Department of Earth, Atmospheric, and Planetary Sciences

The Department of Earth, Atmospheric, and Planetary Sciences (EAPS) has broad intellectual horizons encompassing the solid Earth, its fluid envelopes, and its diverse neighbors throughout the solar system and beyond. The department seeks to understand fundamental physical, chemical, and biological processes that define the origin, evolution, and current state of these systems and to use this understanding to predict future states. The department comprises 39 faculty (including one with a primary appointment in the Department of Civil and Environmental Engineering, and one with a primary appointment in the Engineering Systems Division), and more than 240 research staff, postdoctoral appointments, and visiting scholars.

EAPS is notable for its emphasis on interdisciplinary problems and is involved in numerous laboratories, centers, and programs that address broad questions in the earth sciences, including some of the most pressing societal issues of our time: change in climate and environment, natural resources and hazards, and the origin and evolution of life on Earth and, perhaps, elsewhere. For example, the Earth Resources Laboratory (under directorship of professor Bradford Hager) integrates faculty, staff, and students across disciplinary, department, and school boundaries to investigate geophysical and geological problems in energy and resource development. The Center for Global Change Science (under directorship of professor Ronald Prinn) builds on the programs in meteorology, oceanography, hydrology, chemistry, satellite remote sensing, and policy. EAPS is an active participant in the MIT/Woods Hole Oceanographic Institution (WHOI) Joint Program and supports the program's mission of graduate education and research in ocean sciences and engineering.

Educational Activities

Graduate Program

EAPS has vigorous graduate educational programs in geology, geochemistry, geobiology, geophysics, atmospheres, oceans, climate, and planetary science. In fall 2012, EAPS had 170 graduate students registered in the department, including 75 students in the MIT/WHOI Joint Program. Women constituted 46.7% of the graduate student population, and 7% were members of an underrepresented minority group.

In May 2013, at a special faculty meeting, the ad hoc taskforce on the EAPS education program presented its final report and recommended changes to the department's graduate program. The committee had sought the opinions of EAPS faculty, current students, and alumni on the graduate program structure and academics. An important area of agreement by the members of the faculty concerned moving to a uniform structure for the general exam among the four educational disciplines within the graduate program. The decisions of the faculty will be implemented by the Graduate Education Committee for the graduate students entering in September 2013. A thoroughly revised and updated Handbook for Graduate Education at EAPS will be available in August 2013.

The excellence of the EAPS graduate program is built not only on the strength of teaching and supervision by the faculty but also on the involvement of EAPS graduate students in departmental activities. Students develop formal and informal ways to improve the educational experience as well as student life by continuing to take responsibility for an expanded orientation program for incoming graduate students; planning a number of social events to introduce newcomers to EAPS, MIT, and the Cambridge area; and holding regular student research presentations and encouraging undergraduate majors to attend. The departmental Graduate Student Mentoring Program continues as a well-received approach to provide peer support for new students. In addition, students are increasingly engaged in issues of department management (this includes governance committees, strategic planning, faculty recruitment, organization of departmental lecture series, and space renewal).

The Program in Atmospheres, Oceans, and Climate, within EAPS, awards the Carl-Gustaf Rossby Prize to recognize the best PhD thesis in the preceding year. Malte Jansen and Laura Meredith were the recipients for this past year. Dr. Jansen was also awarded a National Oceanic and Atmospheric Administration Climate and Global Change Postdoctoral Fellowship, and has now been hired as an assistant professor by the University of Chicago. Kimberly Huppert was awarded a NASA Earth and Space Science Graduate Fellowship, and Colin Pike-Thackray was awarded a Natural Sciences and Engineering Research Council of Canada graduate research fellowship.

EAPS awards an annual prize for excellence in teaching to highlight the superior work of its teaching assistants. During AY2013, Ann Bauer, Timothy Cronin, Katherine French, Erin Shea, and Allison Wing were recognized for their contributions.

EAPS students were also recognized by their respective professional societies. Martin Singh received the Best Student Paper Award for "The Temperature Dependence of Rainfall Intensity, CAPE, and Vertical Velocities in Radiative-convective Equilibrium," presented at the American Meteorological Society's 19th Conference on Atmospheric and Oceanic Fluids Dynamics. At the 2012 annual meeting of the American Geophysical Union, four EAPS students were recognized with Outstanding Student Paper Awards: Anton Ermakov, by the Planetary Sciences section for "Modeling of Vesta's Interior Structure Using Gravity and Shape Model from the Dawn Mission and Hydrodynamic Impact Simulations"; Benjamin Linhoff, by the Cryosphere section for "Greenland Ice Sheet Hydrology: Insights from an Isotope Mixing Model during the 2011 and 2012 Melt Seasons"; Ben Mandler, by the Volcanology, Geochemistry, and Petrology section for "Magma Storage Conditions Prior to the Caldera-forming Eruption of Newberry Volcano, Oregon"; and Alejandra Ortiz, by the Earth and Planetary Surface Processes section for "Turbulent and Mean Velocity Near Rigid and Flexible Plants, and Implications for Deposition." At the 17th Conference on the Middle Atmosphere, Justin Bandoro was awarded the Best Student Oral Presentation for his talk "Influence of the Antarctic Ozone Hole on Seasonal Changes in Climate in the Southern Hemisphere."

Undergraduate Program

In fall 2012, EAPS had 19 undergraduate majors—90% were women, and 10% were members of an underrepresented minority group. Seven students were awarded the bachelor of science degree in earth, atmospheric, and planetary sciences in AY2013.

The department maintains a strong presence in MIT's undergraduate program beyond the population of majors so that the general student body has access to the geoscientific aspects of climate and environmental change, natural hazards, and natural energy resources.

The department is committed to supporting the Terrascope program, with its problem-based approach to education during the first year at MIT and to offering Freshman Advising Seminars (FAS). In fall 2012, EAPS offered five FAS, and in fall 2013 will offer a total of 11 FAS. With the combined enrollment of Terrascope and the advising seminars, EAPS teaches 10% of the students in the freshman class on a weekly basis. Similarly, EAPS is an active participant in three interdisciplinary minor programs: the broad-based Energy Minor; the Astronomy Minor, with Physics; and the new Atmospheric Chemistry Minor. Professor Susan Solomon, with the enthusiastic support of the EAPS faculty, was a leader of an interdisciplinary team of interested faculty that organized the Atmospheric Chemistry minor, which will enroll its first students in AY2014.

At the 2013 Student Awards and Recognition Dinner, the Christopher Goetze Prize for Undergraduate Research was awarded to Shaena Berlin in recognition of her outstanding senior thesis, Thomas Ben Thompson received the W. O. Crosby Award for Sustained Excellence, and Ann Alampi and Ryan Keating were the recipients of the Award for Excellence as an Undergraduate Teaching Assistant. Jessica Fujimori and Kathryn Materna were the recipients of the EAPS Achievement Award, which recognizes a rising senior from across the EAPS disciplines. The award is presented to a student who has distinguished her or himself through a combination of high grade point average, focused coursework, and leadership within EAPS.

Community Events

In AY 2013, EAPS worked with Resource Development, the School of Science, and the MIT Alumni Association to organize a full calendar of events and programs to engage EAPS alumni and prospective donors. The year kicked off with Professor Solomon presenting the Dean's Colloquium to a full house in Room 10-250, followed by a celebratory dinner at Boston's Liberty Hotel. Assistant professors Taylor Perron and Noelle Selin were the featured speakers at the October and April School of Science breakfasts. These breakfasts, held four times a year at MIT's faculty club, give Boston-area major gift prospects the opportunity to hear about cutting-edge research in the School of Science. EAPS sponsored four events this year, including the November 1 John Carlson Lecture and Dinner, cosponsored by the New England Aquarium and featuring Oxford University's professor Timothy Palmer, and EAPS's annual reception during the American Geophysical Union Fall Meeting, which had a record turnout of more than 350 attendees. In addition, EAPS coordinated two "state of EAPS" breakfasts for alumni and friends in Houston, TX, and Cambridge, MA, and capped off the year with a celebration of the new Earth Resources Laboratory (during the annual consortium for corporate sponsors), at which a seminar room was dedicated in honor of professor M. Nafi Toksöz and the successful completion of the M. Nafi Toksöz Fellowship Fund was announced. In collaboration with the MIT Alumni Association, professor Kerry Emanuel and associate professor Daniel Cziczo spoke at all-call alumni events in Austin, TX, and Boulder, CO. Professors Emanuel and Cziczo also participated in two online faculty forums, which proved an effective way to expose an even larger audience to their work. A reception for members of the William Barton Rogers Society (MIT donors of $1,000 plus) was held at the American Museum of Natural History, in New York City, with associate professor Benjamin Weiss giving a lecture in the Hayden Planetarium.

Geared towards graduate students and postdoctoral appointments, the annual Long Pond weekend, coordinated by the EAPS Graduate Student Activities Committee, took place over the weekend of September 21–23. This activity provides a valuable opportunity for community building at the start of each year.

Over the same weekend, professors Samuel Bowring and Thomas Herring led a two-day field trip to explore the geology of central and western Massachusetts. The trip, a recurring EAPS activity, brought together around 30 participants, among them EAPS graduate students, undergraduate majors, postdoctoral appointments, and staff and researchers, as well as undergraduates outside Course XII.

This year saw two author nights, the first featuring senior research scientist Michael Follows (October 26, 2012), and a second featuring Professor Emanuel (May 3, 2013). Each were attended by over 100 guests and culminated in book signings and refreshments.

Over the course of the year, EAPS hosted over 30 department lectures, with topics ranging across the full spectrum of the earth and planetary sciences. Adding to these, the well-attended January 2013 Independent Activities Period lectures series "The Atmosphere as an Intersection with..." (organized and hosted by Professor Cziczo) provided an introduction to the atmospheric sciences as they intersect the solid Earth, its oceans and hydrodynamic cycles, and space.

January also saw residency of the year's one Houghton Lecturer, Joseph LaCasce (PhD '96, now a professor at the University of Oslo, Norway), who gave a three-lecture course on "Lagrangian Methods and Mixing" (as applied to the ocean and atmosphere) and a fourth lecture, "Defending the Use of Linear Models to Understand the Ocean."

On February 16, 2013, the head of department made his second annual "State of EAPS" presentation to an audience of around 250 department members and friends. This year, special emphasis was given to the many new communications initiatives EAPS has undertaken, as well as to emphasizing development and fundraising priorities and educational and faculty recruitment goals.

The year ended with the sixth annual Student Recognition Dinner (May 17, 2013), at which internal student awards were announced and presented. A highlight of the evening was EAPS alumnus Lisa Song (BS '08, and master of science '09 from the

Graduate Program in Science Writing), a recent joint winner of the Pulitzer Prize in National Reporting and the Rachel Carson Environment Book Award, who shared her journey from undergraduate major in EAPS to award-winning science journalist.

Faculty

The department continues its efforts to hire and help young faculty members develop careers. Two new assistant professors will join the department in July 2013: Hilke Schlichting, a planetary scientist, and German Prieto, a geophysicist. Senior research scientist Michael Follows will be appointed to the rank of associate professor during the same timeframe. The department extended an offer to Kristin Bergmann, a geologist who recently finished her PhD at the California Institute of Technology (Caltech), and who is now a junior fellow at Harvard University. Dr. Bergmann will join the EAPS faculty in July 2015.

Honors and Awards

Associate professor Tanja Bosak received the Harold E. Edgerton Faculty Achievement Award, the junior faculty equivalent of the James R. Killian, Jr., Faculty Achievement Award.

Professor Bowring was elected a fellow of the American Academy of Arts and Sciences.

Professor Cziczo was awarded a Victor Starr Career Development Chair. He was also honored with a National Aeronautics and Space Administration (NASA) Group Achievement Award for his work on the Mid-latitude Airborne Cirrus Properties Experiment Mission.

Senior research scientist Michael Follows was named a Gordon and Betty Moore Foundation Investigator.

Professor Timothy Grove was selected as the next Cecil and Ida Green professor of geology and was elected an honorary fellow of the European Association of Geochemistry.

Assistant professor David McGee received two internal MIT awards in the past year: the Ally of Nature Fund award, and a Research Support Committee Fund award.

Professor Alan Plumb was awarded the Jule G. Charney Award by the American Meteorological Society.

Professor Paola Rizzoli was appointed the first Singapore-MIT Alliance for Research and Technology program chair for the year 2013, by provost Chis Kaiser.

Professor Daniel Rothman was selected as a fellow of the American Physical Society.

Professor Leigh Royden was the recipient of the Stephan Mueller Medal by the European Geophysical Union.

Professor Sara Seager was selected the co-winner of the Raymond and Beverly Sackler Prize in the Physical Sciences.

Professor Selin was selected as a Leopold Leadership Fellow by the Stanford Woods Institute for the Environment.

Professor Solomon received the following awards over the past year: Honorary Member, the American Meteorological Society; the Vetlesen Prize, the Vetlesen Foundation; Honorary Member, the American Polar Society; the Banco Bilbao Vizcaya Argentaria (BBVA) Foundation Frontiers of Knowledge Award, the BBVA Foundation; and an honorary doctorate from Leeds University, UK, to be awarded in July 2013.

John Southard (alumnus) received the William H. Twenhofel Medal of the Society for Sedimentary Geology.

Professor Weiss was honored by having Asteroid 8069 named "Benweiss," after him.

Professor Maria Zuber was honored with the Harry Hess Medal by the American Geophysical Union

Research Highlights

Samuel Bowring

Professor Bowring and his research group have worked on a number of diverse projects during the past year, involving high-precision U-Pb geochronology. Their work on mass extinctions and large igneous provinces was featured in *Science* (Terrence Blackburn, et al., 2013); they showed that the end-Triassic extinction was exactly coincident with the first eruptions associated with the Central Atlantic Magmatic Province within ± 30 thousand years 201 million years ago. Other contributions involved using high-precision geochronology combined with astrochronology to determine the duration of the "Messinian gap," corresponding to the evaporative drawdown of the Mediterranean following the closure of the Mediterranean-Atlantic gateway to be 28 ± 9.6 k.y., consistent with the notion of a fast desiccation and refilling of the Mediterranean ca 5.53 million years ago. Professor Bowring's PhD students are working on projects that range from high-precision dating of the largest known volcanic province, the Siberian Traps, to the time scales for constructing granitic plutons to Hf isotopic investigations of the 4.0-billion-year-old Acasta Gneisses. He continues to lead Terrascope, a freshman learning group program that uses experiential learning to teach students about problems of sustainability and the environment.

Edward Boyle

Professor Edward Boyle has obtained the most highly resolved sections of anthropogenic lead (Pb), Pb isotopes, and colloidal Fe on the US GEOTRACES North Atlantic Transect (Woods Hole–Bermuda–Cape Verde Islands–Lisbon). This data shows that hydrothermal vents at the mid-Atlantic ridge are scavenging anthropogenic Pb out of the mid-depth waters. It also shows that there is a high-salinity, high-Pb, low $^{206/207}$Pb isotope signal in an Atlantic water mass at approximately 100m depth (subtropical underwater). Professor Boyle finds that half of the so-called "dissolved" Fe in the Atlantic Ocean is in the form of 0.02-0.2 micrometer colloids. He has also used sediments and annually-banded corals from the northern Persian Gulf to reconstruct the history of anthropogenic Pb pollution in this region, with a rise from the 1950s until the mid-1980s, then a decrease when leaded gasoline was phased out in this region.

Clark Burchfiel

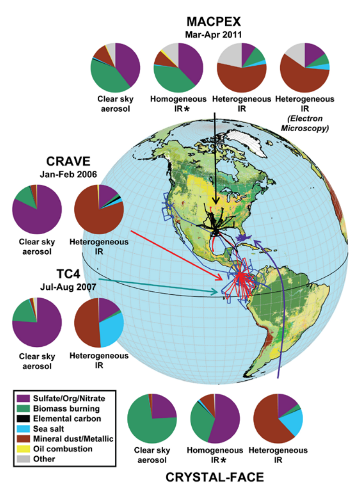
Professor Clark Burchfiel's research has been focused in three areas. The primary focus has been on the tectonic development of the Tibetan plateau, and a memoir covering his research effort has been jointly published this year by the Geological Society of America and the Chengdu Institute of Geology and Mineral Resources, China. This work has been ongoing for 28 years. Research on the tectonic development of the Balkan Peninsula and Greece has been a second area of research, and the work is now in its concluding phase. The third area of research is on the tectonic evolution of the southeast part of the Cordilleran orogen of the western US in Southeast California. A book on this region is in progress, with several large geologic maps, and is scheduled for completion in early 2014.

Daniel Cziczo

Professor Cziczo is an atmospheric chemist interested in the relationship of the small particles found in the atmosphere and cloud formation. His research combines laboratory and field studies to elucidate how these small particles interact with water vapor to form droplets and ice crystals and how they can impact the Earth's climate system and water cycle. His group conducts experiments, including using small cloud chambers in the laboratory to mimic atmospheric conditions that lead to cloud formation, as well as conducting field studies, such as observing clouds *in situ* from remote mountaintop sites or aboard research aircraft. Professor Cziczo and postdoctoral fellow Karin Ardon-Dryer participate in WGBH's Nova Cloud Lab by editing educational video and answering viewer questions.

Kerry Emanuel

Professor Emanuel expanded his research efforts into two new areas: self-aggregation of convection, and climate control of severe local storms. Self-aggregation is a phenomenon observed in cloud-resolving models run into states of statistical radiative-convective equilibrium. Normally, such states exhibit moist convective plumes that are nearly randomly distributed in space and chaotic in time, but if certain conditions are present the convection spontaneously aggregates into a single large cluster. The atmosphere around it dries dramatically, suggesting that self-aggregation can strongly regulate tropical climate. Working with graduate student Allison Wing, Professor



Emanuel's research group members have uncovered the essential physical mechanisms underlying self-aggregation, and are beginning to understand its role in regulating climate. With graduate student Vince Agard, they are beginning a new project to understand how severe local storms, which produce damaging wind, hail, and tornadoes, respond to climate change. Work continues with coprincipal investigator Peter Molnar and graduate student Timothy Cronin on the nonlinear rectification of the diurnal cycle of moist convection over land and its possible implications for the climate of the Pliocene, and with graduate student Morgan O'Neill on the dynamics of Saturn's polar vortices.

Raffaele Ferrari

Professor Raffaele Ferrari's research focused on two main questions. The first was to quantify the role of oceanic turbulence in driving the meridional circulation in the Southern Ocean. This is a crucial question for climate because our uncertainty in the ocean uptake of carbon in a warming climate is largely associated with uncertainties in the dynamics of ocean turbulence. Using a combination of observations collected as part of the Diapycnal and Isopycnal Mixing Experiment in the Southern Ocean (DIMES) project and numerical simulations, Professor Ferrari's research group produced the first direct estimates of the rate at which turbulence mixes tracers into the Southern Ocean. It is now using these estimates to improve the representation of ocean turbulence in climate models. A second focus of the research is the study of biological productivity in the subpolar oceans. The group began a large observational program in the Eastern North Atlantic using a combination of traditional ship-based and glider measurements, and has obtained the first detailed record of biological blooms in the subpolar Atlantic for a full year. Contrary to common wisdom, it has been found that much growth occurs in winter and is missed by satellite observations. The group is now studying the implications of these observations for estimates of oceanic carbon uptake.

Glenn Flierl

Professor Glenn Flierl and his students are investigating physical and biological dynamics in the ocean and other more general problems in geophysical fluid dynamics. Three students coadvised by Professor Flierl finished their PhD research this year. Ru Chen examined the energetics of ocean variability and showed that the transfers from the mean to the eddies was generally not local. She also showed that "striations" in ocean currents (long bands of coherent flow appear in the time-averaged fields) contain significant amounts of the low-frequency energy in the ocean and are greatly altered by the large-scale flows. Nicholas Woods studied physical processes which would lead to aggregation (in the Great South Channel area) of copepods, the primary food source for right whales. He examined models of the coastal river-fed buoyant plume and showed that, in its progression down the coast, it could build up the concentration of copepods near the nose of the plume by an order of magnitude. The mixing by eddies can break up patches; he analyzed this using drifter data from the Gulf of Maine and the University of Massachusetts Dartmouth mode. The dispersive processes varied significantly in different subregions of the Gulf and the two-particle statistics showed that "eddy diffusivity" is not a good measure of the potential for breaking up patches of copepods. Juliana Albertoni (University Sao Paolo) modelled the flow of the Brazil current around coastal protrusions and bays. Professor Flierl's students are also studying the physical and biological dynamics of spring blooms in collaboration with Professor Ferrari.

Timothy Grove

Professor Grove and his students have developed a model for predicting the major element compositions of melts of garnet lherzolite over the pressure range of 1.9 to 6 GPa. The model estimates the major element compositions of garnet-saturated melts for a range of mantle lherzolite compositions and predicts the conditions of the spinel to garnet lherzolite phase transition for natural peridotite compositions at above-solidus temperatures and pressures. They compare our predicted garnet lherzolite melts to those of pyroxenite and carbonated lherzolite and develop criteria for distinguishing among melts of these different source types. They also use the model in conjunction with a recently published predictive model for plagioclase and spinel lherzolite (Christy Till, et al., *Journal of Geophysical Research*, 2012) to characterize the differences in major element composition for melts in the plagioclase, spinel, and garnet facies and develop tests to distinguish between melts of these three lherzolite facies based on major elements. There has been a continuing debate about the source materials (peridotite vs. pyroxenite) of basaltic melts of the Earth's upper mantle that has been largely based on evidence from trace elements. The major element-based model brings another set of criteria to bear on this long-standing problem.

Bradford Hager

Professor Hager became the Director of the Earth Resources Laboratory (ERL) in June, 2012. His research focus relevant to energy includes induced seismicity; developing techniques for monitoring and verification of geologic storage of CO_2; and more safe, efficient, and effective techniques for extracting shale gas. In addition, he is colead of a NASA InSAR satellite mission for measuring ground deformation, ice sheet velocities, and the inventory of woody biomass from space.

Colette Heald

Associate Professor Heald and her group (Department of Chemical Engineering and EAPS), work on a range of problems examining the role of atmospheric chemistry and composition in the Earth system. Recent work has focused on the sources, evolution, and impacts of aerosol particles in the atmosphere. This includes studies investigating the representation of dust in global models, the origins and transport of smoke, the impact of bark beetle infestation in Western North America on aerosol formation and visibility, and the satellite constraints on aerosol formation in the southeastern US. Ongoing projects include analyzing the impacts of climate and ozone pollution on projections of global crop productivity, investigating the origin of poor particulate air quality in California, assessing the role of aging on the radiative impacts of black carbon, and exploring the drivers of air quality extremes.

Thomas Herring

Professor Herring is using global positioning system (GPS) and very-long-baseline interferometry (VLBI) data to develop geophysically based models of Earth deformations on global, regional, and local scales and changes in the rotation of the Earth. He is also using interferometric synthetic aperture radar to study small surface deformations and geodetic methods to study Earth's gravity field. His group is using high-precision GPS measurements in many different study areas, including over much of the southern Eurasian plate boundary and the western US. It is investigating processes on time scales of years leading up to earthquakes, transient deformation signals lasting days to many weeks, postseismic deformation after earthquakes on time scales of day to decades, and surface wave propagation during earthquakes using high rate GPS data. All of these measurements have submillimeter to few millimeter precision. The group is also monitoring and modeling human-induced deformations in oil fields and on tall buildings.

Alison Malcolm

Assistant Professor Malcolm's research program continues to focus on imaging complex structures, and particularly on nonlinear imaging. Her group has gone from very preliminary experiments, suggesting that it could sense the passage of one wave with another wave, to experiments which demonstrate that the signal is robust, though small, and challenging to measure. The group is working on applications of this work to hydraulic fracturing, imaging the fracture system and understanding the fluids that may be contained within it. Further, the group had a summer student (from the University of Science and Technology of China, through the program initiated by professor Jie Zhang) who will attempt to model an application to steering hydraulic fractures. Professor Malcolm also spent significant time on full-waveform inversion, an imaging technique that is rising in popularity with increasing computer power. She and her students are working on three aspects of this technique: (1) estimating the Hessian in a unique way that may allow its computation, at reasonable cost, for the first time, (2) estimating the initial model in a more efficient manner, and (3) beginning to use the results in a statistical sense to determine whether injected CO_2 remained in the reservoir or not. She and her group continue to focus on microseismic data. They are working on jointly locating different events to estimate things like fracture extent rather than simply the locations of events individually, and are extending this work to estimate uncertainties in seismic images. They are also working on velocity analysis and imaging using microseismic data as sources, and are in the process of applying these ideas to a field data set from Iceland to understand the location and extent of a magma chamber.

One of Professor Malcolm's papers was selected as one of the top 30 papers of the fall 2012 Society of Exploration Geophysicists (SEG) meeting: Oleg Poliannikov, Michael Prange, Alison Malcolm, and Hugues Djikpesse: "Relative Event Localization in Uncertain Velocity Model." *SEG Technical Program Expanded Abstracts*, 2012.

John Marshall

Professor Marshall's research interests are in the role of the ocean in climate and climate variability. A recent focus has been on the dynamics and biogeochemistry of the Southern Ocean and asymmetries in the response of the two poles to climate perturbations. He has also been studying geometrical constraints on ocean heat transport and the possibility that the climate may possess multiple equilibria. In the past year, Professor Marshall has been instrumental in organizing oceans@mit, a cross-disciplinary amalgam of all things related to the ocean across the Institute.

David McGee

Professor McGee's research focuses on reconstructing and understanding past changes in Earth's hydrological cycle. During the past year, he and his group have made important contributions to our understanding of the regional expression of global climate changes in the time from the last ice age to the recent past (i.e., the last 25,000 years). First, they have produced unique new records of the drying of the US Great Basin over the last 25,000 years (McGee, et al., *Earth and Planetary Science Letters [EPSL],* 2012). Results comprise the most precisely dated and highest resolution records from this region covering this important time period. Their work with Great Basin cave deposits continues, and they anticipate more high-impact publications to come based on stalagmite data recently collected. Second, they have produced quantitative estimates of windblown dust emissions from the Sahara Desert over the last 20,000 years (McGee, et al., *EPSL,* 2013). This work provides important documentation of the abrupt impacts of past global climate changes on North Africa and was featured on the MIT homepage on April 5, 2013. A key contribution of these data is that they will allow for the first time the ability to estimate the direct role of eolian dust in amplifying past climate changes in the region. Ongoing work seeks to extend these records through the last ice age to provide calibration data for climate models of the last glacial maximum. Finally, in collaboration with Professor Marshall's group, they have begun investigating the interpretation of paleo-records of tropical rainfall patterns using models and theory. This work has provided novel constraints on the response of tropical hydrology to past climate changes (Aaron Donohoe, et al., *Journal of Climate,* 2013).

Paul O'Gorman

Associate Professor O'Gorman's group has continued to investigate how the atmosphere behaves in different climates. Graduate student Michael Byrne is the lead author on a paper examining the differential surface warming of land and ocean over a wide range of climates. His theoretical results indicate that the greatest contrast in warming should occur for an ocean surface temperature near 290K, although changes in surface relative humidity over land are also an important factor. Graduate student Martin Singh has investigated the reasons for an upward shift of atmospheric fields in comprehensive simulations of warming climates. Recently published results from the group indicate that there is also some observational evidence for an upward shift in the middle and upper troposphere over the period 1960–2005.

Taylor Perron

Professor Perron and his group study the processes that shape landscapes on Earth and other planets. Their efforts are currently focused on understanding widespread patterns in landscapes, climate's effects on erosion, and the landscapes of Mars and Saturn's moon Titan. Professor Perron, graduate student Paul Richardson, and postdoctoral researcher Kenneth Ferrier recently showed how erosional instabilities create the familiar branching pattern of river networks, a common feature of many landscapes that has lacked a theoretical explanation. Professors Perron and Royden collaborated on a new mathematical approach for inferring a landscape's tectonic and climatic history from the elevation profiles of rivers. Dr. Ferrier, graduate student Kimberly Huppert, and Professor Perron measured erosion rates across one of the world's steepest rainfall

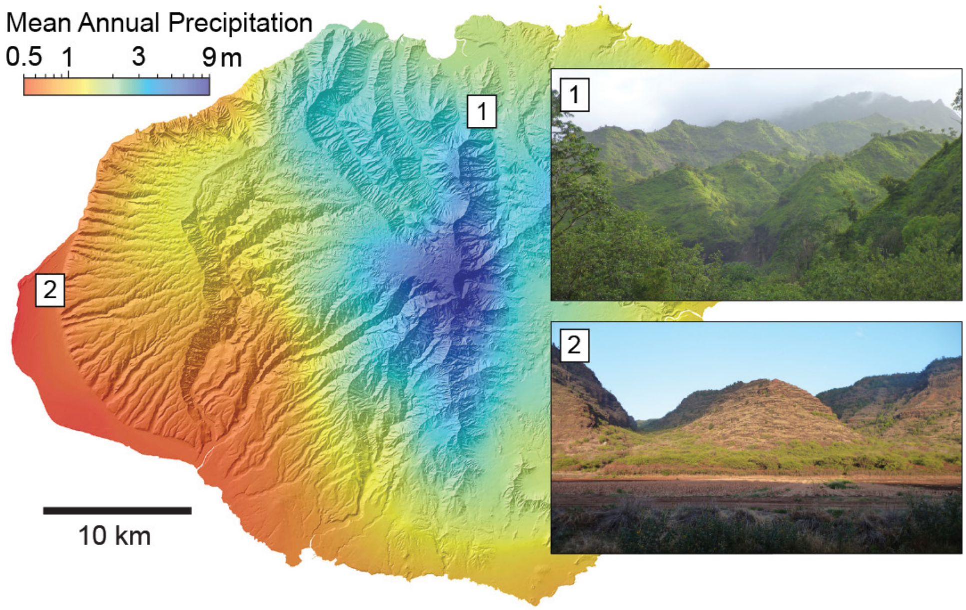


Figure 1. Precipitation map of the island of Kaua'i. Numbered insets show landscapes on the wet and dry sides of the island. Modified from Kenneth Ferrier, et al. (2013).
Figure 3. False-color mosaic of Cassini synthetic aperture radar images showing river networks draining into liquid hydrocarbon lakes in Titan's north polar region. Width of scene is roughly 600 km. Image: NASA/JPL–Caltech/US Geological Survey.

gradients on the Hawaiian island of Kaua'i (Figure 1) to discover how rainfall controls the rate at which rivers cut valleys into rock, a relationship that has been surprisingly difficult to detect. MIT-WHOI Joint Program student Michael Toomey, WHOI researcher Andrew Ashton, and Professor Perron revisited Charles Darwin's theory for the development of coral atolls and found that glacial sea level cycles have left an imprint on coral reefs around the world. Finally, Professor Perron collaborated on two reviews of the surface geology of Titan, where rivers of liquid methane erode into a surface made of ice (Figure 2).

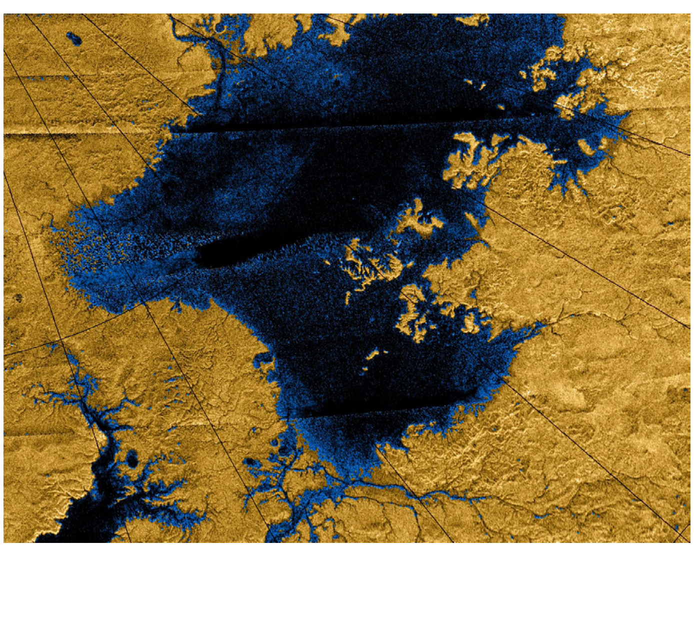


Figure 2. False-color mosaic of Cassini synthetic aperture radar images showing river networks draining into liquid hydrocarbon lakes in Titan's north polar region. Width of scene is roughly 600 km. Image: NASA/JPL–Caltech/US Geological Survey.

Ronald Prinn

Professor Prinn's Atmospheric Chemistry Group published 17 papers in 2012–2013—five led by students, four by research scientists, and eight using Advanced Global Atmospheric Gases Experiment (AGAGE) network greenhouse gas and ozone-depleting gas data. There is international scientific and political interest in the MIT Integrated Global System Model that links submodels of the human and natural systems (Prinn, "Development and Application of Earth System Models," *Proceedings of the National Academy of Sciences*, 2012), with invited talks by Professor Prinn at the Joint National Academy of Sciences/Royal Society 2012 Sackler Forum, in London, and the 2013 100th Raman Indian Science Conference, in Kolkata. The AGAGE network, now in its 35th year, is expanding into Africa with instruments now being installed in Rwanda by Kat Potter (PhD '11). During the year, group member and research scientist Eri Saikawa became an assistant professor at Emory University, and group members Diane Ivy, Laura Meredith, and Anita Ganesan received their PhD degrees.

Paola Rizzoli

Professor Rizzoli and her collaborators—research scientists Jun Wei, Pengfei Xue, Danya Xu, and Haoliang Chen—have continued their research on the South China Sea and Indonesian Through Flow, reconstructing the climate and circulation of the basin over four decades, 1960–2000, emphasizing local climate changes in the strait and shelf adjacent to Singapore that show considerable warming. Numerical simulations have successfully reproduced this warming, which has implications for the local ecosystem and the fisheries of the coastal waters.Their second major focus is in collaboration with professor Elfahih Eltahir's group in the coupling of Professor Rizzoli's ocean model with Professor Eltahir's atmospheric model for simulations of the present climate of the South East Maritime Continent. The two-way coupling has been successfully completed. Research has started using the MIT statistical approach for projections of future climate change of the Maritime Continent over the decadal time scale.

Daniel Rothman

Professor Rothman continues to develop a basic understanding of Earth's carbon cycle. In work published in the past year, Professor Rothman and his graduate student David Forney show, by a combination of empirical analysis and mathematical theory, that the decay of plant matter exhibits a lognormal distribution of degradation rates. This result derives in part from an understanding of the ways in which microorganisms interact with a fluctuating physical environment. Professor Rothman's current work in this area attempts to develop an understanding of the ways in which such interactions influence the long-term stability of the carbon cycle, including the Precambrian rise of atmospheric oxygen.

Noelle Selin

Professor Selin's research focuses on linking atmospheric chemistry modeling to decision making about air pollution, particularly from toxins that can harm health and the environment. Professor Selin uses models to track the transport, chemical transformations, and environmental fate of pollutants such as mercury, persistent organic pollutants (POPs), ozone, and atmospheric particulate matter. In the past year, her group has developed new models of POPs in the atmosphere, a first effort at inverse modeling for mercury, and applied new uncertainty techniques to atmospheric chemical models and projecting pollution health impacts. In addition, Professor Selin will participate in the Southeast Atmosphere Study, a major atmospheric chemistry campaign, in summer 2013. Her role will be to contribute forecast and near-real-time modeling for the distribution of mercury, to help plan and interpret measurements of mercury from an aircraft platform.

Professor Selin was selected to be an Esther and Harold E. Edgerton Career Development Professor for a three-year term, effective July 2013.

Susan Solomon

Over the past year, Professor Solomon and her group have focused on the variability of climate in the context of the past and future character and detection of human-induced changes, not only in atmospheric temperatures but also in precipitation and ecosystem shifts. In a paper published in *Nature Climate Change* (Irinia Mahlstein, et al., 2013), it is shown that climate change should be expected to result in an increasing pace of shifts of ecosystems as the world warms in the 21st century, implying that species will have less and less time to adapt.

Scientific and public attention worldwide has been directed at the question of the recent rate of global warming and the processes that are making it occur at a different rate than in previous decades. In particular, an important result of the group's work is that increases in stratospheric aerosol particles have made significant contributions to the recent slowing of the decadal rate of global warming compared to the previous two, an unexpected result. The group has shown that these stratospheric aerosols are due to volcanic eruptions previously thought to be of no relevance for climate. Thus, a surprising number of relatively small volcanoes can indeed influence the stratospheric aerosol layer and thereby the total global optical thickness and surface climate. Recent work has revealed how small volcanoes can overwhelm coal-burning sources and has also included a new analysis of how volcanic eruptions can be used to infer information about the sensitivity of the Earth's climate to volcanic eruptions.

Professor Solomon's group also focuses on how stratospheric ozone is changing, its chemistry, and how it affects changes in temperatures in the stratosphere as well as at the ground. Two important papers published in the past year have shown that the past changes in stratospheric ozone content based on a comprehensive analysis of observations display a greater range than previously thought. This is important because of questions regarding whether the vertical structure of warming agrees with climate model calculations, which is key to detection and attribution of human influences. The group's work shows that larger uncertainties need to be applied to the cooling due to stratospheric ozone loss, which in turn has important implications for the range of uncertainty in stratospheric and tropospheric climate responses.

Several of the group's current studies focus on how climate changes in the stratosphere are linked to the troposphere. A new paper, in preparation with graduate student Justin Bandoro as first author, probes how the Antarctic ozone hole appears to have more farreaching effects on the surface climate of many parts of the southern hemisphere than previously thought. His presentation of this work at the recent American Meteorological Society Middle Atmosphere meeting was recognized with an outstanding oral student paper award. Another new paper, with PhD candidate Diane Ivy, is focused on how the Arctic stratosphere is changing, and reveals how changes in the upper stratosphere can propagate to the lower stratosphere and upper troposphere, particularly in those winters when sudden stratospheric warmings do not occur.

Roger Summons

Research in the Summons Lab addresses fundamental questions about the antiquity of life on Earth and the habitability of worlds beyond. What are the earliest records of microbial life on Earth? How can geochemistry constrain the timing and environments of the origin and early evolution of life? How have biological and geological processes combined to shape the surface of the planet as we see it today? What are the environmental drivers that led to the development of complex multicellular life on Earth?

The Summons Lab employs state-of-the-art mass spectrometric methods to interrogate the best preserved sedimentary rock records of organic and inorganic carbon, nitrogen, and sulfur for isotopic and molecular evidence of biogeochemical cycling of these elements. Studies of contemporary natural settings and laboratory experiments provide a framework for the interpretation of the data gathered from ancient rocks. The laboratory also collaborates widely; most recently, its work with leading microbiologists has provided new knowledge about the biological origins and biosynthetic pathways leading isoprenoid lipids that are prominently preserved in sedimentary rocks. With geologist colleagues, it has uncovered molecular evidence for a pervasive association between ocean anoxia and biological mass extinction events. The Summons Lab is currently exploring the diversity and physiologies of microbes that are involved in the formation and modification of stromatolites and oolitic sands. It is also engaged with other members of the Mars Science Laboratory team in interpretation of results that are coming down from NASA's Curiosity rover.

Robert Van der Hilst

Professor Robert Van der Hilst and his group continue to follow three main lines of research in their quest to understand the geological and dynamical processes that have been forming Earth's interior from the crust to the core-mantle boundary, some 2,900 km below our feet. With collaborators in China, they have used data from a densely spaced array of almost 300 seismograph stations to study the structure of the lithosphere of western Sichuan Province, SW China, home to the devastating earthquake in May 2008 that killed almost 80,000 people. With new imaging methods, they have been able to create a high-resolution 3-D model of elastic properties from the surface to a depth of 100 km, which gives unprecedented insight into the tectonic framework of this geologically complicated and seismically active part of China, and which helps in understanding how the majestic Tibetan Plateau deforms and (slowly) expands eastward. Their latest results are under review in *Nature Geosciences*. A second line of research focuses on Earth's deeper interior, where variations in depth to mineralogical phase boundaries are diagnostic of lateral variations in temperature and composition around 400–700 km depth. Using new imaging tools adapted from hydrocarbon reservoir exploration, Professor Van der Hilst's group has been able to detect hitherto unknown structures in the mantle beneath Hawaii, which will help in understanding the deep dynamic processes that lead to massive volcanism at Earth's surface, forming the Hawaiian island chain. A third line of research focuses on the development of new theory and approaches to the inversion of large—and exponentially growing—data volumes. This work proceeds in close collaboration with professor Maarten de Hoop, an applied mathematician at Purdue University.

Jack Wisdom

Professor Jack Wisdom has been studying the early evolution of the Earth-Moon system after the giant impact that is presumed to have formed the Moon. Isotopic similarities of the Earth and Moon suggest that the Moon-forming impact was more severe than previously thought, but this would leave the system with too much angular momentum. It was proposed that a resonance between the Moon and the Earth's motion about the Sun could remove the excess angular momentum, but Professor Wisdom has recently shown that this mechanism does not work because extreme tidal heating affects the resonance dynamics and insufficient angular momentum is lost. The Moon remains a mystery.

Robert D. Van der Hilst
Department Head
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