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 41 faculty members (including two with a primary appointment in the Department of Civil and Environmental Engineering, one with a primary appointment in the Engineering Systems Division, and another with a primary appointment in the Department of Aeronautics and Astronautics), and more than 240 research staff, postdoctoral associates, 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 those that are among 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 the directorship of professor Bradford Hager) draws on 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 the directorship of professor Ronald Prinn) builds on the programs in meteorology, oceanography, hydrology, chemistry, satellite remote sensing, and policy. The Lorenz Center (under the directorship of professors Kerry Emanuel and Daniel Rothman) fosters creative approaches to learning how climate works. Furthermore, EAPS is an active participant in the MIT/Woods Hole Oceanographic Institution (WHOI) Joint Program and supports its mission of graduate education and research in ocean sciences and engineering.

Educational Activities

EAPS faculty members are committed to the development and maintenance of vibrant education programs at both the undergraduate and graduate level. Students meet with the department head and associate head at least once per term to discuss concerns and issues arising in their programs, with the goal of sustaining active and open conversation around educational issues. During the 2013–2014 academic year the EAPS graduate and undergraduate handbooks were both revised with direct student participation. Because fieldwork is such an important component of the EAPS pedagogical approach, the department also took time to define new best practice procedures for field activity and revised safety and information forms accordingly.

Graduate Program

EAPS has vigorous graduate educational programs in geology, geochemistry, geobiology, geophysics, atmospheres, oceans, climate, and planetary science. In fall 2013, there were 161 graduate students registered in the department, including 73 students in the MIT/WHOI Joint Program. Women constituted 44.7% of the graduate student population; 5% percent were members of an underrepresented minority group.

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 both formal and informal ways of improving the educational experience as well as the student life of the department. For example, the department's graduate students continue to take responsibility for an expanded orientation program for incoming graduate students. They plan a number of social events to introduce the newcomers to EAPS, MIT, and the Cambridge area. The graduate students are well organized and meet regularly, with one student presenting his or her research to the student body at the weekly Graduate Student Seminar. Undergraduate majors are encouraged to attend these talks. The Graduate Student Mentoring Program continues to be a well-received approach to provide peer support for new students.

Within EAPS, the Program in Atmospheres, Oceans, and Climate awards the Carl-Gustaf Rossby Prize in recognition of the best PhD thesis in the preceding year. Jessica Fitzsimmons (advised by professor Edward Boyle) and Chris Kempes (advised by professor Michael Follows) were the 2013 recipients. EAPS awards an annual prize for excellence in teaching to highlight the superior work of its teaching assistants. During the 2013–2014 academic year, Ann Bauer, Stephanie Brown, Claire Bucholz, Niraj Inamdar, Yavor Kostov, and Elena Steponaitis were recognized for their contributions.

The department's students were also recognized by their respective professional societies. Allison Wing received the Max A. Eaton Award for the best student paper at the American Meteorological Society's 31st Conference on Hurricanes and Tropical Meteorology; her talk was titled "Physical Mechanisms Controlling Self-Aggregation of Convection in Idealized Numerical Modeling Simulations." At the 2013 fall meeting of the American Geophysical Union (AGU), Britta Voss won an Outstanding Student Paper Award for her talk in the Earth and Planetary Surface Processes section, "Toward Quantitative Flux and Provenance Assessments of Riverine Suspended Sediments: A Geochemical Investigation of the Fraser River, Canada." Rebecca Jackson was awarded an Outstanding Student Talk Award for "The Competition Between Buoyancy Forcing from a Glacier and Remote Forcing from Shelf Winds in a Greenlandic Fjord," at the February 2014 Ocean Sciences Meeting.

A total of 25 doctoral students graduated from EAPS in academic year 2013–2014.

Undergraduate Program

In fall 2013, EAPS had 20 undergraduates majoring in the department, 90% of whom were women and 5% of whom were members of an underrepresented minority group. Ten students were awarded the SB degree in Earth, Atmospheric and Planetary Sciences in academic year 2013–2014.

The EAPS undergraduate population has always been small and the department id exploring ways to increase the number of students majoring in EAPS. These activities include events for incoming freshmen, involvement through freshman advising and teaching beyond EAPS, better use of social media, and increased visibility on campus. These efforts seem to be paying off, with 12 students joining the department in fall 2014.

Beyond its own undergraduate program, EAPS maintains a strong presence in undergraduate education across MIT so that the general MIT student body has ready access to education in geoscientific aspects of climate and environmental change, natural hazards, and natural energy resources. In addition to co-teaching classes cross-listed with other departments in the School of Science and the School of Engineering, EAPS supports and provides leadership for two major undergraduate programs at MIT, Terrascope (directed by professor Samuel A. Bowring) and the Experimental Studies Group (directed by professor Leigh Royden), and offers a relatively large number of freshman advising seminars. With the combined enrollment of Terrascope and the advising seminars, EAPS taught 7% percent of the students in the freshman class on a weekly basis. Similarly, EAPS is an active participant in three interdisciplinary minor programs: the broadly based energy studies minor, the astronomy minor with the Department of Physics, and the Atmospheric Chemistry Minor, with the departments of Civil and Environmental Engineering and Chemistry., Aero/Astro, and ESD

At the 2014 Student Awards and Recognition Dinner, the Goetze Prize was awarded to Jessica Haskins (advised by professor Susan Solomon) and Hosea Siu (advised by professor Richard Binzel) in recognition of their outstanding senior theses. Kathryn Materna received the W.O. Crosby Award for Sustained Excellence, recognizing her achievements, both academic and intellectual, as well as her general contributions to the department. Casey Hilgenbrink was the recipient 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 course work, and leadership within EAPS. Naomi Schurr and Jessica Fujimori were elected to membership in Phi Beta Kappa.

Eight students earned BS degrees from EAPS in academic year 2013–2014.

Community Events

Notable events during AY2014 included two Kendall Lectures. The first, in October 2013, "How Air Pollution Affects Climate and What We Can Do About It," was presented by Dr. Drew Shindell of NASA's Goddard Institute for Space Studies. The second, "Ice Sheets and Sea Level: Is the Long Tail Attached to a Dragon?" was presented by Dr. Richard Alley of Pennsylvania State University, College of Earth and Mineral Sciences, in May 2014. Both lectures were co-sponsored by the Center for Global Change Science.

The Lorenz Center's annual John Carlson Lecture, "Sea Ice, Climate and Observational Mathematics,"was delivered in the New England Aquarium in October 2013 by John Wettlaufer, Professor of Applicable Mathematics, Oxford University,and A.M. Bateman Professor of Applied Mathematics, Geophysics, and Physics, Yale University, John Wettlaufer.

In May 2014, more than 300 faculty and students, together with members of the public, packed the Stata Center Lecture Hall for the inaugural lecture of the newly established William F. Brace Lecture Series. "Exploring Mars with the Curiosity Rover: The Search for Ancient Habitable Environments" was presented by former EAPS faculty member John Grotzinger, now chief scientist for NASA's Mars Curiosity Rover. This lecture series has been established to honor the deep and lasting legacy of the first head of EAPS, Bill Brace. It is intended to become a flagship annual event reflecting the full disciplinary diversity of the department, as well as raising the profile of EAPS across the Institute.

To a similar end, the EAPS departmental lecture series was subjected to an organizational refreshing. This resulted in two highly successful semesters' worth of 25 well-attended, hour-long weekly presentations, featuring many internationally renowned speakers in the earth and planetary sciences.

New too in AY2014 was the weekly Graduate Lecture Series. Reprising talks prepared for the weekly faculty luncheons, EAPS faculty members and senior researchers shared their work, providing an opportunity for students in all four educational programs to become familiar with research activity across the department as a whole.

In February 2014, the Lorenz Center organized a highly successful workshop at MIT's Endicott House. The three-day event, attended by many in the EAPS Program in Atmospheres, Oceans, and Climate, brought together 37 leading climate researchers to discuss water in the climate system.

A symposium to honor the life and work of former professor Theodore "Ted" Madden, who died in November 2013, was held in March 2014. The Theodore Madden Memorial Symposium brought together the Madden family, current EAPS faculty, Professor Madden's former colleagues and students. The event was a daylong reflection on the broad scope of Madden's research, which extended from Earth's core to the outer magnetosphere.

In February, department head Robert van der Hilst addressed more than 200 members and friends of the Department of Earth, Atmospheric and Planetary Science with his third annual "State of EAPS" presentation. This year, special emphasis was given to the breadth and quality of EAPS research and to its relevance to such pressing issues as natural hazards, climate change, natural resources, and life on Earth. The benefits of the EAPS interdisciplinary approach were lauded, past successes, such as the transiting exoplanet survey satellite and the regolith X-ray imaging spectrometer (REXIS) were noted. Professor van der Hilst mentioned new collaborative programs, such as Oceans at MIT and the MIT Environment Initiative, where EAPS will play a significant role. He also acknowledged some of the pressing challenges that have to be tackled, such as shrinking federal funding and the critical importance of upgrading the department's aging space and facilities so as to remain competitive and be able to recruit and retain the best faculty and students.

On a lighter note, EAPS faculty, staff, and students celebrated professor Sara Seager's achievements and recent MacArthur Foundation award with a department-wide pre-Thanksgiving reception.

Throughout the year, EAPS hosted multiple events geared toward donor development. In early September 2013, EAPS faculty participated in four ocean-themed events in San Francisco during the America's Cup race: two private receptions for potential "principal gift" donors, a gathering for MIT alumni hosted by the MIT Club of Northern California, and a symposium on The Future of the Ocean. Later in the fall, the Earth Resources Laboratory sponsored a reception for EAPS alumni, corporate sponsors, research scientists, and graduate students who were attending the Society of Exploration Geophysics annual conference in Houston. In December, EAPS invited alumni and friends to a reception at the AGU meeting in San Francisco. Together, these events attracted more than 500 attendees.

In outreach activities, EAPS again participated in the public Cambridge Science Festival. This year Tanja Bosak joined in the popular Big Ideas for Busy People series, discoursing on the question "How Did Our Atmosphere Become Breathable?" Members of the MIT NASA Astrobiology Team served as docents along the to-scale geologic timeline installation along Memorial Drive between Massachusetts Avenue and Ames Street. Associates of Oceans at MIT, including several from EAPS, helped members of the public reach a better understanding of aquatic environments and technology, so that they would be able to further explore the world's oceans in the *Dive into Oceanography* exhibit at the MIT Museum.

Finally, this year's Alumni Association–sponsored Tech Day Symposium, The Future of Planet Earth, explored what we know about the emergence of life, the Earth, its systems, and its stresses—those that are inherent as well as those imposed by human activity. In a program dedicated to thinking about the future of the planet, Kerry Emanuel, Taylor Perron, Tanja Bosak, Christopher Knittel (Sloan School of Management), John Lienhard (Department of Mechanical Engineering), and Sara Seager shared their insights into how what we have learned about the past can help us to predict where we are going and lay the groundwork for a sustainable future.

Communications and Development

The department's communications strategy supports its development objectives. It is critical to offer timely updates on EAPS research, accomplishments, and fundraising opportunities to engage not only EAPS alumni and prospective donors but also our internal audience, such as development colleagues in the MIT Alumni Association, the School of Science, and Resource Development. There is significant progress in both inter- and extra-departmental communication supporting department objectives to increase private funding as well as to educate the wider MIT community and the broader public about the education and research under way within EAPS.

Following the widely appreciated biannual electronic alumni newsletter reinstituted in fall 2011, an enthusiastically received print newsletter was reintroduced in fall 2013. This compendium of faculty, event, and research news is now scheduled to become an annual publication.

Experiments in social media (Facebook, Twitter, YouTube, and Flickr) have also proved highly successful as a tool for raising the department's profile among constituencies across campus and beyond. EAPS can now boast a large (approximately 3,000 members) and growing community of followers on Facebook, where multiple daily postings are now the norm.

The thoughtful recruitment of staff with an emphasis on strong communications skills, especially in marketing and graphics, is benefiting both EAPS print and electronic media. Electronic informational postings in the lobby of Building 54 have proven to be a particular hit as a tool for putting EAPS news in plain view.

EAPS is committed to working with Resource Development, the MIT Alumni Association, and the School of Science to raise private philanthropic support. Since EAPS hired a part-time senior development officer in 2009 there has been a strategic resource development plan for EAPS, with an emphasis on individual fundraising. Private support for EAPS has increased by 175% over the past five years. In fiscal year2014, EAPS raised a total of $2.8 million in gifts and new pledges from private donors. The department is gradually building a stronger pipeline of key supporters, and 10 major gifts were secured from individuals in fiscal year 2014, ranging from $50,000 to $500,000. In spring 2014, Dawn Adelson, senior development officer, left EAPS to rejoin the Office of Leadership Giving at MIT. Angela Ellis will become the new full-time senior development officer for EAPS starting on July 1, 2014.

Fundraising Priorities and Successes

The senior development officer has focused on raising fellowship support for graduate students and post-doctoral associates. Continuing to attract the very best young scientists will ensure that EAPS maintains its leadership role in research and education. Only about 30% of incoming students are supported with funds from the EAPS endowment. The goal is to become self-sufficient, so that EAPS remains an attractive option for incoming graduate students, and faculty can be confident that funding will be provided for their students during their first year or two at MIT. A gift of $1 million is required to fully endow a fellowship; a gift of $80,000 will provide expendable support for one year. During the past year our goal was to surpass the one million dollar fundraising goals for both the M. Nafi Toksöz Fellowship Fund and the Theodore Madden Fellowship Fund. Thanks to our ongoing campaigns and communications efforts, as well as the outreach to alumni and donor constituencies afforded by the Theodore Madden Memorial Symposium, this was achieved. A new endowed fund for graduate student support was also launched in the past year in honor of Sven Treitel ’53, SM ’55, PhD ’58, thanks to a generous pledge from Arthur C.H. Cheng SCD ’78. Fundraising efforts will continue during fiscal year 2015. Our goal is to again surpass the $1 million threshold for an endowed fellowship to support at least one graduate student in perpetuity. During FY2014, Neil Rasmussen ’76, SM ’80, a former member of the EAPS Visiting Committee, also pledged an additional $400,000 over two years for expendable fellowships for first- and second-year graduate students with an interest in climate science.

In the past year, fundraising efforts were targeted to two main constituencies: central resource-development field staff and EAPS alumni and friends. Central resource-development field staff members are a key audience because they often have primary relationship management responsibility with MIT’s most influential alumni and prospective donors. One of the department’s most important goals is to continue building a network of key supporters through broad-based MIT alumni events and strategic cultivation events for major gift donors and new prospects. Fostering relationships between alumni and friends and the department head and faculty members is important to the continuing success of this effort. As EAPS faculty members begin to become more engaged with MIT campaign priorities, such as the Environment Initiative, we expect that EAPS will benefit from even more opportunities to inspire philanthropic support for the department.

Faculty

The department continues its efforts to hire the best young scientists and help them develop successful careers. Two new assistant professors joined the department in July 2013 — Dr. Hilke Schlichting, a planetary scientist, and Dr. German Prieto, a geophysicist — and in July 2014, Dr. Gregory Fournier joined the geobiology group as assistant professor. We are excited to have the opportunity to bring such talent into EAPS. Dr. Michael Follows was appointed to the rank of associate professor and EAPS extended an offer to Kristin Bergmann, a young geologist who has finished her PhD at Caltech and currently has a junior fellowship with the Harvard Society of Fellows. She will join the EAPS faculty in July 2015.

We are now halfway through the third year of the junior faculty mentorship program that was introduced in January 2012. Each junior faculty is assigned a mentor team comprising a primary mentor (often a close colleague) and two senior faculty members from outside the candidate's disciplinary group. They meet, as a group, once a semester and report to the head of department. Junior and senior faculty alike are satisfied with the new system, but feedback solicited from junior faculty will be used to make further improvements.

Effective July 2014, professors Tanja Bosak, Paul O'Gorman, and Taylor Perron were awarded tenure, Ben Weiss was promoted to the rank of full professor, and Oliver Jagoutz was promoted to the rank of associate professor.

Assistant professor of geophysics Alison Malcolm left EAPS to assume the Chevron Chair in reservoir characterization at Memorial University of Newfoundland.

Honors and Awards

Professor of ocean geochemistry and director of the MIT/WHOI Joint Program Edward Boyle was awarded the 2014 Urey Medal of the European Association of Geochemistry.

Schlumberger professor of geology B. Clark Burchfiel was awarded the 2013 Distinguished Career Award of the Geological Society of America.

Cecil and Ida Green professor of geology and associate department head Timothy Grove was awarded the 2014 Goldschmidt Award of the Geochemical Society. He was also elected to the National Academy of Sciences.

Cecil and Ida Green professor of earth sciences and director of the Earth Resources Laboratory Brad Hager was awarded the AGU's 2013 Lehman Medal.

Professor of geophysics Thomas Herring was among five from MIT named as new fellows of the American Association for the Advancement of Science.

Cecil and Ida Green professor of oceanography John Marshall was awarded the 2014 Sverdrup Medal of the American Meteorological Society.

Sara Seager, Class of 1941 Professor and chair in the EAPS Program in Planetary Science, was awarded a 2013 MacArthur Fellowship.

Professor emeritus John Southard was awarded the 2014 Twenhofel Medal from the Society for Sedimentary Geology, the society's highest honor.

Schlumberger professor of earth and planetary sciences and department head Robert van der Hilst was elected to the American Academy of Arts and Sciences.

Assistant professor of engineering systems and atmospheric chemistry Noelle Selin was appointed to the Global Young Academy.

Research Highlights

Richard Binzel

Planetary scientist Richard Binzel is one of the world's leading scientists in the study of asteroids and Pluto. As the inventor of the Torino Scale, a method for categorizing the impact hazard associated with near-Earth objects, such as asteroids and comets, his ongoing telescopic research includes the spectral characterization of asteroids that pose a potential hazard to Earth as well as those that may be most easily reached by future robotic and human missions. Currently he serves on NASA's Task Force for Planetary Defense, which has responsibility for assessing possible future asteroid hazards, and as co-investigator on the Origins Spectral Interpretation Resource Identification Security Regolith Explorer (OSIRIS-REx) mission.

This year Professor Binzel has been heavily occupied as principal investigator leading a student team spanning EAPS and Aerospace Engineering in building REXIS, which is scheduled to launch aboard NASA's OSIRIS-REx spacecraft in 2016 to perform an asteroid sample return. In recognition of this School of Science–School of Engineering role, he has accepted the offer of a joint appointment with the Department of Aeronautic and Astronautics.

Looking ahead and deeper into the solar system, Binzel is a co-investigator finalizing planning for the 2015 encounter of NASA's New Horizons mission with Pluto, arriving after its nine-year flight from launch in 2006.

Tanja Bosak

Geobiologist Tanja Bosak studies biosignatures of microbial processes in modern and ancient sediments to understand the parallel evolution of life and the environment. Her work integrates microbiology, sedimentology, and stable-isotope geochemistry into experimental geobiology to ask how microbes shape sedimentary rocks, how organisms fossilize, and how microbial metabolisms leave biogeochemical patterns in sediments. Her lab uses this approach to explore modern biogeochemical and sedimentological processes and interpret the record of life on the early Earth. She recently became a Simons Foundation investigator.

Dr. Giulio Mariotti, a postdoctoral associate in the Bosak group, received the Luna B. Leopold Young Scientist award given by the AGU to one young geomorphologist yearly for a significant and outstanding contribution that advances the field of earth and planetary surface processes. Mariotti is interested in the fundamental geomorphic mechanisms governing the morphological evolution of coastal environments and in predicting their long-term trajectories under different scenarios.

Dr. Shikma Zaarur, another postdoctoral associate in the Bosak group, received the William Ebenezer Ford Prize from the Department of Geosciences at Yale University for the best thesis in geochemistry.

In outreach, Dr. Zaarur gave a talk in the Big Ideas for Busy People series during the 2014 Cambridge Science Festival and another to alumni during the Tech Day symposium, The Future of Planet Earth. This year, her lab also hosted a three-hour-long hands-on visit by 40 students from the Weston Middle School. Professor Bosak also supervised a research project by a student from Cambridge Rindge and Latin high school.

Publications

Mariotti, G., Pruss, S.B., Perron, J.T. and Bosak, T., "Microbial Shaping of Sedimentary Wrinkle Structures, *Nature Geoscience*, in press.

Mariotti, G., Perron, T. and Bosak, T. (2014), "Elongation of Stromatolites through Feedbacks between Flow, Sediment Motion and Microbial Growth on Sand Bars," *Earth and Planetary Science Letters*, 397, 93–100.

Liang, B., Wu, T.D., Guerquin-Kern, J.L., Vali, H., Sun, H.-J., Sim, M.S., Wang, C.-H., Bosak, T. (2014), "Cyanophycin Mediates the Accumulation and Storage of Carbon in Non-heterocystous Filamentous Cyanobacteria from Coniform Mats," *PLoS One.*

Meredith, L.K., Rao, D., Bosak, T., Hansell, C.M., Ono, S., Prinn, R.G. (2014), "Consumption of Atmospheric H2 during the Life Cycle of Soil-dwelling *Actinobacteria. Environmental Microbiology Reports*, 6, 226–238.

Samuel Bowring

Professor Bowring's research group focuses on high-precision geochronology applied to the stratigraphic record, timescales of pluton construction, links between large igneous provinces and extinctions, the earliest history of Earth's continental crust, and the thermal history of continental lithosphere deduced from lower crustal xenoliths. The group has shown that it is possible to integrate the stratigraphic and paleontological record with high-precision uranium-lead geochronology to investigate Earth's history at the millennial scale.

During the past year, Bowring's group has published two papers that were concerned with mass extinction and its relationship to large igneous provinces. Blackburn et al. (2013) demonstrated that the end-Triassic extinction occurred in less than five thousand years and can be directly linked to the Central Atlantic Magmatic Province. They tested and corroborated the astrochronologic timescale allowing examination of the extinction at the millennial scale, 201 million years ago.

Burgess, Bowring, and Shen (2014) presented a new timescale for the largest mass extinction known, the end-Permian, and showed that it occurred in approximately 60 thousand years 252 million years ago; the work was published in *Proceedings of the National Academy of Sciences* and received considerable media attention.

At the fall 2013 AGU meeting, Burgess, Bowring, and Shen presented new data on the age and duration of the largest eruption know in Earth history, the one that formed the Siberian Traps, and made a case for a direct link between the eruption and extinctions.

Graduate students Erin Shea and Seth Burgess both graduated and have moved on to a faculty position at the University of Alaska and a US Geological Survey Mendenhall postdoctoral fellowship, respectively.

Publications

Blackburn, T.J., P.E. Olsen, S.A. Bowring, N.M. McLean, D.V. Kent, J. Puffer, G. McHone, E.T. Rasbury, M. Et-Touhami (2013), "Zircon U-Pb Geochronology Links the End-Triassic Extinction with the Central Atlantic Magmatic Province," *Science*, 340 (6135): 941–945.

Burgess, S.D., S. Bowring, and S.-Z. Shen (2014), "High-precision Timeline for Earth's Most Severe Extinction, *Proceedings of the National Academy of Sciences,* 111(9): 3316–3321.

Edward Boyle

Professor Boyle is interested in marine chemistry especially the distribution of trace elements in the ocean and their use as paleochemical tracers. His group is particularly concerned with the response of the ocean to anthropogenic lead emissions, and the relation between dust, iron in the ocean, and marine biological activity.

This year, Boyle's research group worked to create the most detailed ever lead and lead isotope data from the International GEOTRACES transect GA-03, the North Atlantic Zonal Transect (Woods Hole-Bermuda-Cape Verde Islands-Lisbon) voyage on which Professor Boyle was the chief scientist. The data show that anthropogenic lead has declined by a factor of 10 in ocean surface waters since the 1970s and is now concentrated in a mid-depth layer composed of water that sank from the surface in the 1970s during the peak years of leaded-gasoline consumption. Conversely, coral and water data from the Indian Ocean shows that lead has increased during the past decades, as industrialization has boomed and the phasing out of leaded gasoline lagged behind the countries surrounding the North Atlantic. Lead in the Indian Ocean is now more concentrated than in surface waters near Hawaii and Bermuda.

Boyle was awarded the Urey Medal of the European Association of Geochemistry, a "lifetime achievement" award and the highest honor of that organization.

Publications

Lee, J.M., E.A. Boyle, I.S. Nurhati, M. Pfeiffer, A. Meltzner, and B. Suwargadi (2014), "Coral-based History of Lead and Lead Isotopes of the Surface Indian Ocean Since the Mid-20th century," *Earth and Planetary Science Letters,* 398: 37–47.

Noble, A.E., Y. Echegoyen-Sanz, E.A. Boyle, D.C. Ohnemus, PJ. Lam, R. Kayser, M. Reuer, J. Wu (in press), "Dynamic Variability of Dissolved Lead and Lead Isotope Composition from the US North Atlantic," *GEOTRACES*, Transect, Deep-Sea Research II.

Daniel Cziczo

Professor Cziczo and his research group focus on the ways in which atmospheric aerosol particles can affect the Earth's climate system. Aerosols can directly impact climate by absorbing or scattering solar and terrestrial radiation. Particles can also indirectly affect climate by acting as the seeds on which cloud droplets and ice crystals form. To elucidate how particles' properties, especially their chemical composition, affect the climate system as a whole, Cziczo's group conduct experiments using small cloud chambers in the laboratory to mimic atmospheric conditions that lead to cloud formation, as well as field studies, such as observing clouds *in situ* from remote mountaintop sites or aboard research aircraft.

Cziczo and his team were involved in several outreach activities this year. Professor Cziczo gave a "Science for the Public" guest interview in October 2013. He was a guest speaker at the MIT Alumni Association's meeting in Denver in June 2013, at the MIT Cardinal and Grey Society in October 2013, and at the MIT Club of Northern California in June 2014. His group continues to participate as consultants on the PBS NOVA Labs program "Cloud Lab."

Publications

Cziczo, D.J., C. Hoose, E.J. Jensen, M. Diao, M.A. Zondlo, J.B. Smith, C.H. Twohy, D.M. Murphy (2013), "Clarifying the Dominant Sources and Mechanisms of Cirrus Cloud Formation," *Science* 340: 1320–1323.

Czico, D.J., S. Garimella, M. Raddatz, K. Hoehler, M. Schnaiter, H. Saathoff, O. Moehler, J.P.D. Abbatt, L.A. Ladino (2013), "Ice Nucleation by Surrogates of Martian Mineral Dust: What Can We Learn about Mars without Leaving Earth?" *Journal of Geophysical Research: Planets*, 118: 1–10.

Cziczo, D.J. and K.D. Froyd (2014), "Sampling the Composition of Cirrus Ice Residuals," *Atmospheric Research*, 142: 1–17.

Kerry Emanuel

Professor Kerry Emanuel is a prominent meteorologist and climate scientist who specializes in moist convection in the atmosphere and on tropical cyclones. His research interests focus on tropical meteorology and climate, with a specialty in hurricane physics. His interests also include cumulus convection; the role of clouds, water vapor, and upper-ocean mixing in climate regulation, and advanced methods of sampling the atmosphere in aid of numerical weather prediction.

During AY2014, Professor Emanuel and his research group continued several lines of research. They published a set of papers uncovering the physics of the self-aggregation of moist convection in the atmosphere, a process that leads to tropical cyclones and possibly the Madden-Julian Oscillation. Self-aggregation is a phenomenon observed in cloud-resolving models that 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, they uncovered the essential physical mechanisms underlying self-aggregation and are working on understanding its role in regulating climate. Graduate student Vince Agard and Emanuel are studying how severe local storms—which produce damaging wind, hail, and tornadoes—respond to climate change. Emanuel worked with co-principal investigator Peter Molnar and graduate student Tim Cronin on the nonlinear rectification of the diurnal cycle of moist convection over land and its possible implications for the climate of the Pliocene Epoch; they also showed that the time scale of relaxation to radiative-convective equilibrium is much longer when the surface is coupled to the atmosphere. With graduate student Morgan O'Neill, Emanuel explored a hypothesis for the dynamics of Saturn's polar vortices, and with Diamilet Perez-Betancourt explored the dynamics of spiral rainbands in hurricanes.

In addition to multiple media appearances, Professor Emanuel was the anchor for EAPS's first MOOC, 12.340x *Global Warming Science*. Emanuel serves as the founding co-director of the Lorenz Center, the department's climate think-tank.

Publications

Aerts, C.J.H.J., W.J.W. Botzen, K. Emanuel, N. Lin, H. de Moel, and E.O. Michel-Kerjan (2014), "Evaluating Flood Resilience Strategies for Coastal Megacities," *Science*, 344, 473-475.

Emanuel, K.A. (2013), "Downscaling CMIP5 Climate Models Shows Increased Tropical Cyclone Activity over the 21st Century," *Proceedings of the National Academy of Sciences*, 110.

Kossin, J.P., K.A. Emanuel, and G.A. Vecchi (2014), "The Poleward Migration of the Location of Tropical Cyclone Maximum Intensity," *Nature*, 509, 349–352.

Wing, A.A. and K.A. Emanuel (2014), "Physical Mechanisms Controlling Self-aggregation of Convection in Idealized Numerical Modeling," *Journal of Advances in Modeling Earth Systems*, 6.

Raffaele Ferrari

Raffaele Ferrari is a physical oceanographer interested in the dynamics of the ocean and climate with active research efforts in the areas of atmospheric and oceanic turbulence, air-sea interactions, the energetics of ocean circulation, the impact of ocean physics on biology, and questions of paleoclimate. In his research Ferrari uses a combination of theoretical fluid dynamics, numerical modeling, and analysis of observations.

In work focused on the role of the ocean in present and past climates, particularly exciting results obtained in the last 12 months include a paper that appeared in the *Proceedings of the National Academy of Sciences* showing that the sudden drop in atmospheric concentrations of carbon dioxide observed during glacial periods is due to the expansion of sea ice around Antarctica which modified the ocean circulation and trapped carbon in the ocean abyss. Working with a new generation of ocean floats equipped with bio-optical sensors, it was found that phytoplankton in the Nordic Seas bloom when daylight exceeds nine hours. Such a photoperiodic control of blooms is well documented in terrestrial plants, but has never before been observed in the open ocean, and is not included in models used to quantify ocean carbon uptake during algal blooms. In addition, Ferrari and Alexandre Mignot continued their study of the role of ocean turbulence on the exchange of heat and carbon dioxide at the air-sea interface using a combination of observations collected in the Southern Ocean and state of the art numerical simulations, as well as the generation of fronts in the upper ocean and the role of fronts in triggering algal blooms. They explored how the circulation in the Southern Ocean will change under global warming. They also studied the physics of turbulence experienced by commercial airplanes flying at the tropopause.

Publications

Ferrari *et al.* (2014), "Antarctic Sea Ice Control on Ocean Circulation in Present and Glacial Climates," *Proceedings of the National Academy of Sciences*, 111.

Tulloch, R., R. Ferrari, O. Jahn, A. Klocker, J. LaCasce, J. Ledwell, J. Marshall, M.-J. Messias, K. Sperr, A. Watson, "Direct Estimate of Lateral Eddy Diffusivity Upstream of Drake Passage," *Journal of Physical Oceanography* (submitted).

LaCasce, J.H., R. Ferrari, R. Tulloch, D. Balwada, and K. Speer (2014), "Float-driven Isopycnal Diffusivities in the DIMES," *Journal of Physical Oceanography*, 44.

Callies, J. and R. Ferrari (2013), "Interpreting Energy and Tracer Spectra of Upper-Ocean Turbulence in the Submesoscale Range (1–200 km)," *Journal of Physical Oceanography*, 43.

Callies, J. and R. Ferrari, "Interpreting Energy and Tracer Spectra of Submesoscale Turbulence," *Journal of Physical Oceanography* (submitted).

Timothy Grove

Professor Grove is a geochemist whose research focus is on the processes that have led to the chemical differentiation of the crust and mantle of the Earth and on the processes of formation and evolution of the interiors of other planets, including the moon, Mars, and meteorite parent bodies. Combining geology, geophysics, and geochemistry to interpret the thermal histories of geologic materials, his group studies magma generation processes, crystal growth and nucleation, phase transitions in minerals, diffusion in crystalline solids and silicate melts, and the time dependence of diffusion-controlled processes.

Over the past year Professor Grove and his students have completed a series of experiments on a back-arc basaltic lava that provide the first quantitative understanding of the influence of small amounts of water (~ 1.5 wt. % H_2O) on crystallization processes. Their earlier work established the profound effect of water on the stability and composition of minerals during fractional crystallization. Sisson and Grove (1993) demonstrated that the influence of water changes the proportions and compositions of crystallizing minerals, promoting the early appearance of olivine, pyroxene and Fe-bearing oxides and destabilizing plagioclase. "Wet" magmas therefore evolve by fractional crystallization to high SiO_2 and low FeO, while dry magmas become FeO-enriched at relatively constant SiO_2. As such, the pre-eruptive water content is the single most important control on the compositional evolution of a crystallizing magma. Their new experiments that explore the effects of modest H_2O content produce a distinctive fractionation trend and provide a quantitative and reliable tool for determining pre-eruptive H_2O content using major element data from arc magmatic systems.

References:

Grove T.L. and M.B. Baker (1984), "Phase Equilibrium Controls on the Calc-Alkaline vs. Tholeiitic Differentiation Trends," *Journal of Geophysical Research*, 89:3253–3274.

Sisson, T.W. and T.L. Grove (1993), "Experimental Investigations of the Role of H_2O in Calc-Alkaline Differentiation and Subduction Zone Magmatism," *Contributions to Mineralogy and Petrology*, 113:143–166.

Publications

Charlier, B., Namur, O., Grove, T.L. (2013), "Compositional and Kinetic Controls on Liquid Immiscibility in Ferrobasalt-Rhyolite Volcanic and Plutonic Series," *Geochimica et Cosmochimica Acta*, 113.

Grove, T.L., Holbig, E.S., Barr, J.A., Till, C.B., Krawczynski, M.J. (2013), "Mantle Melting in the Garnet Stability Field: Experiments and Predictive Models," *Contributions to Mineralogy and Petrology*, 166.

Laubier, M., Grove, T.L., Langmuir, C.H. (2014), "Trace Element Mineral/Melt Partitioning for Basaltic and Basaltic Andesite Melts: An Experimental and LA-ICPMS Study with Application to the Oxidation State of Mantle Source Regions," *Earth and Planetary Science Letters*, 392.

Grove, T.L. and C.B. Till (2014), "Melting the Earth's Upper Mantle: Chapter 1," in *Encyclopedia of Volcanoes*, 2nd edition, Sigurdsson, H. R., ed., Elsevier (in press).

Suavet, C., B.P. Weiss, J. Gattacceca, T.L. Grove (2014), "Controlled-atmosphere Thermal Demagnetization and Paleointensity Analyses of Extraterrestrial Rocks," *Geochemistry, Geophysics, Geosystems* (in press).

Mandler, B.E., J.M. Donnelly-Nolan, T.L. Grove (2014), "Straddling the Tholeiitic/Calc-alkaline Transition: The Effects of Small Amounts of Water on Magmatic Differentiation at Newberry Volcano, Oregon," *Contributions to Mineralogy and Petrology* (submitted).

Donnelly-Nolan, J.M., D.E. Champion, T.L. Grove (2014), "Late Holocene Volcanism at Medicine Lake Volcano, Northern California Cascades," *US Geological Survey Scientific Investigation Reports* (submitted).

Behn, M.D., Grove, T.L. (2014), "Melting Systematics in Mid-ocean Ridge Basalts: Application of a Plagioclase-Spinel Melting Model to Global Variations in Major Element Chemistry and Crustal Thickness," *Geochemistry, Geophysics, Geosystems* (in preparation for submission).

Honors and Activities

Professor Grove was selected for the 2014 V.M. Goldschmidt Award of the Geochemical Society. In April 2014 he became a member of the National Academy of Sciences.

Institute Service

Professor Grove continued as associate department head and implemented changes to the EAPS graduate and undergraduate programs. This year's efforts included identifying ways to improve course offerings, the structure of our undergraduate and graduate programs, and our graduate admissions procedures. Professor Grove along with the department also began to explore a joint major (in the area of environment) between EAPS and the Department of Civil and Environmental.

Other Service

A former American Geophysical Union (AGU) president, Grove became chair of the AGU Ethics Committee. He continues as executive editor of *Contributions to Mineralogy and Petrology*.

Thomas Herring

Professor Thomas Herring's research is in the applications of high precision geodetic measurement systems, primarily the Global Position System (GPS), Very Long Baseline Interferometry (VLBI), and Satellite Laser Altimetry.
Herring and his group use primarily GPS data to develop geophysically based models of Earth deformations on global, regional, and local scales, and changes in the rotation of the Earth. Group members also use interferometric synthetic aperture radar to study small surface deformations as well as geodetic methods to study Earth's gravity field. Herring's group uses high-precision GPS measurements in many different areas of study, including much of the southern Eurasian plate boundary and the western United States. They are investigating processes on time scales of years leading up to earthquakes, transient deformation signals lasting days to many weeks, post-seismic deformation after earthquakes on time scales of a singe day to decades, and surface wave propagation during earthquakes using high-rate GPS data. All of these measurements have sub-millimeter to few-millimeter precision. The group is also monitoring and modeling human-induced deformations in hydrocarbon fields as well as on tall buildings such as the Green building at MIT.

Publications

Ji, K.H. and T.A. Herring (2013), "Testing Kalman Smoothing/PCA Transient Signal Detection Using Synthetic Data," *Seismological Research Letters*, May/June 2013.

Ji, K.H., T.A. Herring, and A.L. Llenos (2013), "Near Real-time Monitoring of Volcanic Surface Deformation from GPS Measurements at Long Valley Caldera, California," *Geophysical Research Letters*, 40, 1054–1058.

Collilieux, X., Z. Altamimi, D.F. Argus, C. Boucher, A. Dermanis, B.J. Haines, T.A. Herring, C.W. Kreemer, F.G. Lemoine, C. Ma, D.S. MacMillan, J. Mäkinen, L. Métivier, J. Ries, F.N. Teferle, X. Wu (2014), "External Evaluation of the Terrestrial Reference Frame: Report of the Task Force of the IAG Sub-commission 1.2," in C. Rizos and P. Willis (eds.) *Earth on the Edge: Science for a Sustainable Planet*, International Association of Geodesy Symposia.

John Marshall

Professor John Marshall is an oceanographer with broad interests in climate and the general circulation of the atmosphere and oceans, which he studies through the development of mathematical and numerical models of physical and biogeochemical processes. His research has focused on problems of ocean circulation involving interactions between motions on different scales, using theory, laboratory experiments, and observations, as well as innovative approaches to global ocean modeling pioneered by his group at MIT.

During AY2014, Professor Marshall and his group have been working on the role of the ocean in anthropogenic climate change, in particular studying patterns, particularly inter-hemispheric asymmetries in the amplitude and timing of the sea surface temperature response to greenhouse gas forcing, and southern hemisphere stratosphere-troposphere-ocean interaction in response to forcing by the Antarctic ozone hole. In 2014 Marshall was the recipient of the Sverdrup Gold Medal of the American Meteorological Society for his "fundamental insights into water mass transformation and deep convection and their implications for global climate and its variability."

The ocean has an enormous, yet temporary, capacity to absorb thermal energy and delay global warming.

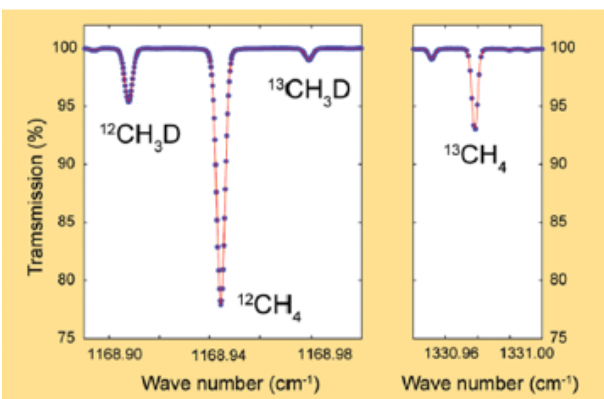
Publications

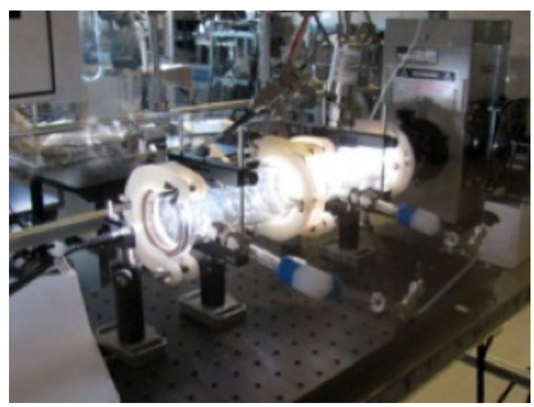
Kostov, Y., *et al.* (2014), "Impact of the Atlantic Meridional Overturning Circulation on Ocean Heat Storage and Transient Climate Change," *Geophysical Research Letters*, 41.

Marshall, J., *et al.* (2014), "The Ocean's Role in Setting the Mean Position of the Inter-Tropical Convergence Zone," *Climate Dynamics*, 42.

David McGee

Professor David McGee's group focuses on understanding the response of precipitation patterns to past climate changes and on investigating the role of windblown dust in the climate system. A recent paper by McGee and co-authors in professor John Marshall's group offers important new energetic constraints on the response of tropical precipitation patterns to past climate changes, providing an interpretive framework for precipitation reconstructions. The opening of a state-of-the-art clean laboratory and the acquisition of an inductively coupled plasma mass spectrometer has provided essential resources for the group's use of high-precision uranium-thorium geochronology to anchor paleoclimate records. Using these tools, the group has produced new records of past precipitation changes in the US Great Basin and the Atacama desert of northern Chile that point to dramatic changes in dryland hydrology in response to past changes in the interhemispheric temperature gradient. Additional research investigates past and present fluctuations in windblown dust emissions from North African and East Asian deserts, offering insights into changes in continental aridity, atmospheric circulation, and dust-related climate impacts.





Left: Mid-IR spectrum of four methane isotopologues measured by tunable laser infrared direct absorption spectroscopy (Ono et al., 2014). Right: Photochemical flow-reactor to study mass-independent isotope effects (Whitehill et al., 2013).

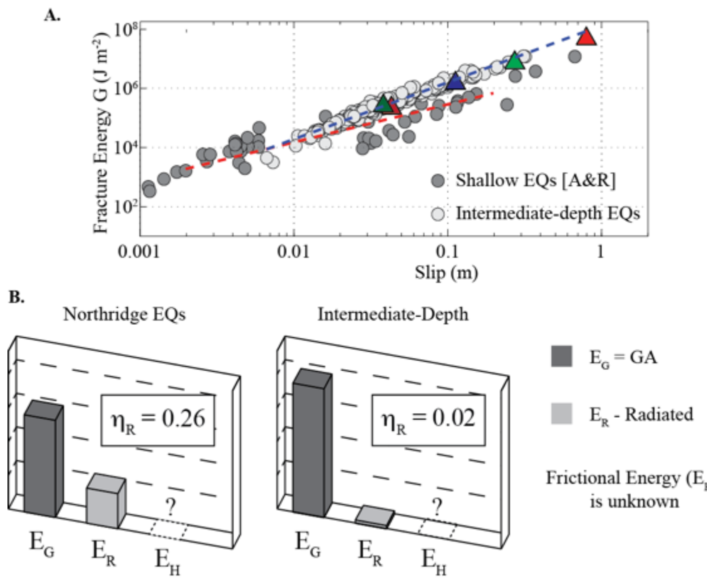
Publications

Donohoe *et al.* (2014), "The Interannual Variability of Tropical Precipitation and Interhemispheric Energy Transport," *Journal of Climate*, 27.

Marshall *et al.* (2014), "The Ocean's Role in Setting the Mean Position of the Inter-Tropical Convergence Zone," *Climate Dynamics*, 42.

Shuhei Ono

Professor Shuhei Ono's stable isotope geobiology group studies physical chemistry of stable isotope fractionation in biological, geochemical, and photochemical processes. His group continues to study multiple-sulfur isotope effects by microbial sulfate reduction as well as by photochemical reactions in order to reconstruct the early atmospheric chemistry and the evolution of biogeochemical cycles. A new research area for Ono's group is to constrain the sources and sinks of methane, an important energy source and significant greenhouse gas. His group developed state-of-the-art laser spectroscopy to measure its rare isotopologue, $^{13}CH_3D$, which will provide new and critical source constraints for sources of methane in an atmosphere and geologic environments.



Diversity of earthquake behavior. Comparison of Fracture energy and energy partitioning of earthquake rupture for shallow and intermediate-depth earthquakes. Intermediate-depth earthquakes are less efficient, such that the radiated energy ER is a smaller percentage of the total earthquake budget compared to shallow earthquakes.

Publications

Ono, S., D.T. Wang, D.S. Gruen, B. Sherwood Lollar, M.S. Zahniser, B.J. McManus, D.D. Nelson (2014), "Measurement of a Doubly Substituted Methane Isotopologue, $^{13}CH_3D$, by Tunable Infrared Laser Direct Absorption Spectroscopy," *Analytical Chemistry*, 86, 6487–6494.

Whitehill, A.R., X. Xie, X. Hu, D. Xie, H. Guo, S. Ono (2013), "Vibronic Origin of Mass-Independent Isotope Effect in Photoexcitation of SO_2 and the Implications to the Early Earth's Atmosphere. *Proceedings of the National Academy of Sciences*, 110.

J. 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, the effect of climate on erosion, and the landscape of Mars and Saturn's moon Titan. In a recent paper in *Science*, Perron, postdoctoral researcher Scott McCoy, and collaborators from the Swiss Federal Institute of Technology in Zürich presented a new technique for predicting how river networks will adjust their shape through time as they respond to changing external factors such as plate tectonics and climate. Changes in geographical barriers that accompany this shifting of the landscape can influence the evolution of fish and other freshwater organisms. In a complementary effort, graduate student Alan Richardson developed a new, highly scalable parallel algorithm for routing flow across very large topographic datasets, which should allow researchers to use new computer architectures to take advantage of the ever-improving resolution of remote sensing data. W. O. Crosby postdoctoral fellow Giulio Mariotti is collaborating with Perron and Professor Tanja Bosak to study how microbial processes shape sedimentary features in the geologic record. The first papers from this collaboration showed how patterns of microbial growth on sand bars may have set the template for certain types of stromatolite mounds, which provide early macroscopic evidence of life's interaction with its physical environment. On the planetary side, Perron's group continues to uncover new insights about Titan's rivers, including graduate student Yodit Tewelde's use of lake shorelines to estimate erosion rates in Titan's active north polar region. Graduate student Mike Sori and Undergraduate Research Opportunity Program's Elizabeth Bailey are developing new techniques to unravel the recent climate history encased in the polar caps of Mars.

References

Aharonson, O., A.G. Hayes, R. Lopes, A. Lucas, P. Hayne and J.T. Perron (2014), "Titan's Surface Geology," in *Titan: Interior, Surface, Atmosphere and Space Environment*, I. Mueller-Wodarg, C. Griffith, E. Lellouch, and T. Cravens (eds.), Cambridge University Press.

Bosak, T., G. Mariotti, F.A. Macdonald, J.T. Perron, and S.B. Pruss (2013), "Microbial Sedimentology of Stromatolites in Neoproterozoic Cap Carbonates," *Ecosystem Paleobiology and Geobiology*: *The Paleontological Society Papers*, 19.

Burr, D.M., S.A. Drummond, R. Cartwright, B.A. Black, and J.T. Perron (2013), "Morphology of Fluvial Features on Titan: Evidence for Structural Control," *Icarus*, 226, 742–759.

Mariotti, G., J.T. Perron, and T. Bosak (2014), "Feedbacks between Flow, Sediment Motion and Microbial Growth on Sand Bars Initiate and Shape Elongated Stromatolite Mounds," *Earth and Planetary Science Letters*, 397, 93–100.

Richardson, A., C. Hill, and J.T. Perron (2014), "IDA: An Implicit, Parallelizable Method for Calculating Drainage Area," *Water Resources Research*, 50, 4110–4130.

Sori, M., J.T. Perron, P. Huybers, and O. Aharonson (2014), "A Procedure for Testing the Significance of Orbital Tuning of the Martian Polar Layered Deposits," *Icarus*, 235, 136–146.

Tewelde, Y., J.T. Perron, P.G. Ford, S.R. Miller and B.A. Black (2013), "Estimates of Fluvial Erosion on Titan from Sinuosity of Lake Shorelines," *Journal of Geophysical Research,* 118, 2198–2212.

Willett, S.D., S.W. McCoy, J.T. Perron, L. Goren, and C.Y. Chen (2014), "Dynamic Reorganization of River Basins," *Science*, 343.

Germán A. Prieto

Professor Prieto uses seismic records to accurately predict the way the surface of the Earth will shake after an earthquake. In order to answer this question, his earthquake seismology team tries to understand three fundamental factors that affect these ground motions: the physics of earthquakes, how the 3D complex structure alters seismic waves, and how the shaking is propagated through structures like buildings or bridges.

Prieto and his colleagues are trying to understand the amplification of seismic waves in sedimentary basins and how using very small ground motions—sometimes referred as seismic noise and not noticeable by humans—it is possible to infer how strong ground motions due to large earthquakes will be observed. Earthquakes, although similar to each other, show significant diverse behavior. An M5.0 earthquake in California or Japan may be quite different from an M5.0 in Oklahoma or Brazil. Professor Prieto's group is examining the physics behind earthquakes that can explain this diversity of behavior.

Publications

Denolle, M.A., E.M. Dunham, G.A. Prieto, G.C. Beroza (2014), "Strong Ground Motion Prediction Using Virtual Earthquakes," *Science,* 343, 399–403.

Prieto, G.A., M. Florez, S.A. Barrett, G.C. Beroza, et al. (2013), "Seismic Evidence for Thermal Runaway during Intermediate-depth Earthquake Rupture," *Geophysical Research Letters*, 40, 1–5.

Ronald G. Prinn

Professor Ronald Prinn's principal research interests involve the chemistry, dynamics, and physics of the atmospheres of the Earth and other planets, and the chemical evolution of atmospheres. He is currently principal investigator on a wide range of projects in atmospheric chemistry, biogeochemistry, planetary science, climate science, and integrated assessment of science and policy regarding climate change.

Professor Prinn and his Center for Global Change Science colleagues are collaborating with Rwanda to build a world-class observatory on Mt. Karisimbi. They plan to measure more than 50 atmospheric gases involved in climate change. The observatory will ultimately be run by Rwandan researchers and will join the multinational Advanced Global Atmospheric Gases Experiment (AGAGE) network. This observatory measures air from Rwanda and many other nations within and beyond Africa. Rwandan President Kagame recently visited Prinn's laboratory, where the scientific instruments are tested before being deployed.

Prinn and colleagues in the MIT Global Change Joint Program have completed a major study of climate and air pollution benefits and the economic implications of a global switch from coal and oil to hydraulically fractured shale gas. The study applies the MIT Integrated Global System Model.

A recent paper written together with AGAGE colleagues showed that emissions of the refrigerants and solvents hydrofluorocarbons and hydrochlorofluorocarbons are now the primary drivers of the positive growth in synthetic greenhouse gas climate forcing.

The climate benefits of proposals to reduce future hydrofluorocarbon use under the Montreal Protocol were also elucidated.

Professor Prinn currently teaches four subjects in Atmospheric and Climate Sciences at MIT: 12.806G/12.306U Atmospheric Physics and Chemistry, 12.815G Atmospheric Radiation, 12.335U/12.835G Experimental Atmospheric Chemistry, and 12.848G/12.348U Global Climate Change: Economics, Science and Policy.

Publication

Rigby *et al.* (2014), "Recent and Future Trends in Synthetic Greenhouse Gas Radiative Forcing, *Geophysical Research Letters*, Volume 41, Issue 7, pages 2623–2630.

Paola Rizzoli

Professor Paola 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 for 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 considerable implications for the local ecosystem and the fisheries of the coastal waters.

The second major focus of the group has been the collaboration with Professor Eltahir's group, coupling Rizzoli's ocean model with Eltahir's atmospheric model for simulations of the present climate of the South East Maritime Continent. The two-way coupling has been successfully completed and the results compared with the available oceanographic and atmospheric climatological observations. The investigation has successively been extended to the seasonal and intra-seasonal variability. Negative feedback mechanisms between the atmosphere and the ocean have been identified which correct for negative/positive biases in oceanic/atmospheric variables.

Publications

Xu, D. and P. Malanotte-Rizzoli (2013), "The Seasonal Variation of the Upper Layers of the South China Sea Circulation and the Indonesian Through-Flow: An Ocean Model Study," *Journal of Geophysical Research: Oceans*, 63, 103–130.

Wei, J., P. Malanotte-Rizzoli, E.A.B. Eltahir, and P. Xue (2013), "Coupling of a Regional Atmospheric Model and a Regional Oceanic Model over the Maritime Continent," *Climate Dynamics*, 2014.

Wei, J., D. Wang, M. Li, and P. Malanotte-Rizzoli, "Coupled Seasonal and Intraseasonal Variability in the South China Sea," revised for *Climate Dynamics*, 2014.

Xue, P., E.A.B. Eltahir, P. Malanotte-Rizzoli, and J. Wei, "Local Feedback Mechanisms of the Shallow Water Regions around the Maritime Continent," revised for *Journal of Geophysical Research*, 2014.

Daniel Rothman

Daniel Rothman's work has contributed widely to the understanding of the organization of the natural environment, resulting in fundamental advances in subjects ranging from seismology and fluid flow to biogeochemistry and geobiology. He has also made significant contributions to research in statistical physics. Much of his recent interests focus on the dynamics of Earth's carbon cycle, the co-evolution of life and the environment, and the physical foundation of natural geometric forms.

This year, Professor Rothman, in collaboration with postdoctoral associate Greg Fournier, graduate student Kate French, and professors Eric Alm, Ed Boyle, and Roger Summons, advanced a new hypothesis to explain the end-Permian extinction. This event, the most severe biotic crisis in the fossil record, has often been attributed to increased CO^2 levels deriving from massive Siberian volcanism. Rothman and his collaborators propose instead that the disruption of the carbon cycle resulted from the emergence of a new microbial metabolic pathway that enabled efficient conversion of marine organic carbon to methane. The methanogenic expansion was catalyzed by nickel associated with the volcanic event. Their hypothesis is supported by an analysis of carbon isotopic changes leading up to the extinction, phylogenetic analysis of methanogenic archaea, and measurements of nickel concentrations in South China sediments. The results of this work highlight the sensitivity of the Earth's system to microbial evolution.

Reference

Rothman, D.H., G.P. Fournier, K.L. French, E.J. Alm, E.A. Boyle, C. Cao, and R.E. Summons (2014), "Methanogenic Burst in the End-Permian Carbon Cycle," *Proceedings of the National Academy of Sciences*, 111(15): 5462–5467.

Hilke Schlichting

Hilke Schlichting's research spans all aspects of planet formation theory, extrasolar planets, and solar system dynamics. She studies the solar system and uses the diversity and statistical properties of extrasolar planets to test planet formation theories. Her research combines observations from our solar system, which is the only place where we can examine the outcome of planet formation in detail, with the new wealth of data from extrasolar planets to shed light on the process of planet formation and subsequent dynamical evolution.

Recent work has demonstrated that the orbital architectures of multiple-planet systems discovered by NASA's Kepler mission are consistent with formation at larger separations from their host stars and subsequent inward migration to their current locations. She has also investigated atmospheric mass loss due to giant impacts and planetesimal accretion over the history of the solar system and its implications for terrestrial planet formation and Earth's atmosphere. She found that planetesimals are the most efficient impactors (per unit impactor mass) for atmospheric loss. Her research demonstrates that, despite being bombarded by the same planetesimal population, the current differences in Earth's and Venus's atmospheric masses can be explained by modest differences in their initial atmospheres and that the current atmosphere of the Earth could have resulted from an equilibrium between atmospheric erosion and volatile delivery to the atmosphere from planetesimal impacts.

Publications

Goldreich, P. and H.E. Schlichting (2014), "Overstable Librations Can Account for the Paucity of Mean Motion Resonances among Exoplanet Pairs," *Astronomical Journal*, 147, 32.

Schlichting, H.E., R. Sari, and A. Yalinewich (2014), "Atmospheric Mass Loss During Planet Formation," (submitted to *Icarus*).

Noelle E. Selin

Professor Selin's research aims to better understand the fate and transport of atmospheric pollutants. This research addresses fundamental scientific questions about the atmospheric behavior of contaminants, including long-lived pollutants such as mercury and persistent organic pollutants. The ultimate goal of her work is to inform efforts to manage pollution.

In the past year, her work on mercury examined the implications of the recently signed global treaty on mercury, the Minamata Convention. She examined how treaty provisions would affect the emissions and global biogeochemical cycling of mercury, finding that full implementation of mercury control provisions would result in only small changes to the global mercury cycle. She presented this work in a scientific symposium coinciding with the signing of the Minamata Convention.

In other work, her research group examined how changes in emissions and meteorology, separately and together, may affect the transport of the toxic contaminants polycyclic aromatic hydrocarbons (PAHs) to the Arctic. They showed that the volatility of these substances affects their transport in ways that can help distinguish the impacts of climate and direct emissions on their transport pathways. They also tested the hypothesis (based on a published laboratory study) that PAHs are trapped in secondary organic aerosol (SOA) upon its formation in the atmosphere. If this trapping occurs, this has important implications for their ability to undergo long-range atmospheric transport. They evaluated this hypothesis with their model, finding that including a trapping process improves ability to simulate long-range transport, but that trapping in black carbon, rather than SOA, better reproduces measurement constraints.

To more directly address the implications of air pollution on society, Selin has extended her analyses to link output of atmospheric models with health-relevant analysis, including economics. Asking the question of how fine an atmospheric model resolution is necessary to analyze the health impacts of air pollution, they found that at national scale in the US, health benefits calculated at even coarser resolution (36 km) agree within errors with finer-scale modeling (4 km).

Selin's group participated in the summer 2013 "Nitrogen, Oxidants, Mercury and Aerosol Distributions, Sources and Sinks" field campaign, based out of Smyrna, TN, which used an aircraft to measure air pollution over the Southeast United States. Their group used atmospheric modeling to forecast air pollution to inform the sampling strategy, and is currently participating in data analysis efforts.

In the area of education, her subject 12.845, Global Environmental Science and Politics, was offered to undergraduates for the first time in fall 2013. As part of this class, students went on a "virtual" field trip to global climate change negotiations, watching webcasts of the proceedings in real time, and using social media (blog, http://esd110.mit.edu, and twitter) to share their experiences. This subject will be offered again in fall 2014.

In 2013, Professor Selin was awarded the Esther and Harold E. Edgerton career development assistant professorship. In 2014, she was elected as a member of the Global Young Academy for a four-year term.

Publications

Friedman, C.L., Y. Zhang, and N.E. Selin (2014), "Climate Change and Emissions Impacts on Atmospheric PAH Transport to the Arctic," *Environmental Science and Technology*, 48: 429–437.

Selin N.E. (2014), "Global Change and Mercury Cycling: Challenges for Implementing a Global Mercury Treaty," *Environmental Toxicology and Chemistry*, 33(6):1202–1210.

Thompson, T.M., R. Saari, and N. E. Selin (2014), "Air Quality Resolution for Health Impacts Assessment: Influence of Regional Characteristics," *Atmospheric Chemistry and Physics*, 14:969–978.

Susan Solomon

Susan Solomon is internationally recognized as a leader in atmospheric science, particularly for her insights in explaining the cause of the Antarctic ozone "hole." She and her colleagues have made important contributions to understanding chemistry/climate coupling, including leading research on the irreversibility of global warming linked to anthropogenic carbon dioxide emissions, and on the influence of the ozone hole on the climate of the southern hemisphere. Her current focus is on issues relating to both atmospheric chemistry and climate change.

Solomon's work includes a focus on stratospheric ozone and how it is changing. A paper published in *Proceedings of the National Academy of Sciences* shows fundamental differences in ozone depletion between the Arctic and Antarctic, and reveals that these are strongly linked to polar stratospheric cloud chemistry and chlorofluorocarbons. The paper shows how important removal of nitrogen species in polar stratospheric clouds is for ozone depletion in a novel way. A related paper quantifies the relative effects of stratospheric ozone loss and carbon dioxide in affecting stratospheric temperatures in more detail than previous studies, suggesting an important role for ozone in controlling temperature trends and polar stratospheric clouds in the Arctic stratosphere.

Several of their most current studies focus on how climate changes in the stratosphere are linked to the troposphere. A new paper with EAPS graduate student Justin Bandoro as first author probes how the Antarctic ozone hole has much more far-reaching effects on the surface climate of many parts of the southern hemisphere than previously thought. A related paper with EAPS postdoctoral associate 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.

Finally, a new and highly policy-relevant paper published in *Atmospheric Chemistry and Physics* shows for the first time the significant climate commitments due to 'banks' of hydrofluorocarbons contained in refrigeration and air conditioning. These banks imply that the impact of these gases upon the Earth's climate is more severe than estimates that neglect the banks.

Publications

Bandoro, J., S. Solomon, D.W.J. Thompson, A. Donohoe, and B.D. Santer (2014), "Influence of the Antarctic Ozone Hole on Seasonal Changes in Climate in the Southern Hemisphere" (in press), *Journal of Climate*.

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Roger Summons

Professor of Geobiology Roger Summons has wide-ranging interests in biogeochemistry and geobiology. His research group studies the co-evolution of Earth's early life and environment, microbially dominated ecosystems, the structure and biosynthesis of membrane lipids, biological mass extinction events and the origins of fossil fuels. Specific areas of interest include lipid chemistry of geologically significant microbes and microbially dominated ecosystems, organic and isotopic indicators of climate change, biotic evolution and mass extinction, age- and environment-diagnostic biomarkers in sediments and petroleum and Archean, Proterozoic and extraterrestrial biogeochemical fossils. As principal investigator of the MIT NASA Astrobiology Institute, Summons is involved with the Sample Activity on Mars instruments aboard NASA's Curiosity Rover being used to study potential organic material within the rocks on Mars.

This year the Summons laboratory continued its quest to elaborate geochemical records of early life on the Earth, a search that is funded by five-year grants from the NASA Astrobiology Institute and the Simons Foundation Collaboration on the Origins of Life. A drilling project in the Pilbara Craton using ultra-clean drilling protocols recovered pristine cores of 2.5 billion year old rocks that are being analyzed for the isotopic compositions of carbon and sulfur at micron-scale resolution. They continued their support of the Mars Science Laboratory mission via pyrolysis experiments on Mars analog materials. They attempt to mimic and verify key aspects of experiments conducted on the surface of Mars by the Curiosity Rover. They also conducted forays into more recent evolutionary events by the application of geochemical methods in collaborations on the behavior of ocean plankton and examined the diet of Neanderthals.

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Grotzinger, *et al.* (2013), "A Habitable Fluvio-Lacustrine Environment at Yellowknife Bay, Gale Crater, Mars," *Science*, 343, 1242777.

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Robert van der Hilst

Robert van der Hilst is a geophysicist whose cross-disciplinary and collaborative research focuses on understanding geological processes in Earth's deep interior, both on a regional scale—for instance continental structure and evolution of Tibet, East Asia, and North America, the subduction of oceanic plates beneath western Pacific island arcs, the upper mantle transition zone beneath Hawaii, and the complex region just above the core mantle boundary beneath Asia and Central America—and the global scale, unraveling, for instance, the pattern and nature of mantle convection. The main tools he uses and develops are global reflection seismology and seismic tomography, but he integrates these findings with constraints from geology, geomagnetic plate reconstructions, mineral physics, and geodynamics.

Professor van der Hilst has been head of EAPS since January 2012. Research in the van der Hilst Group continues to focus on regional tectonics in southeastern Tibet (in collaboration with colleagues at the Institute of Geology of the China Earthquake Administration), imaging of Earth's deep interior using dense seismograph arrays and methods adapted from hydrocarbon resource exploration (in collaboration with professors De Hoop and Shim), and further theoretical development of algorithms for high-resolution seismic imaging with natural earthquakes (in collaboration with De Hoop). With an imaging method adapted from use in hydrocarbon exploration, Van der Hilst's team discovered seismic reflectors in Earth's lowermost mantle (between 2,200–2,800 kilometer depth) suggesting previously unknown changes in material properties hundreds of kilometers above the core mantle boundary . With his collaborators in China, he constructed a detailed 3D model of the crust and uppermost mantle beneath southwest China, which helps explain the eastward expansion of the Tibetan Plateau and the characteristics of regional seismicity in Sichuan Province.

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Xuefeng S., S. Sang-Heon, M. de Hoop, and R.D. van der Hilst (2014), "Multiple Seismic Receptors at Earth's Lowermost Mantle," *Proceedings of the National Academy of Sciences,* 111(7): 2442–2446.

Liu, Q.Y., R.D. van der Hilst, Y. Li, H.J. Yao, J.H. Chen, B. Guo, S.H. Qi, J. Wang, H. Huang, and S.C. Li (2014), "Eastward Expansion of the Tibetan Plateau by Crustal Flow and Strain Partitioning across Faults," *Nature Geoscience* 7, 361–365.

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