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Catching Up With Climate

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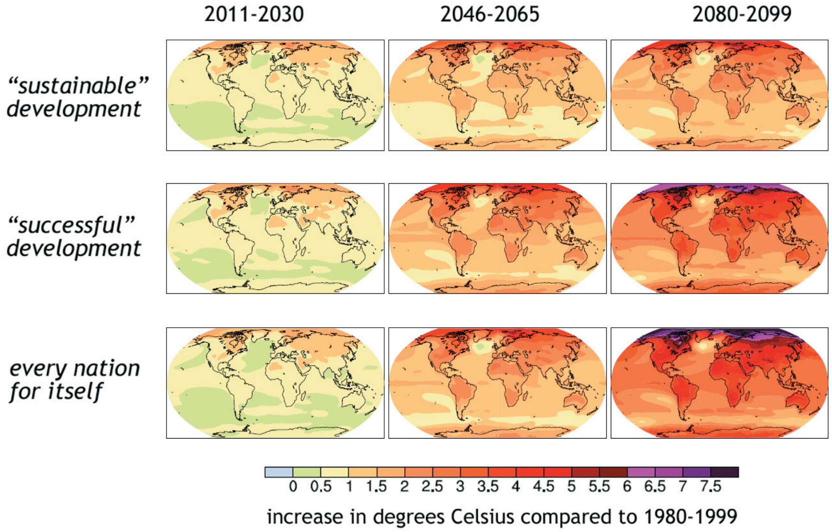
From the evidence of tree rings, the last 50 years were the warmest half-century in 1,300 years. Eleven of the past 12 years are the hottest on record since reliable record-keeping began in 1850; since 1870, sea level has risen some eight inches worldwide, and the rate is accelerating; since 1900, glaciers have shrunk 80 percent, and polar ice is melting fast; concentrations of carbon dioxide are 35 percent higher than preindustrial levels.



A century of global warming: three scenarios. In top panels, widespread environmental consciousness and a commitment to sustainable development is assumed; the middle panels assume rapid and successful economic development worldwide, and a shrinking gap between rich and poor nations; at bottom, each nation acts without regard to others, resulting in a growing gap between rich and poor. Global warming is already locked in, but at first there are no significant differences among the scenarios; by century's end differences grow larger.

(After IPCC Working Group I]

Meanwhile, humans keep pouring CO2 into the air, ratcheting temperatures toward the tipping point. To buy time, we need the best mix of conservation, alternative energy sources, new fuels, carbon sequestration, and other strategies. Decisions we make now, or fail to make, will lead at best to discomfort—or to disaster for many. The shape of things to come may crucially depend on better climate models, based on better climate science.

Climate models, climate science

"Current climate models are a blunt tool. We want to sharpen that tool," says Bill Collins of the Lab's Earth Sciences Division (ESD). "Climate models of the future will have to be able to zoom in on the regional scale, make accurate predictions for the near term, and account for what humans actually do."

Collins set out to be an astrophysicist, earning his B.A. in physics from Princeton University and, in 1988, his Ph.D. in astronomy and astrophysics from the University of Chicago. By then, he says, "I was already attracted to problems that evolved on a shorter time scale than that of the cosmos, and were directly relevant to society."

Climate change fit the bill, leading to postgraduate work in atmospheric science at the Scripps Institution of Oceanography, where Collins joined the scientific staff. Early on, he applied his physics know-how to the study of clouds and their effect on Earth's radiation budget. It's a complex equation: clouds reflect some of the sun's heat back into space, but airborne chemicals and other factors affect their reflectivity; meanwhile, water vapor contributes more to the greenhouse effect than any other greenhouse gas.

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The physics of clouds and aerosols remains a major challenge in climate modeling. "We can't build a cloud in a box," Collins says, "because we don't understand the physics well enough. We need to correct that. If cloud cover changes just a little, it could have a big feedback effect on warming—positive or negative."

For 10 years Collins was at the National Center for Atmospheric Research (NCAR) in Boulder, where he led development of the third iteration of the powerful Community Climate System Model (CCSM3) sponsored by the National Science Foundation and the Department of Energy. CCSM3 was the basis for the 2007 scientific working group report of the Intergovernmental Panel on Climate Change, IPCC's Working Group I, of which Collins was a lead author.

But climate models must do even better, he says. Describing himself as "an iconoclast regarding error budgets," Collins says, "The climate community has waffled a long time about uncertainties in models. We have to stop that. When it comes to global warming, we need to be able to tell people what to do."

In the spring of 2007 Collins joined Berkeley Lab and UC Berkeley, where he is professor in residence in the Department of Earth and Planetary Science. At Berkeley Lab he has established a new Department of Climate Science, operating in close collaboration with members of other divisions and institutions, including the Berkeley campus. His goal is to form "the first climate group I know of to work closely with large research teams on new strategies for addressing climate change."

"For one thing, we need a closer link between models and mitigation efforts," Collins says. "We need rapid prototyping for biofuels, for example. Biofuels don't just reduce carbon, they may also reduce aerosols"—which include particles like pollen, volcanic ash, wood smoke, and smog. "Because of the climatic effects of aerosols, reducing particulate pollutants could alter the rate of global warming."

One example can be found in the work of Surabi Menon, of Berkeley Lab's Environmental Energy Technologies Division, who has studied the effects of cloud formations and aerosols in China. She found that absorbent black carbon—soot—affects the heating rates of surface and atmosphere and changes how precipitation is distributed. As a result, droughts in North China and floods in South China have been increasing for decades.

Biofuels derived from plants like miscanthus will reduce carbon emissions, but large-scale changes in patterns of land use will affect climate in ways that have yet to be assessed.

"There are just so many things about the earth we don't understand," says climate modeler Inez Fung. "For example, soil moisture is a major uncertainty in climate models. What will happen when we start growing large expanses of biofuel plants and changing vegetation patterns?"

Fung was born and raised in Hong Kong and graduated from high school there, but her undergraduate work carried her half-way around the world, to MIT. As a math major, Fung was delighted by mathematical toys like the chaotic Lorenz waterwheel; soon fluid dynamics became her enthusiasm, and she went on to earn her doctorate in meteorology at MIT with an award-winning thesis on the "organization of spiral rainbands in a hurricane."

Though large, the step from geophysical fluid dynamics to computational models of the global climate is logical. Fung spent years at NASA's Goddard Institute for Space Sciences and other institutions before joining Berkeley Lab's ESD and UC Berkeley in 1998.

Here she founded the Berkeley Atmospheric Sciences Center and the Berkeley Institute of the Environment, working closely with earth scientists to develop new ways of observing the earth and using this data to project the world's changing climate with ever greater power and sophistication.

Water remains key to her interests. "When I say climate I mean water," Fung says. "It's the basis of the whole earth system. As the planet grows warmer, precipitation may not decrease much, but the soil will dry faster, and plants are gonna croak."

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Collaborating with Collins when he was NCAR, Fung cofounded CCSM3's biogeochemistry working group to incorporate new variables, from microbial action to crops and forests. In modeling the ability of terrestrial and marine carbon sinks to absorb atmospheric CO2, Fung says, the researchers found that "the faster the emissions from fossil fuels, the less effective the land and ocean as carbon sinks. As natural carbon storage lags ever further behind, climate warming accelerates."

The new Berkeley-based Integrated Earth System Model that Collins, Fung, and their colleagues envision will predict interactions among climate, water, and energy on a global scale. It will be able to incorporate fresh data and generate new scenarios at any point: energy demand and carbon emissions; changes in the composition of the atmosphere and the heat entering and leaving it; impacts on ecosystems and human well-being; and different strategies to mitigate or adapt to change.

Working with Berkeley Lab's Computational Research Division and National Energy Research Scientific Computing Center (NERSC), scientists from several institutions are devising an integrated model that can deliver detailed predictions on the regional scale more than 20 years out, and global models that can forecast worldwide changes to the end of the century. The initiative will make DOE a leader in the fundamental science of climate modeling.

Carbon epicycles

Better climate models depend on observations of the kind that ESD geochemists Jim Bishop and Margaret Torn conduct to understand the carbon cycle and monitor natural carbon sinks.

The ocean is the biggest carbon sink, mostly because of phytoplankton, microscopic plants living in untold numbers near the surface. Fertilizing the growth of phytoplankton by adding iron to iron-poor but otherwise nutrient-rich waters has been touted as a quick way to force greater atmospheric CO2 absorption.

"Before we can decide whether schemes for storing excess atmospheric carbon in the ocean are safe, or would even work at all, we need to know a lot more about the biology of the ocean carbon cycle," says Bishop.

While majoring in chemistry at the University of British Columbia, Bishop got himself a summer job collecting marine life for Canada's Department of Fisheries. Intrigued by both chemistry and oceanography, he earned his doctorate in an MIT/Woods Hole program that featured both.

From the beginning, ocean carbon has been Bishop's passion. One way to gather data is to lower collectors over the ship's side, bring up water from various depths, and analyze its chemistry and the remains of life it contains. Satellites provide another data source. Both approaches have limits. "Ships can't stick around for weeks at a time," Bishop says, "and satellites can't see through clouds."

A professor of marine science at UC Berkeley, Bishop came to Berkeley via the Goddard Institute for Space Studies and the University of Victoria; at Berkeley Lab he seized the opportunity to develop new kinds of data collectors. Here he and his colleagues developed free-ranging Carbon Explorers, based on the successful salt-and-temperature-measuring robotic SOLO floats engineered by Russ Davis of the Scripps Institution of Oceanography, and using commercial instrumentation. Carbon Explorers measure particulate carbon by diving to depths of up to two kilometers, then surface to report via satellite.

The Carbon Flux Explorer was successfully tested on a three-day cruise off the coast of California early in the summer of 2007. The Scripps Institution of Oceanography's Research Vessel Sproul provided support for the test.
(Photo Roy Kaltschmidt, CSO)

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Carbon Explorers in the North Pacific reported the first evidence of a plankton bloom fertilized by wind-blown dust, from a storm in Central Asia—the iron-fertilization phenomenon long predicted but never before observed. Carbon Explorers in the Southern Ocean tracked plankton blooms created by artificial iron fertilization. But dust effects were shorter-lived than expected, and adding iron to Southern Ocean waters yielded complex, unpredicted results.

Shipboard work and analysis of samples at Berkeley Lab's Advanced Light Source have uncovered new clues to the nutrition of marine plants. Bishop's recent studies show that plankton blooms are fertilized mostly by continental run-off, a far more significant source of iron than wind-blown dust.

Given these surprises, says Bishop, "Quick-fix solutions involving stimulation of ocean ecosystems are not the best way to address the issue of atmospheric CO2. We need a better recipe for ocean biology and the way it cycles carbon."

The Carbon Flux Explorer (CFE), which passed its ocean-going performance tests in the summer of 2007, is the latest addition to the Lab's stable of autonomous robots. The CFE uses a buoyancy engine provided by Scripps and carries improved instruments (and more of them) designed and built at Berkeley Lab, "capable of telling us what's happening with carbon sedimentation moment by moment, while operating for seasons at a time," Bishop says. "I'm proud the instrumentation was entirely engineered at Berkeley Lab. Everything we build meets special challenges in the ocean."

With enough Carbon Explorer-series robots ranging the seas, the ocean's ability to cycle carbon could finally become clear. Robotic floats that can observe biological processes on the appropriate space and time scales, plus advanced analysis of samples collected from ships, are both essential to building models with predictive capability. "Otherwise," says Bishop, "we're flying blind."

Bishop believes we've learned enough already to revise our attitude regarding the ocean as a carbon dump. "The carbon capacity of the ocean, and the resulting impacts of acidification on ocean ecosystems, should be thought of as constraints, beyond which we simply cannot afford to add more carbon to the air."

The ARM Carbon Project in Oklahoma is one of the world's best-equipped sites for carbon studies, using a variety of instruments mounted on the ground, in towers, and in aircraft to measure a variety of interactions among soils, plants, and the atmosphere.

(Photo Roy Kaltschmidt, CSO)

The science of dirt

Soil is second only to the ocean as a dynamic carbon reservoir. Soils contain twice as much carbon as the atmosphere, and the terrestrial carbon cycle exchanges carbon with the air—into plants, out of soil—at 10 times the rate of fossil fuel emissions. Organic carbon is stored in plant roots and decaying matter; remarkably, erosion and deposition can also sequester carbon.

"Whether soil organic carbon constitutes a net carbon sink or is a net source of atmospheric CO2 is an unresolved question," cautions Margaret Torn, who pioneered climate change and carbon science programs in ESD. An even more important question is how climate will affect carbon exchanges in the future; soils could form harmful feedback loops that accelerate global warming.

It was during a summer spent studying acid rain in the Colorado Rockies that Torn, then a UC Berkeley undergraduate, realized she was hooked on geochemistry: "I knew I had to spend my career doing fieldwork." As a staff scientist in ESD and an adjunct professor at UC Berkeley's Energy and Resources Group (where she did her own graduate work) she has done fieldwork aplenty, heading up formative research in carbon science and its relation to climate change.

Torn examines how water and gases cycle between air and soils under a range of ecological, geographical, and climatic conditions. Her research has taken her around the world, from

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Hawaiian volcanoes to the Russian steppes, as well as far back in time, linking greenhouse gases trapped in Antarctic ice cores to positive feedback between climate and ecosystems.

If the macrocosm is global climate change, moisture, nutrients, the isotope chemistry of rocks and soil, and other factors are the microcosmic sources of indispensable data. Torn's focus is on the intricate connections among these variable: "How, for example, the methane flux of a single wetland contributes to controlling the temperature of the whole earth."

The role of soils in the terrestrial carbon cycle remains poorly understood, and Torn's research has brought surprises: that roots are the principal source of soil organic carbon, for example; that soil erosion, a worldwide environmental problem, can paradoxically result in net carbon storage on land.

Torn directs one of the world's best-instrumented sites for regional carbon studies at DOE's Atmospheric Radiation Measurement (ARM) Carbon Project, centered in Oklahoma in the Southern Great Plains. Automated flask systems on the ground and instruments mounted on towers and in aircraft follow tell-tale isotopes of carbon and oxygen and collect other data, tracing interactions of water, carbon dioxide, and solar energy between the atmosphere and soils of prairies, farmlands, and forests.

The goal is to understand these exchanges on a range of scales—as Torn says, "from a single leaf to an entire continent." From a handful of dirt to the climate of the planet: by means of fundamental science, Torn and her colleagues hope to make clear the social impacts of global warming and find ways to avert its worst consequences.

Additional information

Bill Collins on the Future of the Earth's Climate: Frontiers in Forecasting, at http://www.lbl.gov/publicinfo/summerlectures/assets/docs/CollinsLecture071107.pdf, and on the 2007 ICPP reports at http://abclocal.go.com/kgo/story?section=global_warm&id=5272019

More about Inez Fung's research is at http://www-esd.lbl.gov/ESD_staff/fung/index.html

More about Jim Bishop's research is at http://www-ocean.lbl.gov/people/bishop/bishop.html.

More about Margaret Torn's research is at http://www-esd.lbl.gov/ESD_staff/torn/

More on the Intergovernmental Panel on Climate Change, at http://www.ipcc.ch/

More on the Community Climate System Model, version 3 (CCSM3), at http://www.ccsm.ucar.edu/index.html

More about carbon cycle and climate model research at UC Berkeley is at http://sciencematters.berkeley.edu/archives/volume3/issue18/story3.php.

More about measuring ocean carbon with robotic floats is at http://www.lbl.gov/Science-Articles/Archive/sb-Apr-04-ESD-ocean-carbon.html.

More about measuring iron fertilization of phytoplankton with shipboard instruments is at http://www.lbl.gov/Science-Articles/Archive/sabl/2006/Mar/02-winter-iron.html.

More about the Atmospheric Radiation Measurement (ARM) Carbon Project at Berkeley Lab is at http://esd.lbl.gov/ARMCarbon/.

More about feedback loops in global warming is at http://www.lbl.gov/Science-Articles/Archive/ESD-feedback-loops.html.

More about erosion as a carbon sink is at http://www.lbl.gov/Science-Articles/Archive/sabl/2007/Apr/05-erosion.html.

From top, Bill Collins, Inez Fung, Jim Bishop, and Margaret Torn