

## **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 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 Civil and Environmental Engineering and one with a primary appointment in Engineering Systems Division) and more than 170 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. The Earth Resources Laboratory and Kuwait-MIT Center for Natural Resources and the Environment bring together faculty, staff, and students in intensive and multidisciplinary efforts to investigate geophysical and geological problems in energy and resource development. The Center for Global Change Science builds on the programs in meteorology, oceanography, hydrology, chemistry, satellite remote sensing, and policy. The MIT/Woods Hole Oceanographic Institution (WHOI) Joint Program continues in its 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 2010, EAPS had 165 graduate students registered in the department, including 73 students in the MIT/WHOI Joint Program. Women constituted 49 percent of the graduate student population, and 6.6 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 formal and informal ways to improve educational experience as well as student life. In this past year the graduate students took responsibility for an expanded orientation program for the incoming graduate students. They planned a number of new social events to introduce the newcomers to the EAPS, MIT, and the Cambridge area. The department graduate students meet regularly, with one of the students presenting his or her research. Undergraduate majors are encouraged to attend these talks. The departmental Graduate Student Mentoring Program continues as a well-received approach to providing peer support for new students.

EAPS awards a prize for excellence in teaching to highlight the superior work of teaching assistants. During the 2011 academic year, Ben Black, Chris Follett, Kathleen Munson, and Alessondra Springmann were recognized. Brian Rose received the 2011

Rosby Award, presented for the best PhD thesis in the Program of Atmospheres, Oceans, and Climate.

Our students were also recognized by professional societies. Malte Jansen was a recipient of a Student Award for his presentation at the American Meteorological Society's 18th Conference on Atmospheric and Oceanic Fluid Dynamics. Erin Shea received the Stephen E. *Dwornik Award* for Best Graduate Oral Presentation at the 2010 Lunar and Planetary Science Conference. Shea also received the Outstanding Student Paper Award at the annual fall meeting of the American Geophysical Union (AGU). Brian Tang won the first Joanne Simpson Award from the National Center for Atmospheric Research at the same time that he was admitted to its prestigious Advanced Studies Program. At the fall 2010 AGU meeting, Christy Till received the Volcanology, Geochemistry, and Petrology Section Outstanding Student Paper Award.

### **Undergraduate Program**

In fall 2010, EAPS had 32 undergraduate majors, 72 percent of whom were women and 25 percent of whom were members of an underrepresented minority group. Ten students were awarded the SB degree in Earth, Atmospheric, and Planetary Sciences in AY2011.

At the 2011 Student Awards and Recognition Dinner, the Goetze Prize was awarded to Sean Wahl in recognition of his outstanding senior thesis, John Vince Agard received the W.O. Crosby Award for Sustained Excellence, and Alexandra Jordan was the recipient of the Award for Excellence as an Undergraduate Teaching Assistant.

The department maintains a strong presence in the undergraduate program at MIT beyond the population of majors so that the general student body has access to the science underlying energy, environmental, and climate change issues. The department is committed to the Terrascope program and its problem-based approach to education during the first year at MIT and to offering Freshman Advising Seminars. Similarly, EAPS is an active participant in two interdisciplinary minor programs, the broadly based energy minor and the astronomy minor, with the Department of Physics. EAPS has two courses that are components in the Energy Science Foundation section of the requirements and two classes that are electives for the minor.

### **Community Events**

The department aims to create collaborative opportunities within EAPS, at MIT, and outside the Institute. In the past year the department hosted several weekly lecture series and a memorial lecture, open to the MIT community and the public. The 11th annual Henry Kendall Memorial Lecture was held on April 15, and the Honorable Lisa P. Jackson, administrator of the U.S. Environmental Protection Agency, gave a talk on the state of environmental protection in the United States. Professor Tapio Schneider of the California Institute of Technology was this year's invited Houghton Lecturer and gave five lectures focused on atmospheric dynamics. Additionally, there was significant departmental involvement in the Gulf of Mexico Oil Spill Symposium on September 28, the MIT Workshop on the Future of the Oceans on December 2, the Women in

Aerospace Symposium on January 27 and 28, the Cambridge Science Festival held on April 30, and the MIT 150th Open House and Symposia.

In alumni outreach, EAPS faculty were active in the department's development efforts, participating in 14 events geared toward alumni and friends in cooperation with the School of Science, Resource Development, and the MIT Alumni Association. These included the annual reception for EAPS alumni and friends at the fall meeting of the American Geophysical Union in San Francisco, a dinner for major gift prospects in Silicon Valley generously hosted by Roger Bamford '77, and talks at MIT clubs of Boston, Southwest Texas, Long Island, Denver, and New York.

## Faculty

The department continues its efforts to hire and help young faculty members develop careers. Noelle Selin joined the department with a joint appointment as assistant professor of atmospheric chemistry; her primary appointment is with the Engineering Systems Division (ESD). Effective July 1, 2011, Daniel J. Cziczo will join our faculty as professor of atmospheric chemistry. Kerri Cahoy will also join the department with a joint appointment as assistant professor of planetary science; her primary appointment will be in the Department of Aeronautics and Astronautics. Sara Seager, the Ellen Swallow Richards professor of planetary science, was promoted to full professor. Linda Elkins-Tanton was promoted to associate professor without tenure.

With great sadness, we note the loss of Professor James L. Elliott. Professor Elliot was one of the great observational planetary astronomers, well known for leading the research team that discovered the rings of Uranus in 1977. A memorial service was held in June at the MIT Chapel, where family, friends, and colleagues celebrated his life, friendship, and many accomplishments.

## Honors and Awards

Professor Samuel A. Bowring received the N. L. Bowen Award, presented by the American Geophysical Union at its annual fall meeting, for his contributions to our understanding of the history of the Earth and its biosphere.

Professor Bradford H. Hager was awarded the 2011 Augustus Love Medal by the European Geophysical Union for his contributions to understanding the Earth's geoid and mantle flow.

Assistant professor Taylor Perron was awarded the Cecil and Ida Green Career Development chair.

Professor Maria Zuber shared a NASA Group Achievement Award for achievements by the Mars Reconnaissance Orbiter Radio Science Gravity Team that she leads.

## Research Highlights

Professor Richard Binzel is a coinvestigator for a newly selected NASA spacecraft mission, OSIRIS-REx, scheduled for launch in 2016. Professor Binzel is the lead scientist for an X-ray spectrometer instrument that will be designed and built by students in

EAPS and Aerospace Engineering, in collaboration with the MIT Kavli Institute and the Harvard College Observatory. The MIT-built instrument, called REXIS, will map the elemental abundance of the target asteroid's surface for sample site collection and global context for the returned sample.

Professor Edward Boyle was cochief scientist on a research expedition from Lisbon to the Cape Verde Islands, as part of the first US transect contributing to the international GEOTRACES project during the coming decade. They obtained detailed samples at 12 profile stations for a wide variety of trace elements, trace element isotope ratios, and radioisotopes that will be used to calibrate and model the behavior of trace elements in the ocean and how they can be used to understand the modern and ancient operation of the ocean biogeochemical system. At two sites near prior occupations in 1989 and 1999, the anthropogenic lead (Pb) concentrations continued to decrease in the upper 2,000 m as a result of the phasing out of leaded gasoline. The  $^{206}\text{Pb}/^{207}\text{Pb}$ ,  $^{208}\text{Pb}/^{207}\text{Pb}$ , and  $^{206}\text{Pb}/^{204}\text{Pb}$  isotope ratios also evolved as different lead sources dominated. The project will continue in November 2011 with a transect from Woods Hole to the Cape Verde Islands.

Associate professor Linda Elkins-Tanton's progress in planetary science shows that the Earth had likely cooled to clement conditions, with liquid oceans, while the Moon's internal magma ocean was still solidifying; the Moon likely accreted with not more than tens of parts per million water. The Moon's measured internal water content may be partly a result of late impacts of water-rich bodies, before the internal shell of lingering magma ocean was entirely solidified, and many planetesimals may have melted internally during the first few million years of planet formation in our solar system, producing magnetic dynamos.

Professor Kerry Emanuel continued research on his long-standing interest in tropical cyclones and initiated a new line of work on clustering of cumulus convection and its effect on tropical climate. He continues to be interested in how tropical cyclones may influence the Earth's climate, and he published a paper with Alexey Federov and Chris Brierley arguing that tropical cyclone activity during the Pliocene period was somewhat greater than today's and may have helped sustain the weak longitudinal sea surface temperature gradients in the equatorial Pacific. He also started a new National Science Foundation-sponsored research project on self-aggregation of convection, under the hypothesis that this phenomenon is ubiquitous and strongly regulates tropical climate.

Professor Raffaele Ferrari's group is working on the effect of ocean turbulence on climate. They are halfway through a three-year observational campaign aimed at estimating the role of ocean turbulence in setting the rate of ocean heat and carbon uptake in the Southern Ocean. Preliminary results show that the ocean carbon uptake is likely to continue in a global warming climate, contrary to common wisdom, because the decrease in uptake resulting from a strengthening in the wind-driven circulation is offset by an increase in the oceanic turbulence. In the last year his group has also engaged in studies of the ocean productivity and its impact on the carbon cycle. They showed that the exchange of carbon between the ocean and the atmosphere is most efficient at oceanic fronts, i.e., the sharp temperature filaments generated by oceanic turbulence.

Professor Timothy Grove and graduate student Christy Till made progress on the melting of an important mantle rock called peridotite in the presence of excess  $H_2O$ . The process, which is often referred to as vapor-saturated melting, is important for understanding the origin of island arc magmas. Until now there has been a long-standing debate about the melting temperature of the vapor-saturated mantle. They have shown that the temperature of melting at pressures relevant for melting beneath subduction zones is about  $600^\circ C$  lower than the beginning of melting under dry conditions.

Professor Bradford H. Hager and his group have solved a classic problem in geodynamics—how the wobble of Earth's rotation axis, known as the Chandler wobble, is excited. Geodetic observations of the position of the rotation axis show a spiraling motion, with a radius of up to tens of meters, caused by a beating between the annual forced response and the 14-month period of the free Eulerian wobble. But high-precision very-long-baseline interferometry (VLBI) observations show that this radius changes in amplitude on time scales as short as weeks. Hager's group demonstrated that the forcing of polar motion by MIT's global ocean circulation model, plus observed variations in atmospheric angular momentum, predicts the observed polar motion on time scales from weeks to decades.

Professor Thomas Herring is using global positioning system (GPS) and VLBI data to develop geophysically based models of changes in the rotation of the Earth and Earth deformations on global, regional, and local scales. 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 United States. They are investigating processes on time scales of years leading up to earthquakes, days to years in the domain of postseismic deformation, and seconds for surface wave propagation during earthquakes. The group is also monitoring and modeling human-induced deformations in oil fields.

Assistant professor Oliver Jagoutz's group is making promising progress on the formation and evolution of the continental crust. Based on detailed geological mapping in the remote northwestern Himalayas, the only place on Earth where the transition from the lower continental crust to the upper mantle is well exposed, Jagoutz and his group are studying the nature and composition of mass exchange between crust and the upper mantle. They demonstrated that the preserved approximately 40 km thick continental crust represents only the uppermost ~ 30 to 50 percent of the original volume of crust formed in subduction zones. The remaining 50 to 70 percent of lower crustal material undergoes complex chemical densification reactions that ultimately result in a density inversion at the lower crust–upper mantle interface. These results, for the first time, constrain the magnitude and composition of this return flux, which is key to understanding chemical differentiation of the shallow Earth.

Professor Alison Malcolm's research program has continued to focus on imaging complex structures. She is particularly excited about progress in seismic interferometry, which has applications to geothermal energy. As part of this research, her group is

working on methods to estimate the scattering strength of a medium. They are also using interferometric techniques to form traditional seismic images with multiply scattered waves. In the past year she has also become more interested in a rising imaging technique called full-waveform inversion. She is working on several aspects of this method, including improving robustness to noise and estimating a more accurate initial guess at the Earth's structure.

Professor John 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. As part of MIT's Climate Modeling Initiative, he has also been studying geometrical constraints on ocean heat transport and the possibility that the climate may possess multiple equilibria.

Professor Taylor Perron and his group are studying how patterns in landscapes record the geologic processes that shape planetary surfaces. They recently uncovered the mechanism that makes rivers form branching tributary networks, one of the most widespread erosional features on Earth and other planets. By comparing a numerical model of landscape evolution with high-resolution laser altimetry maps of sites in California and the Allegheny Plateau, they additionally found that the scale of branching river networks is controlled primarily by aridity and rock strength.

Professor Ronald Prinn and colleagues have published four new probabilistic forecasts for 21st-century climate under four different policy assumptions indicating a major reduction of the probability of warming exceeding  $3^{\circ}\text{C}$  if greenhouse gases are constrained to be less than 550 parts per million (ppm) of  $\text{CO}_2$  equivalents. (We are currently at 470 ppm.) Other papers with colleagues report on new emission estimates for four hydrofluorocarbon greenhouse gases, new methodologies for estimating emissions from infrequent observations, estimation methods combining Eulerian and Lagrangian models, a new fast code for computing city-scale air chemistry in global models, and demonstration of the significant over-prediction of aerosol climate effects in models that neglect this city-scale processing.

Professor Paola Rizzoli and her postdoctoral associates have continued in their work in the tropical Pacific/Indian oceans, with focus on the South China Sea and the Indonesian through-flow. Areas of emphasis include transport dynamics, storm surges, and coupled models of climate variability in the Pacific and Indian oceans.

Professor Daniel Rothman and his students and colleagues have been developing theoretical methods that reveal the kinetic structure of the carbon cycle. One study shows that the decay of plant matter universally exhibits a lognormal distribution of decay rates. Another study shows how to tease apart the 5000-year mean age of marine dissolved organic carbon into distinct components with different ages. Both lines of work suggest the existence of internal organization in the disordered kinetics of global respiration.

Research in professor Roger Summons's laboratory continues to be focused on gathering and interpreting geological and geochemical data pertinent to understanding Earth's earliest biosphere, the advent of biological complexity, and the environmental changes this brought about. Over the past year they have elucidated molecular and isotopic records of microbial communities present on the early Earth and conducted comparative studies of modern environments and microbes. Their current research is pertinent to the search for molecular biosignatures on Mars.

Professor Benjamin Weiss has been developing a new model for the structures and interiors of asteroids and planetesimals in the early solar system. Motivated by his recent magnetic studies of chondrites, primitive meteorites that have never experienced melting, he and colleagues Linda Elkins-Tanton and Maria Zuber have argued that many of the small bodies had melted interiors but retained primordial exterior crusts. This motivates a new paradigm for the nature of meteorite parent bodies, suggesting that seemingly disparate meteorite groups could have originated from one or more partially melted asteroids. It also suggests that there may be a spectacular but unrecognized petrologic diversity in the asteroid belt.

Professor Carl Wunsch and his colleagues and collaborators have focused on the global circulation of the ocean and its changes over years to decades and beyond. This work uses very large global observational data sets and state-of-the-art general circulation models of the ocean. The main results are three-dimensional time-varying estimates of the top-to-bottom ocean at all latitudes from 1992 to present that are used to understand the changing climate system, as well as to discuss the design of more optimal observation systems. A major achievement of the last several years has been the development of modeling and data components representing the high latitudes generally and the Arctic in particular, especially focused on the behavior of sea ice.

Using data from radio tracking and their laser altimeter on the MESSENGER spacecraft, professor Maria Zuber and her colleagues and students developed the first models for the topography and gravity fields of the northern hemisphere of Mercury. The topography shows the floor of the major impact basin Caloris to have been significantly modified, with northern sections rising above the basin rim. The topography also shows an irregular topographic depression of 2- to 4-km depth centered on the north pole that may have migrated to the pole because of reorientation of the planet's inertia axes. The gravity field displays mass anomalies that correlate with some impact basins that hold the promise of modeling regional crust and upper mantle structure.

**Maria T. Zuber**  
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