reductions by Income Group (*Environ Sci Technol*)

2017-4. The CO_2 Content of Consumption Across U.S. Regions: A Multi-Regional Input-Output (MRIO) Approach (*Energy Journal*)

2017-5. Twenty-First-Century Changes in U.S. Regional Heavy Precipitation Frequency Based on Resolved Atmospheric Patterns (*J. Climate*)

PEER-REVIEWED STUDIES & PENDING REPRINTS

Assessing climate change impacts, benefits of mitigation, and uncertainties on major global forest regions under multiple socioeconomic and emissions scenarios (*Environmen Res Lett*)

Biomass burning aerosols and the low-visibility events in Southeast Asia (*Atmospheric Chemistry & Physics*)

Centuries of thermal sea-level rise due to anthropogenic emissions of short-lived greenhouse gases (*PNAS*)

Climate model uncertainty in impact assessments for agriculture: A multi-ensemble case study on maize in sub-Saharan Africa (*Earth's Future*)

Economics of U.S. Natural Gas Exports: Should Regulators Limit U.S. LNG Exports? (*Energy Economics*)

Ecosystem fluxes of hydrogen in a mid-latitude forest driven by soil microorganisms and plants (*Global Change Biology*)

Energy Scenarios: The Value and Limits of Scenario Analysis (*WIREs - Energy & Environment*)

Model Sensitivity Studies of the Decrease in Atmospheric Carbon Tetrachloride (*Atmospheric Chemistry & Physics*)

Role of OH variability in the stalling of the global atmospheric CH_4 growth rate from 1999 to 2006 (*Atmospheric Chemistry & Physics*)

The economic viability of Gas-to-Liquids technology and the crude oil-natural gas price relationship (*Energy Economics*)

The global methane budget: 2000-2012 (*Earth System Science Data*)

The role of natural variability in projections of climate change impacts on U.S. ozone pollution (*Geophysical Research Letters*)

JOINT PROGRAM REPORTS

305. Is Current Irrigation Sustainable in the United States? An Integrated Assessment of Climate Change Impact on Water Resources and Irrigated Crop Yields

306. A Drought Indicator based on Ecosystem Responses to Water Availability: The Normalized Ecosystem Drought Index

307. Economic Projection with Non-homothetic Preferences: The Performance and Application of a CDE Demand System

308. Transparency in the Paris Agreement

309. Climate Stabilization at 2°C and Net Zero Carbon Emissions

310. The Future of Coal in China

PERSONNEL CHANGES

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Horacio Caperan, program officer

Ruth Mattson, administrative assistant to Joint Program Co-Director Ronald Prinn

Abbas Ghandi, postdoctoral associate

Daniel Rothenberg, postdoctoral associate

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Wei-Hong Hong, visiting researcher, the Institute of Nuclear Energy Research, Taiwan

Xueqin Zhu, visiting scholar, Wageningen Univ.

Cicero Zanetti de Lima, visiting PhD student from the Federal University of Vicosa, Brazil

TRANSITIONS:

Joshua Hodge, from deputy executive director (Joint Program) to executive director (CEEPR)/ advisor to the Joint Program

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MIT JOINT PROGRAM ON THE SCIENCE AND POLICY of GLOBAL CHANGE

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