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 (CEE), one with a primary appointment in the Engineering Systems Division (ESD), and one with a primary appointment in the Department of Aeronautics and Astronautics (AeroAstro)]. EAPS also has 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 issues of our time: changes 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, integrates faculty, staff, and students across disciplinary, department, and school boundaries to investigate geophysical and geological problems in energy and resource development. The Center for Global Change Science, under the directorship of Professor Ronald Prinn, builds cross-Institute activity in meteorology, oceanography, hydrology, chemistry, satellite remote sensing, and policy. The Lorenz Center (founded in 2011 under the directorship of Professors Kerry Emanuel and Daniel Rothman) aspires to be a climate think-tank devoted to fundamental scientific enquiry. Further, EAPS is MIT's largest participant in the MIT/Woods Hole Oceanographic Institution (WHOI) Joint Program, supporting its mission of graduate education and research in ocean sciences and engineering.

Educational Activities

The EAPS faculty is committed to the development and maintenance of vibrant education programs at both the undergraduate and graduate levels. The past year saw a major change in the way EAPS conducts oversight of these programs. The EAPS faculty voted to replace the Undergraduate Education Committee and the Graduate Education Committee with the Committee on the Education Program. The membership of the Committee on the Education Program includes the associate department head, the graduate officer, the undergraduate officer, and the education officer. The new committee is in charge of regular oversight of teaching and student progress; it will create a task force, with membership from the broader faculty, for any special project that might arise. Student engagement with the education program is a continuing departmental goal. 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.

Graduate Program

EAPS has vigorous graduate educational programs in the areas of Earth, planets, climate, and life, including geology, geochemistry, geobiology, geophysics, atmospheres, oceans, climate, and planetary science. In fall 2014, EAPS had 154 registered graduate students, including 73 students in the MIT/WHOI Joint Program and three fifth-year master's degree students. Women constituted 41.6% of the graduate student population; 5.8% 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 of improving the educational experience as well as the student life of the department. For example, the graduate students continue to take responsibility for an expanded orientation program for incoming graduate students. They plan a number of social events to introduce newcomers to EAPS, to MIT, and to the Cambridge area. The department's 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 providing peer support for new students. In the past year, the graduate students expanded the program to provide a mentor to each EAPS senior.

EAPS awards an annual prize for excellence in teaching to highlight the superior work of its teaching assistants. During the 2015 academic year, Neesha Schnepf, Tom DeCarlo, David Wang, and Emily Zakem were recognized for their contributions.

EAPS students were also recognized by professional societies. In April 2015, Julien de Wit received the Prix Scientifique aux Jeunes de l'Association des Ingénieurs de l'Université de Liège 2014. At the 2014 Annual Meeting of the American Geophysical Union (AGU), the Outstanding Student Paper Award was presented to Jean-Arthur Olive for his thesis research, "Mechanical and Geological Controls on the Long-Term Evolution of Normal Faults," and to Jörn Callies for his research on atmospheric and oceanic wave fluctuations. Sudhish Bakku received the Best Student Poster Paper award, presented at the 2014 Society of Exploration Geologists Annual Meeting, for his research on monitoring hydraulic fracturing using distributed acoustic sensing in a treatment well. Jared Atkinson was a member of the team that won this year's Caltech Space Challenge, a five-day international student space mission design competition at the California Institute of Technology. Notes on other student awards for academic year 2015 are available.

EAPS Graduated 24 Doctoral Students and Six Master's Degree Students in AY2015.

Undergraduate Program

In fall 2014, 23 undergraduates were majoring in EAPS, 87% of whom were women and 13% of whom were members of an underrepresented minority group.

The EAPS undergraduate population has always been small but satisfaction is high and the department continues its efforts to increase the number of students majoring in EAPS. These activities include events for incoming freshmen, involvement through freshman advising and teaching beyond EAPS, widened use of social media, and increased visibility on campus. In fall 2014 a good number of freshmen again chose EAPS as a major, with 10 new students joining us in fall 2015.

Beyond the department's own undergraduate program, EAPS maintains a strong presence in undergraduate education across MIT so that the 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, the department supports and leads two major undergraduate programs at MIT, Terrascope (under the directorship of Professor Samuel Bowring) and the Experimental Studies Group (under the directorship of Professor Leigh Royden). EAPS also offers a relatively large number of freshman advising seminars. With the combined enrollment of Terrascope and the advising seminars, EAPS connected with 6.4% 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 minor, the astronomy minor (with the Department of Physics) and the atmospheric chemistry minor (with ESD and the Chemistry and AeroAstro Departments).

At the 2015 Student Awards and Recognition Dinner, the Goetze Prize was awarded to Casey Hilgenbrink (advised by Professor Kerry Emanuel) in recognition of her outstanding senior thesis. Molly Kosiarek (advised by Professor Richard Binzel) received the W.O. Crosby Award for Sustained Excellence, recognizing her academic and intellectual achievements and her general contributions to the department. Madison Douglas and Judy Pu received 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 a high grade point average, focused course work, and leadership within EAPS. Judy Pu was recognized as an outstanding undergraduate teaching assistant for her work with the students of 12.001 Introduction to Geology.

Kelly Kochanski won the MIT International Science and Technology Initiative's Suzanne Berger Award for Future Global Leaders for her work in India during the past two summers. This included fieldwork in Ladakh, Pakistan (led by Professors Benjamin Weiss and Oliver Jagoutz), and a research internship with Shell International.

EAPS graduated six students with bachelor's degrees in AY15.

Faculty

The department continues its efforts to hire the best young scientists and help them develop successful careers.

Geobiologist Dr. Gregory Fournier joined EAPS as a new assistant professor in July 2014. The department is excited to have brought such talent to MIT.

Kristin Bergmann, who received her PhD from the California Institute of Technology and recently finished a junior fellowship with the Harvard Society of Fellows, joined the EAPS faculty as an assistant professor in July 2015.

Dr. Timothy Cronin, who graduated from EAPS graduate and is currently a postdoctoral researcher at Harvard, has accepted the department's offer and will join the faculty in July 2016.

The department is now halfway through the fourth year of the junior faculty mentorship program introduced in January 2012. Each junior faculty member is assigned a mentor team that includes 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 the department. Junior and senior faculty members alike are satisfied with the new system, but feedback solicited from junior faculty will be used to make further improvements.

Promotions

These promotions will be effective as of July 2015:

- Assistant Professor of Geochemistry Shuhei Ono was promoted to the rank of associate professor with tenure.Associate Professor of Atmospheric Chemistry Colette Heald (joint appointments in CEE and EAPS) was promoted to associate professor with tenure. Assistant Professor of Engineering Systems and Atmospheric Chemistry Noelle Selin (joint appointments in ESD and EAPS) was promoted to associate professor without tenure.

Honors and Awards

Robert R. Schrock Professor of Geology Samuel A. Bowring was elected to the National Academy of Sciences.

Cecil and Ida Green Professor of Atmospheric Science Kerry Emanuel has been invited to give the Bjerknes Lecture at the fall 2015 meeting of the AGU. A paper on flood resilience strategies for coastal cities of which Professor Emanuel was a co-author was awarded a prize by Lloyds of London (Aerts et al., 2014; see Faculty Research Highlights).

Professor of Civil and Environmental Engineering and Earth, Atmospheric and Planetary Sciences Dara Entekhabi was elected a Fellow of the Institute of Electrical and Electronics Engineers for contributions to microwave remote sensing of soil moisture.

Professor of Oceanography Glenn Flierl received the Henry Stommel Research Award of the American Meteorological Society "[f]or fundamental insights into the dynamics of vortices and geostrophic turbulence and their impact on marine ecosystems." He was also elected a fellow of the AGU.

Associate Department Head and Cecil and Ida Green Professor of Geology Timothy Grove was awarded a Docteur honoris causa de l'Universite de Lausanne. In addition, Asteroid (9276) Timgrove was named in his honor in July 2014. He was inducted into the National Academy of Sciences in May 2015.

Professor of Physical Oceanography Paola Malanotte-Rizzoli has been honored with the Fellowship of the International Union of Geology and Geophysics, Prague, 2015.

Cecil and Ida Green Professor of Oceanography John Marshall has been invited to give the Bernhard Haurwitz *Memorial Lecture* of the American Meteorological Society. The lecturer is chosen "in recognition of significant contributions to the understanding of atmospheric and oceanic fluid dynamics, the circulation of the middle atmosphere, or the dynamics of climate."Class of 1941 Professor of Physics and Planetary Science Sara Seager was elected to the National Academy of Sciences. She was also a 2015 recipient of an MIT Amer G. Bose Award, which she plans to use to map biochemical space as she pursues her search of life beyond Earth. Seager also received an honorary doctorate from the University of British Columbia.

Asteroid (9522) was named Schlichting in recognition of Professor Hilke Schlichting's work on the Kuiper Belt.

Ellen Swallow Richards Professor of Atmospheric Chemistry and Climate Science Susan Solomon received honorary doctorates from Brown University, and the University of British Columbia.

Cecil and Ida Green Assistant Professor of Geology Taylor Perron was awarded a James B. Macelwane Medal in recognition of "significant contributions to the geophysical sciences by an outstanding young scientist." Perron also became an AGU Fellow.

Professor of Geophysics Daniel Rothman was elected as a fellow of the AGU.

Emeritus Professor Carl Wunsch has been selected as the 2015 recipient of the Walter Munk Award of the Oceanography Society for "distinguished research in oceanography related to sound and the sea."

Schlumberger Professor and EAPS Department Head Robert van der Hilst was elected to the American Academy of Arts and Sciences in October 2014.

Community Events

Throughout the academic year, the EAPS calendar is full of events, lectures, and seminars that are generally open to the public.

Notable community events during AY15 were the Carlson, Kendall, and Brace Lectures, Planets and Life, a widely appreciated series exploring human and planetary perspectives on life on planet Earth, and the annual EAPS fall geology field trip.

"Planets and Life," the brainchild of EAPS researcher Dr. Vlada Stamenković and Professor Michael Follows, drew together experts from both within and outside MIT for a series of 10 public lectures that were complemented by two panel discussions (hosted at the MIT Museum). The series and discussions explored the grand environmental changes—from a natural planetary perspective—that might endanger the survival of the species *Homo sapiens*. The series was very well attended; it drew a broad cross-Institute audience of students and faculty, as well as the general public.

Open to the entire MIT community, each year the EAPS fall geology field trip provides an opportunity to join a two-day tour of the geology of central Massachusetts. The geology of Central Massachusetts encompasses 200-million-year-old dinosaur footprints, lava flows and sandstones (some with fish fossils) deposited during the early stages of the splitting off of North America from Africa, deposits of sand and gravel from melting glaciers, glacial lake deposits, and other evidence for starkly different pasts. The AY15 trip, led by Professors Samuel Bowring, Thomas Herring, and Gregory Fournier, visited all the usual sites, camped overnight at Barton Cove, Gill, MA, and wrapped up with a fascinating, curated tour of the Beneski Museum of Natural History at Amherst College, Amherst, MA, home of an enormous trove of Connecticut River valley dinosaur footprints.

The Fourth Annual Carlson Lecture at the New England Aquarium, "Big Cats, Panama and Armadillos: A Story of Climate and Life," was given by the distinguished Crafoord Prize winner and former EAPS faculty member Peter Molnar. Molnar's entertaining lecture explored what may have triggered the shift in climate that kicked off the cycle of ice ages Earth began experiencing three million years ago.

The Second Annual William Brace Lecture, "The Inference Spiral of Earthquake System Science," was given by former EAPS Department Head Thomas H. Jordan. Professor Jordan's lecture highlighted efforts to develop and validate earthquake forecasting models based on the coupling of rupture and ground-motion simulators, focusing on how this modeling framework can be used to pose questions of contingent predictability as physics problems in a system-specific context. Jordan is currently the W. M. Keck Foundation Professor of Earth Sciences at the University of Southern California.

Climate expert Jochem Marotzke **delivered the 15th annual Henry W. Kendall Memorial Lecture**, co-sponsored by the Center for Global Change Science. In "Recent Global Temperature Trends: What Do They Tell Us About Anthropogenic Climate Change?" Marotzke discussed the apparent recent climate-warming hiatus as well as the abilities and limitations of climate models. Marotzke, who currently serves as the director of the Max Planck Institute for Meteorology in Hamburg, Germany, was a member of the EAPS faculty in the 1990s.

Communications

The arrival of new Senior Development Officer Angela Ellis in July 2014 accelerated the department's work to define and strengthen the EAPS "brand." The communications team, headed by EAPS Communications Officer Helen Hill, has worked closely with Ms. Ellis to strengthen how research and fundraising news and opportunities are shared on the EAPS website and in the department's regular publications, such as the renamed annual newsletter (EAPS Scope) and the biennial e-newsletter (EAPSpeaks.)

Other print materials were either updated or new materials developed to suit audiences at donor meetings and outreach events throughout the year. Plans are in place for a fresh suite of development materials in fiscal year 2016 that will both reflect the campaign and to convey the four defining EAPS research themes: Earth, planets, climate, and life.

Thanks to the talents of Jennifer Fentress, the department's graphic designer, EAPS materials are now consistently attractive and professional, reflecting a unified and professional look that is recognizably that of the department.The EAPS social media audience continues to grow with the EAPS Facebook page, ably managed by Heather Queyrouze, providing a vibrant, open window on EAPS daily life and culture.

Significant projects during AY15 have included the development of a new website, scheduled for launch in fall 2015, and the commissioning of a short (five-minute) professionally produced promotional video that is also due to be released in fall 2015. Both these initiatives were motivated by the perceived need to raise the department's profile both within MIT, especially for the purpose of engaging more undergraduates, and outside MIT, among alumni and the philanthropic community, for the purpose of increasing funding for graduate student fellowships and discretionary support.

The new website, a full-featured Drupal content management system based on a template developed by MIT's School of Science, will give EAPS the state-of-the-art online tool it needs to efficiently and effectively recast its messaging.

The promotional video will be a vital tool in succinctly communicating the extreme relevance of the research and education taking place in the department.

Development

Fiscal year 2015 was a banner year for fundraising in EAPS, in large part because the department was fortunate enough to receive four seven-figure gifts to establish new funds: the Peter H. Stone and Paola Malanotte Stone Professorship Fund, the Norman C. Rasmussen Fellowship Fund, the Callahan-Dee Fellowship Fund, and the A. Neil Pappalardo Fund for EAPS. The department also received seven other six-figure gifts to support EAPS research and fellowship funds, including the Whiteman Fellowships, the J.H. and E. V. Wade Fellowship Fund, the Frederick A. Middleton (1971) Fellowship, a new EAPS Graduate Student Support Fund, and major grants from the Simons Foundation for Origins of Life Research. New gifts and pledges to EAPS for FY15 totaled $13.45 million, representing a 222% increase over FY14.

Senior Development Officer Angela Ellis has focused her fundraising energies on fellowships, meetings with alumni and friends, stewardship of major donors, and outreach events. In April 2015, the department launched the EAPS Patrons' Circle to celebrate donors who have given $70,000 or more toward endowed or expendable fellowships for EAPS graduate students. EAPS Visiting Committee member Neil Rasmussen '76, SM '80, graciously agreed to be the Founding Chair of the Patrons' Circle and spoke passionately at the inaugural event about the importance of funding future leaders to act as trusted scientific advisors to government and industry partners, especially on societal issues such as climate change and natural hazards. Forty-five

Patrons, students, and faculty enjoyed the event, hearing compelling stories from four graduate fellows about their paths to MIT. The department's first Madden Fellow was also introduced to some of the leadership donors whose gifts had helped the Theodore Madden '49 Fellowship Fund reach its $1 million threshold during the prior year.

In April, President and Mrs. Reif, Vice President for Research Maria Zuber, and School of Science Dean Michael Sipser joined EAPS faculty and friends for a special reception, held in the Ida Green Lounge, to honor Emeritus Professor Peter H. Stone and Professor Paola Malanotte Stone (Rizzoli), and to celebrate their generous gift of a new professorship for EAPS. Other notable events for EAPS alumni and friends during the past year included the Fourth Annual Carlson Lecture (a community event). Hosted by the Lorenz Center and funded by John Carlson, this public lecture was attended by more than 200 people, followed by a special dinner that provided opportunities to thank current major donors to the Lorenz Center and EAPS and to meet potential new supporters.

Throughout the year, EAPS faculty members have been invited to lead tours with the MIT Athletic Association travel program, and to give talks to MIT alumni in Denver, CO, Palo Alto, CA, Berlin, and at home in Cambridge, at the Emma Rogers Society Annual Lunch and the School of Science breakfast series. EAPS alumni and friends also had the opportunity to network and to meet Department Head Rob van der Hilst and other EAPS faculty members at receptions held at the annual Society of Exploration Geophysicists and AGU meetings. Events such as these offer valuable opportunities for EAPS leaders and staff to meet with alumni and friends, to share news about the department, and to make helpful connections for future fundraising efforts.

The senior development officer has also worked closely with colleagues in the School of Science and in MIT Resource Development during the past year to share news about EAPS research and current fundraising priorities (e.g., through regular meetings, the "Campaign Toolkit," and so on), and to foster awareness and excitement about EAPS research among MIT fundraisers, MIT alumni, and new prospects. Discussions have been taking place with fundraising colleagues about potential prospects for a proposed new EAPS building, and a draft case statement has been prepared in the hope that the building will become an institutional fundraising priority. Sustainability and climate research and education remain among the areas of greatest interest to MIT alumni and friends, and in FY15 four gifts ($4.6 million in total) were directed to the support of graduate students whose work is focused in these important areas. The department is confident, as EAPS research, and the achievements of the department's faculty and students become more widely known, that philanthropic support for EAPS will continue to gain momentum as MIT frames its response to the climate challenge.

Faculty Research Highlights

Richard Binzel

Professor Binzel is working with graduate student Alissa Earle to complete preparation for the July 2015 New Horizons mission to Pluto through the analysis of images received while the craft is inbound, on approach. These images are being used to examine Pluto for seasonable variations, using maps of Pluto that Binzel made in the 1990s as a basis for comparison.

In a project spanning EAPS and AeroAstro, Binzel is overseeing the final assembly of the student-built Regolith X-ray Imaging Spectrometer (REXIS) instrument. REXIS is scheduled for launch in September 2016 aboard NASA's Origins Spectral Interpretation Resource Identification Security Regolith Explorer (OSIRIS-REx) asteroid sample return mission.

Tanja Bosak

During the past year, experimental work in Professor Bosak's group, in collaboration with Professor Perron, has demonstrated the dependence of microbial ecology, morphology, and biogeochemical activity on sediment reworking and flow (Liang et al., 2014; Mariotti et al., 2014a, 2014b, submitted).

Her group has also described a previously unknown mechanism for microbially mediated production of macroscopic sedimentary features in sand. These features include simple horizontal trails that were previously attributed to early animal locomotion and used to argue for the presence of moving macroscopic organisms as far back as the Paleoproterozoic (Mariotti et al., 2014b, submitted)].

Their studies of fossils preserved in carbonate rocks during a Snowball Earth event identified a new fossil that resembles some modern red algae (Cohen et al., in press).

A collaboration investigating the evolution of microscopic eukaryotes related the evolution of some testate amoebae to changes in the cycling of carbon and silicon in the Phanerozoic (Lahr et al., submitted).

In collaboration with Professor Roger Summons and postdoctoral associate Dr. Florence Schubotz, members of the Bosak Group studied phosphate-lacking lipids that are abundant in various oxygen-deficient waters and sediments where phosphate limitation is not thought to be a major environmental stress. Results showed that sulfate-reducing bacteria produce phosphate-lacking lipids when limited by phosphate (Shubotz et al., in preparation), thereby alleviating the requirement for phosphate in phospholipids. During her sabbatical in Berkeley, CA, Professor Bosak investigated various genes responsible for the synthesis of these lipids.

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B. Clark Burchfiel

Professor Burchfiel continues to carry out geological research in China, Eastern Europe, and Scandinavia.

References

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Edward Boyle

Professor Boyle's group submitted a manuscript on the first-ever lead isotope data from the Indian Ocean. The data showed that the surface layers have a distinctive isotope composition that matches the anthropogenic aerosols from that region. They also showed a clear difference in isotopic composition throughout the entire water column between the Arabian Sea and the Bay of Bengal that the group attributes to isotope exchange with sinking crustal and anthropogenic particles. In the Southern Ocean sector, the isotopic composition was consistent with natural crustal lead isotope values (Lee et al., in press).Completing almost two decades of research at the Hawaii Ocean Timeseries station, Professor Boyle's group submitted a manuscript containing the largest number of measurements of the essential ocean micronutrient iron ever gathered from a single site in the ocean, with resolution varying from one day to 15 years. There was as much variability in a week as there was throughout the entire duration of the record. (Fitzsimmons et al., in press).

References

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Daniel Cziczo

Professor Cziczo's group is focused on atmospheric chemistry, specifically the interrelationship of particulate matter and cloud formation. The motivation for their work is that the formation and persistence of clouds is currently the foremost source of uncertainty in our understanding of climate. To reduce this uncertainty, the Cziczo Group utilizes laboratory and field studies to elucidate how small particles interact with water vapor to form droplets and ice crystals. Experiments include using small cloud chambers in the laboratory to mimic atmospheric conditions that lead to cloud formation and observing clouds in situ from remote mountaintop sites or through the use of research aircraft.Since joining MIT, Cziczo's research has expanded to include studies of cloud formation on other planets. These include Mars, because clouds are critical in understanding that planet's water cycle, and exoplanets, because clouds are critical for detection of surface features and, ultimately, their ability to support life.

In the past year, the Cziczo group completed and published three experimental studies broadly concerned with the formation of clouds by various particles of atmospheric importance, with a focus on those created by human activities. While continuing its past activities, the Cziczo group also initiated several new studies. These included:

- Studies of possible cloud formation mechanisms around exoplanets and Mars,
- Development of new instruments for studies of clouds at field sites and from aircraft, and
- A novel study to use atmospheric instruments to retrieve an aerosol record from ice cores.

Professor Cziczo also took the time, during his fall 2014 junior faculty leave, to initiate a new project on determining the organic content of mineral dust aerosol, which is critical to understanding their radiative and cloud formation properties. This was during two months that he spent at the National Oceanic and Atmospheric Administration in Boulder, CO. During two months that Professor Cziczo spent at the Kahlsruhe Institute of Technology in Karlsruhe, Germany, co-hosting an international workshop on aerosol chemistry, he started a new joint project using femtosecond lasers to probe aerosol surfaces.

Research Talks Given in the Past Year

D.J. Cziczo et al., "Combining Field and Laboratory Studies to Understand the Dominant Sources and Mechanisms of Cirrus Cloud Formation," Juelich Research Center Atmospheric Science Seminar, Juelich, Germany, December 2014 (invited).

D.J. Cziczo et al., "Understanding Cloud Formation Using Single Particle Mass Spectrometry," ETH-Zurich Institute for Atmospheric and Climate Science Atmospheric Chemistry Seminar, Zurich, Switzerland, December 2014 (invited).

D.J. Cziczo et al., "Combining Field and Laboratory Studies to Understand the Dominant Sources and Mechanisms of Cirrus Cloud Formation," ETH-Zurich Institute for Atmospheric and Climate Science Colloquium, Zurich, Switzerland, December 2014 (invited).

D.J. Cziczo et al., "Understanding Cloud Formation Using Single Particle Mass Spectrometry," Karlsruhe Institute of Technology Atmospheric Science Seminar, Karlsruhe, Germany, November 2014 (invited).

D.J. Cziczo et al., "Combining Field and Laboratory Studies to Understand the Dominant Sources and Mechanisms of Cirrus Cloud Formation," Telluride Science Research Center, Telluride, CO, August 2014 (invited).

Kerry Emanuel

Professor Emanuel and his research group continued several lines of research and initiated several others.

Graduate student Morgan O'Neill received her PhD for work on the atmosphere of Saturn that became the cover story of an issue of *Nature Geoscience*. O'Neill and colleagues (O'Neill et al. 2015) argue that the recently discovered giant polar vortices on Saturn can be explained by the systematic poleward migration of the cyclonic members of convectively generated vortex dipoles that are strongly evident in Cassini images. O'Neill's two-and-a-half layer model shows which nondimensional parameter regimes are likely to give rise to such features and predicts that we should not see them on Jupiter.

Graduate student Vince Agard and Professor Emanuel continued studying how severe local storms, which produce damaging wind, hail, and tornadoes, respond to climate change.

Graduate student Diamilet Perez-Betancourt and Professor Emanuel are beginning an exploration of the dynamics of spiral rainbands in hurricanes.

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O'Neill, M.E., K.A. Emanuel, and G.R. Flierl (2015), Polar Vortex Formation in Giant Planet Atmospheres due to Moist Convection, *Nature Geosciences* 8:523–526, DOI: 10.1038/ngeo2459

Note: A complete list of 2014–2015 references is available.

Brian Evans

Professor Evans's group studies physical properties of rocks, including elastic and inelastic mechanical behavior and fluid transmissivity, at pressures and temperatures found in the Earth's crust.

Recently, his group has investigated the physical mechanisms of inelastic deformation during rock creep, the interactions among fluids, mechanical loading, and permeability, and relations between inelastic deformation and chemical reactions.

Using techniques borrowed from solid-state device fabrication, graduate student Alejandra Quintanilla-Terminel marked rock samples with grids of titanium/gold metal and then deformed them at temperatures between 400°C and 700°C and confining pressures of 200 megapascals (MPa) to 400 MPa. Comparison of the grids before and after deformation allows strain to be mapped at a scale of 10 micrometers. Combining these measurements with electron-back-scattered diffraction observations and other optical and electron microscopy, researchers in the Evans group are able to determine quantitatively the partitioning of inelastic strain among such mechanisms as twinning, grain-boundary sliding, and dislocation slip. Comparison with similar observations in naturally deformed rocks gives improved understanding of creep and localization in the Earth's crust.

Researchers Dr. Yves Bernabe and Dr. Ulrich Mok used rock physics experiments at reservoir pressures and temperatures to understand the changes in permeability of rock matrices and the transmissivity of joints during the flow of aqueous pore fluids and during rock fracture. These experiments are providing data that are important for such applications as carbon-dioxide sequestration, metamorphic alteration, and reservoir exploitation.

In a project led by Professor Bradford Hager, Professor Evans and co-workers are working with groups led by Professors Herbert Einstein and John Williams (CEE) and Professor German Prieto (EAPS) to investigate the evolution of rock properties during hydrofracture processes in tight reservoirs. The project uses laboratory experiments, microseismic observations, and numerical calculations to describe the changes in the rock mass at several spatial scales. The project is funded by Total.

Raffaele Ferrari

Raffaele Ferrari and his group made significant progress on several lines of research. For example, Professor Ferrari showed that the drop in atmospheric carbon dioxide concentrations during glacial climates are associated with changes in the ocean circulation (Ferrari, 2014).

Together with postdoctoral researcher Dr. Ali Mashayek, Ferrari showed that the waters that sink in the ocean abyss at high latitudes return to the surface along the continental shelves in weakly stratified boundary layers. This is in contrast to the textbook view that these waters come back to the surface uniformly in the open ocean. The new theory appears to be supported by radiocarbon observations and implies that the exchange of carbon between the surface and abyssal ocean is much faster than previously assumed (Ferrari et al., submitted).With graduate student Jörn Callies, Ferrari studied the dynamics of upper ocean fronts, which regulate the exchanges of heat and carbon between the ocean and atmosphere (Callies et al., 2015).

With postdoctoral researcher Alexandre Mignot, Ferrari used a combination of float measurements and numerical models to study phytoplankton blooms in the North Atlantic and their role in driving ocean carbon uptake.

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Glenn Flierl

Professor Flierl has been reassessing the theory of mixing by eddies and turbulence using an exact formalism and providing examples that show in detail how it works for both dissolved substances and for substances that are changing via chemical or biological interactions. This research shows, for example, that eddies do not simply move phytoplankton from regions of high concentration to low ones, but may end up transporting them in directions that depend on where the phytoplankton's predators are.

Researchers in the Flierl group have also been examining a simple model of the co-evolution of predators and prey, showing that it can produce "arms races" in which the traits of the predator change to make them more efficient while those of the prey change to reduce their vulnerability. These changes are temporary and produce a see-saw effect—the predator shifts toward one kind of prey that then decays, while a different kind of prey takes advantage of the reduced grazing pressure; the predator then shifts back. These are really changes in which species is dominant. After longer times and at higher resource levels, the system exhibits speciation with discrete types of organisms.

Flierl has also been working with a company, iGlobe Inc., that produces high-resolution, portable, spherical displays for visualizing climate data and models. Flierl's involvement in the project is in coupling the spherical display with a second display for presenting complementary information, such as images of the vertical structure that corresponds to the global horizontal maps pictured on the sphere.Work is also under way to use the globes to visualize directly data stored in databases so that researchers or educators can generate displays of geophysical data as needed. This project has involved outreach events to schools, the New England Aquarium, and the Cambridge Science Festival.

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Michael Follows

Professor Follows's current research investigates the global ocean cycling of carbon, nitrogen, iron, and other elements on seasonal to glacial–interglacial timescales. His group has a particular focus on the ecology of marine microbes and the cellular-scale physiological traits that govern the microbes' interaction with the environment and one another. The groups' tools are largely idealized theory and numerical simulations, but the group also employs analysis of significant data sets, seagoing observations, and (collaboratively) laboratory culture studies.

This year, the Follows group:

- Developed the first global-scale simulations of mixotrophy (combining photosynthesis and predation) in marine plankton, suggesting that this metabolic pattern may dominate marine primary and secondary production.
- Developed a mechanistic, quantitative physiological modeling framework to describe key traits of microbial populations in ocean models, replacing current "black box" parameterizations. This biologically meaningful platform connects with tools from modern cellular systems biology.
- Contributed modeling support for the interpretation of the Tara global oceans survey of the microbial populations of the surface ocean, the first such survey on a global scale. The expedition identified unique microbial populations and biogeochemical signatures associated with Aghulas rings in the South Atlantic. The Follows group's models have provided an explanation for these features and a contextual support for the sparse observations. Villar et al. (2015) suggest how

the special environment of the rings "filters" the plankton communities passing from the Indian Ocean basin to the Atlantic Ocean basin.

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Gregory Fournier

This was Gregory Fournier's first year as professor of geobiology in EAPS. There have been two appointments to his laboratory—postdoctoral associate Dr. Joanna Wolfe and visiting graduate student Cara Magnabosco.

Professor Fournier's current goals consist of continuing to establish his research group, recruiting postdoctoral associates, graduate students, and undergraduate students. He is also continuing to develop his laboratory's main computational resource, a new18-node bioinformatics computing cluster that is housed at the Massachusetts Green High Performance Computing Center, expanding the software and database resources available, and training personnel in its use.

Particular accomplishments include participation in several invited lectures and events:

- Professor Fournier participated as a speaker and panelist in the MIT Museum Soap Box Series, How to Make Life and Influence Planets, which discussed the coevolution of planetary systems and life across Earth's history.
- During Independent Activities Period, Professor Fournier organized a special departmental seminar on the origin of life, inviting speakers with backgrounds in synthetic biology, prebiotic chemistry, computational biology, and evolution to present their current research and views on the subject.
- Professor Fournier represented MIT at the NASA/Smithsonian Early Earth Exobiology Workshop, held at the Smithsonian Museum of Natural History.
- Professor Fournier was involved in the development of a web-based educational tool with PBS NOVA as part of the Life on Earth Project at Harvard University. The purpose of this tool (Evolution Lab) is to provide a series of games in which students construct evolutionary trees of organisms from biological data, to teach the principles of evolution and deep time.

Fournier's laboratory was awarded a grant this year as part of the Simons Foundation Collaboration on the Origin of Life. The purpose of this five-year award is to use genome-based approaches to investigate a set of questions about early life evolution and the early Earth. These questions cover major aspects of early evolution, including the history of the planetary microbial sulfur cycle, the origin of ancient protein families involved in establishing the genetic code, and the evolutionary rate and divergence times for major groups of microbes, to establish their effects on the establishment of geochemical cycles.

During the spring semester, Professor Fournier and Professor Roger Summons were co-instructors of 12.007 Geobiology: History of Life on Earth. The curriculum was updated to include more detailed aspects of prebiotic chemistry, early life, genomics, and the evolutionary history of major groups of organisms.

Several research projects within Fournier's laboratory were started this year that are supported by departmental start-up funds and are operating in collaboration with research groups at MIT and other institutions:

- Dating the Tree of Life: Using computational techniques and genome sequence data, his project attempts to combine genomic, paleontological, physiological, and geological and geochemical evidence to calibrate the evolutionary histories of major groups of microbes. The object is to estimate both when the groups probably evolved and how their metabolisms influenced the planetary system. So far, this project has focused on the history of Archaea and Proteobacteria, the latter in collaboration with the Polz Laboratory in the Department of Civil and Environmental Engineering. Important findings to date include evidence that many major groups of Proteobacteria likely evolved around the same time as the major lineages of multicellular animals, approximately 700 million to 600 million years ago, during a time of extensive glaciation events, and that one of the most important metabolic pathways on the planet, methanogenesis, likely evolved within Archaea very early in Earth's history, around 3.4 billion years ago. Additional calibrations and the development of more precise models will continue to make these dates more accurate, as well as reveal additional connections between microbial evolution and planetary change.
- Genomes and the Rise of Oxygen: This project, a collaboration between the NASA Astrobiology Institute's Foundations of Complex Life team at MIT and the Alternative Earths team at the University of California at Riverside, together with Professor Roger Summons and postdoctoral associate Dr. David Gold, is designed to investigate the history of the emergence and spread of oxygen-related genes across microbial lineages. Mapping the evolutionary histories of these genes using phylogenies based on genome sequence data reveals how and when major groups of microbes probably first encountered oxygen and adapted to changing levels of oxygen across 2.5 billion years of planetary change. Important preliminary findings of this work include the detection of separate origins for many oxygen-related genes within the photosynthetic cyanobacteria, providing independent evidence that this group pre-dates the rise of oxygen in the atmosphere approximately 2.3 billion years ago. It also seems that many groups of oxygen-using Archaea that live in extremely hot ocean vent environments acquired oxygen-related genes fairly recently (within the past 800 million years), independently supporting hypotheses that the deep sea may have become oxygenated only during a later stage of Earth's history.

Timothy Grove

Professor Grove and his students have completed the first comprehensive investigation of the melting behavior of the upper mantle beneath subduction zone volcanoes as a function of variable temperature, pressure, and water content. Using this new data set in conjunction with results from previous hydrous experimental studies, Grove's team developed a model for estimating the amount of dissolved water and the melt generation temperature of a mantle-derived magma as a function of varying pressure. These findings provide the first quantitative characterization of the influence of the magmatic water content of the composition of melts produced during melting in subduction zones. Because the continental crust is largely produced from the crystallization of arc parental magmas like the ones produced in this study, the work is of importance for understanding how the Earth's continental crust has been generated through time.

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Teaching Activities and MIT Service

Professor Grove taught a graduate class, 12.480 Thermodynamics for Geoscientists, and a Freshman Advising Seminar, 12A03 Meteorite from Mars Kills Dog, in the fall. In the spring, he taught 12.108 Structure of Earth Materials and helped Professor Leigh Royden by providing two lectures for 12.002 Introduction to Geophysics and Planetary Science. Grove also led a seminar with Professor Taylor Perron that prepared undergraduate and graduate students for a field trip to the Sierra Nevada and southern Cascades that will take place in August 2015.

Professor Grove continued as associate department head and worked to improve the EAPS graduate and undergraduate programs. This year's efforts included developing collaborative teaching in geobiology with the Biology Department, implementing a new set of graduate admissions procedures, and working with junior faculty members on graduate and undergraduate teaching efforts. He continues to explore joint educational efforts in the area of geobiology and the environment with the Department of Biology and the Department of Civil and Environmental Engineering.

Other Service and Community Outreach

The AGU has appointed Professor Grove to Chair the AGU Task Force on Privacy. Professor Grove also serves on AGU's Development Board.

Professor Grove serves as Chair of the Joint Committee for Marine Geology and Geophysics in the MIT/WHOI Joint Program.

Professor Grove was a member of MIT's Innovation Deficit Committee, chaired by Marc Kastner, which produced a report titled The Future Postponed. He contributed a chapter on space exploration. The report, which is aimed at the 2016 presidential candidates, makes the case that reductions in federal funding are causing the US to fall behind in science and technology.

Professor Grove continues as executive editor for *Contributions to Mineralogy and Petrology* and serves as an editor for the *Proceedings of the National Academy of Sciences*.

Bradford Hager

Professor Hager's research involves understanding dynamic processes in the interiors of the Earth and other rocky planetary bodies on spatial scales that range from reservoirs to the whole Earth and time scales that range from the present to the age of the solar system. Most of his work focuses on the relationship between observations of surface deformation, pore fluid pressure changes, earthquakes, and geodynamical or geomechanical processes. Hager has expertise in tectonic earthquakes in regional fault systems, as well as in deformation, gravity changes, and earthquakes induced by reservoir production. He is also leading a multidisciplinary investigation of the fundamentals of hydrofracturing.

Professor Hager's most important current research focuses on two areas:

- The first area of effort is in developing a mission jointly sponsored by NASA and its Indian counterpart, ISRO, to fly a dual L- and S-band interferometric synthetic aperture radar (InSAR) satellite dedicated to observing surface deformation, ice sheet motions, and above-ground woody biomass. This mission, now called NISAR, will be the most advanced InSAR mission ever flown. Hager is co-chair of the NISAR Science Study Group, responsible for earthquake, hydrocarbon, and carbon sequestration applications. NISAR has just been given the go-ahead to proceed to Phase B.
- The second area of effort is devoted to understanding earthquakes that are induced or triggered by human activities, including hydrocarbon production, carbon dioxide sequestration, hydroelectric reservoirs, and the pumping of aquifers. Hager's group has carried out the first fully coupled poroelastic model of the tragic 2011 earthquake in Lorca, Spain, and has demonstrated that the changes in coulomb stress from the pumping of a nearby aquifer likely triggered the event. Hager has participated in an industry-funded effort to assess the triggering of past and future earthquakes in Italy associated with hydrocarbon production and wastewater injection. He leads a project assessing how to minimize earthquake risks associated with production of natural gas in the Netherlands.

Thomas Herring

Professor Herring is using GPS data to develop geophysically based models of Earth deformations on the global, regional, and local scales and of changes in the rotation of the Earth. He is also using InSAR to study small surface deformations and geodetic methods to study Earth's gravity field.

The Herring group is using high-precision GPS measurements in many different study areas, including much of the southern Eurasian plate boundary and the western United States. Group members are investigating processes, on time scales of years, that lead up to earthquakes, transient deformation signals lasting days to many weeks, postseismic deformation after earthquakes on time scales of day to decades, and surface wave propagation during earthquakes using high-rate GPS data and ice dynamics. All of these measurements are precise to a range of submillimeters to a few millimeters. The group is also monitoring and modeling human-induced deformations in hydrocarbon fields and on tall buildings, including the Green Building at MIT.

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Oliver Jagoutz

Members of the Jagoutz group continued their research on the formation and evolution of the continental crust.

Professor Jagoutz has been working in the Himalayan mountains of northeastern India since approximately 2008 to unravel the history of the ocean that separated India and Eurasia before the India–Eurasia collision. Jagoutz and, among others, MIT colleague Professor Leigh Royden showed that their precollisional scenario, developed from their field work, could explain the unusually fast drift velocity of India during its trajectory to Eurasia (Jaboutz et al., 2015). Their numerical simulations indicated that the anomalously high drift velocity of India between 80 million to 50 million years ago was the result of complex interactions between two subduction systems. The paper was highlighted in a "News and Views" article in *Nature Geoscience* and has been covered by *MIT News* and the wider media including, among others, the *New York Times*.

Graduate student Claire Bucholz completed her PhD work at MIT and has accepted a faculty position at the University of Southern California.

Third-year PhD student Benjamin Klein and Professor Jagoutz are studying how magmatic processes in the deep crust of arcs form continental crust.

Incoming graduate student William Shinevar and Professor Jagoutz will work on an algorithm to convert seismic properties to chemical compositions to better constrain the compositional variations in the lower continental crust.

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Note: A complete list of 2014–2015 references is available.**John Marshall**
John Marshall and his research group continued several lines of research.

Professor Marshall's collaborative project, with Research Scientist Dr. David Ferreira and Professors Alan Plumb and Susan Solomon, on the climatic implications of the ozone hole led to an important publication in the *Journal of Climate*. The response of the Southern Ocean to a repeating seasonal cycle of ozone loss was found to comprise both fast and slow processes—rapid cooling followed by slow but persistent warming. This work may account for the observed increase in Antarctic sea ice over the past few decades, in contrast to declines in Arctic sea ice (Ferreira et al., 2015).Graduate students Yavor Kostov and Brian Green are progressing well with their theses. Kostov, who is studying the role of the ocean in transient climate change, expects to graduate by the end of 2015.

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David McGee

Professor McGee's research continues to focus on understanding the response of precipitation patterns to past climate changes. The goal is to offer insight into the sensitivity of the hydrological cycle to changing forcing and boundary conditions.

Two recent papers from his group—one whose first author was graduate student Elena Steponaitis and a second that is currently in press—use stalagmites from a Nevada cave to reconstruct past shifts from wet to dry conditions in the US Great Basin. The records, anchored by high-precision uranium-thorium dating from McGee's laboratory, document systematic relationships between high-latitude conditions in the northern hemisphere and western US precipitation. In both the current interglacial period and the penultimate interglacial, warming of the high latitudes is associated with pronounced drying, shown in the magnesium/calcium ratios recorded in the cave's stalagmites.

Field work conducted this winter in northern Chile with graduate student Christine Chen laid the groundwork for studies of past precipitation changes in the Altiplano and Atacama region. Chen and McGee mapped and sampled ancient shorelines in hydrologically closed basins. Precise dating of these shorelines in McGee's laboratory has now enabled him to tie wet periods in the Atacama to northern hemisphere cool periods with confidence.

Other 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.

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Frank Dale Morgan

Frank Dale Morgan's research scope includes the exploration for potable river water and groundwater in the island of St. Lucia, innovating new electronics and field deployment methodologies for spectral induced polarization, and electrochemical causes of earthquake inception.

Paul O'Gorman

Paul O'Gorman and his group have continued to investigate how the atmosphere behaves in different climates.

In a paper published in *Nature*, Professor O'Gorman investigated heavy snowfall events in climate-model simulations and observations. An optimal temperature for heavy snowfall was shown to be a key factor for the behavior of snowfall in different climates. In particular, snowfall extremes were found to be less sensitive to climate warming, as compared with seasonal snowfall accumulations, in many cases (O'Gorman, 2014).

Graduate student Michael Byrne received his PhD for his dissertation research on land–ocean contrasts in the climate system. Byrne's research explains why the prevailing paradigm for the response of precipitation to climate warming—wet-gets-wetter, dry-gets-drier—is not applicable over land (Byrne and O'Gorman, in revision).

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Shuhei Ono

Professor Ono and his research group continued several lines of research focusing on stable isotope geochemistry.

Graduate student Andrew Whitehill received his PhD for his dissertation research on mass-independent sulfur isotope fractionation that demonstrated its origin and link to historic stratospheric volcanic events (Whitehill et al., 2015).Professor Ono's group has developed a novel laser spectroscopy instrument to measure doubly isotope-substituted methane ($^{13}CH_3D$) and used the instrument to test the origins of methane from diverse settings. With graduate students David Wang and Danielle Gruen, together with postdoctoral associate Dr. Eoghan Reeves, Ono published the initial results in the journal *Science*. The research was highlighted in MIT news and the wider media (Wang et al., 2015).

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Note: A complete list of 2014–2015 references is available.

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, climate's effects on erosion, and the landscapes of Mars and of Saturn's moon Titan.

Graduate student Kimberly Huppert, in collaboration with Professor Perron and Professor Leigh Royden, helped to resolve a controversy concerning the mechanisms that control how volcanic islands above mantle "hot spots" uplift and subside over millions of years. After assembling a data set of hundreds of uplift and subsidence rates for the Hawaiian Islands, based on tide gauge records and ancient shorelines and coral terraces, they found that nearly all of the vertical motion of the various islands, from the rapid subsidence of Big Island of Hawaii to the slight uplift of Oahu, is explained by the loading of Earth's lithosphere by the massive volcanoes themselves (Huppert et al., 2015).Dr. Giulio Mariotti, the department's first W.O. Crosby Postdoctoral Fellow, collaborated with Professor Perron and Professor Tanja Bosak to study how microbial processes shape sedimentary features in the geologic record. In a laboratory experiment conducted in repurposed fish tanks, they showed that "wrinkle structures"—widespread, millimeter- to centimeter-scale, ripple-like features preserved in sedimentary rocks—were probably created by wave transport of microbial mat fragments, making them early macroscopic evidence of life's interaction with its physical environment (Mariotti et al., 2014). Mariotti received the Luna B. Leopold Young Investigator Award at the December 2014 AGU Annual Meeting.

In complementary work, MIT/WHOI Joint Program graduate student Jaap Nienhuis, postdoctoral researcher Dr. Justin Kao, and Professor Perron published the first complete explanation for the spacing of sand ripples created by waves, like those commonly found at beaches around the world (Nienhuis et al., 2014).

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R. Alan Plumb

Professor Plumb and his graduate students have continued to investigate several aspects of stratospheric dynamics—in particular, their impact on surface climate. Using a general circulation model, graduate student Aditi Sheshadri has shown how wave forcing from the lower atmosphere determines not only the seasonal climatology of the stratosphere but also its interannual variability. She has also shown how Antarctic ozone depletion impacts surface winds in the southern hemisphere. Using the same model, graduate student Erik Lindgren is investigating how even very high-altitude perturbations associated with solar variability can lead to surface impacts.

The surface impact of stratospheric variability is most evident during spectacular events known as stratospheric warmings. One especially dramatic event occurred in January 2013 when the polar vortex split in two, a signal that was observable all the way down to the surface. Graduate student Andreas Miller has shown that, contrary to conventional wisdom, internal stratospheric dynamics were responsible for this split and, ultimately, for the surface impact.

Graduate student Marianna Linz is investigating how observations of trace gases can be used to quantify the overturning circulation of the stratosphere. She is especially interested in how such observations might be used to validate model predications of an accelerated circulation in response to increasing greenhouse gases.

Germán A. Prieto

Professor Prieto's group is focusing on developing tools to analyze ever-larger earthquake data sets, both worldwide and local. The first graduate student in Prieto's group, Manuel Florez, just passed the general examination. Florez has been working on a technique to locate deep earthquakes better. The method is adaptable and has the potential to locate smaller events that may help delineate the seismicity deep inside the Earth.

In collaboration with various students and postdoctoral associates, the Prieto group's postdoctoral associate Dr. Piero Poli has worked to describe the earthquake rupture of large deep teleseismic earthquakes better. Results suggest different behavior of these deep earthquakes compared with what is seen for shallow events. This suggests that that earthquake rupture of deep earthquakes may respond to a different physical mechanism than is true of shallow earthquakes (Poli and Prieto, 2014).In a continuation of this work, Prieto and Poli have submitted a paper to *Geophysical Research Letters* about a large earthquake in the Bucaramanga Nest, the highest concentration of deep earthquakes in the world. The observations they have made with global stations and the local stations they deployed have allowed them to describe the rupture process with unprecedented detail. A similar approach was used to study a deep earthquake in the middle of the US (Froment et al., 2015).

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Ronald G. Prinn

Professor Prinn reports that the Center for Global Change Science, its Joint Program on the Science and Policy of Global Change, and its Advanced Global Atmospheric Gases Experiment (AGAGE), which he directs, produced more than 70 peer-reviewed scientific papers in the past year. Details of these accomplishments are available at the three websites. Five new federal grants and five new industry donors have joined as sponsors of the work. Research spending continues at about $9.5 million annually.

The AGAGE network has expanded into Africa; the first set of greenhouse gas and climate instruments are now operating in the new Rwanda Climate Observatory. This work involved EAPS doctoral candidate Jimmy Gasore.

In addition, the first high-frequency measurements of the isotopic composition of the greenhouse and ozone-depleting gas nitrous oxide have begun at the Ireland AGAGE station. This work involved EAPS doctoral candidate Mr. Michael.

Paola Rizzoli

Professor Paola Rizzoli and her collaborators, Research Scientists Drs. Jun Wei, Pengfei Xue, Danya Xu, and Haoliang Chen, continued their research on the South China Sea and Indonesian Through Flow. They have been reconstructing the climate and circulation of the basin over the four decades from 1960 to 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 (Xu and Malanotte-Rizzoli, 2013), (Chen, Koh, Malanotte-Rizzoli and Guiting, 2014).Professor Rizzoli's second major focus has been the collaboration with Professor Eltahir's group (Department of Civil and Environmental Engineering) in the coupling of Rizzoli's ocean model with Eltahir's atmospheric model for simulations of the present climate of the Southeast Maritime Continent. The two-way coupling has been successfully completed and the results have been compared with available oceanographic and atmospheric climatological observations (Wei et al., 2013). The investigation has been extended to include seasonal and intraseasonal variability (Wei et al., 2014). In addition, negative feedback mechanisms between the atmosphere and the ocean have been identified that correct for negative or positive biases in oceanic and atmospheric variables (Xue et al., 2014).

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Daniel Rothman

Professor Rothman has initiated a new project aimed at developing understanding of the stability of the Earth system, Earth's physical environment, and the life that it supports. Each of the great mass extinctions in Earth history was coincident with a strong perturbation of Earth's carbon cycle, yet many such perturbations are not associated with mass extinction. What makes them different? Preliminary results, both empirical and theoretical, suggest the existence of a critical rate of carbon-cycle change beyond which mass extinction occurs. The results of this work should help inform our understanding of the long-term risks posed by modern environmental change.

Rothman's group also continues to develop a basic understanding of the ways in which the emergence of groundwater at the Earth's surface leads to channelized networks. A few years ago, the group showed that such networks tend to ramify at angles of 2 pi/5 = 72 degrees. Recent work with postdoctoral associate Dr. Hansjorg Seybold shows that this prediction holds wherever climates are sufficiently humid, thus establishing a quantitative connection between the geometry of landscapes and the climate in which they form.

Leigh Royden

Professor Leigh Royden's work focuses on understanding the large-scale processes in the crust and mantle that control the regional deformation of active tectonic systems, and, more recently, the global processes that organize plate tectonics.

Royden has worked on a wide variety of sedimentary basins because the vertical motion at the Earth's surface contains important information that constrains processes within the lithosphere.

Royden's main geographic areas of study are the Tibetan plateau, the Himalaya, and Tibet, although she has worked in a variety of other regions. Through this work she has demonstrated, among other things, the functioning of coupled thrust-belt and back-arc tectonic systems, anomalous and rapid removal of mantle lithosphere during extension, the surface expression of slab pull in continental systems and its influence on regional processes of mountain building, the lateral flow of deep continental crust on a scale of hundreds of kilometers, the thermal and metamorphic histories of a variety of orogenic systems, and the role of double subduction in driving rapid plate convergence.

Royden's most significant work over the past year—work that has absorbed nearly all of her research effort—has been establishing an analytical technique for handling multiple subduction systems. The first results were reported in a paper written with Professor Oliver Jagoutz and others (Jagoutz et al., 2015). The paper shows that the anomalously rapid motion of India relative to Eurasia can be explained by the documented history of subduction, which includes double subduction, and by the timing of arc-continent collisions that occurred east and west of India just prior to the onset of rapid convergence.

The double-subduction method is currently being applied to examining various general geometries of double subduction. Comparison with numerical models is being carried out by Professor Thorsten Becker of the University of Southern California. The Becker group is exploring how the method can be applied to multiple subduction systems on a sphere, which will make it possible to examine the organizing principles of global plate systems. This is especially exciting because the analytic method is so fast compared with the numerical methods. (For one sample run for 10 million years, the analytical method takes 1.5 seconds on a standard laptop; the same experiment using the numerical method takes three days on a supercomputer.)***References***Jagoutz, O., L. Royden, A. Holt, and T. Becker (2015), "Anomalously Fast Convergence between India and Eurasia Linked to Double Subduction," *Nature Geo.* 8:475-478, DOI: 10.1038/NGEO2418

Hilke Schlichting

Hilke Schlichting's research focuses on planet formation theory, extrasolar planets, and solar system dynamics. She studies the solar system, because it is the only place where the outcome of planet formation can be examined in detail, and she uses the diversity and statistical properties of extrasolar planets to test planet formation theories. Her research over the past year has focused on understanding the formation of a new class of planets discovered by the Kepler Space mission—planets that are typically several times more massive than the Earth but that orbit their host stars well inside the orbit of Mercury. Understanding the origin of this new and ubiquitous class of planets is crucial for determining the key processes of planet formation and for assessing the suitability of these bodies to harbor life. Schlichting's recent work has demonstrated that migration of either fully formed planets or of solids in the proto-planetary disk must have played a key role in their formation (Schlichting, 2014).With graduate student Niraj Inamdar, Professor Schlichting also investigated atmospheric mass loss caused by giant impacts that likely took place in the final assembly stage of these close-in exoplanets. Inamdar and Schlichting have shown that atmospheric mass loss was significant and that initial planetary atmospheres were likely much more massive than those that are observed today (Inamdar and Schlichting, 2015).

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Sara Seager

Sara Seager's main research focus is on exoplanet atmospheres and biosignature gases—gases that could be observed in the future in exoplanet atmospheres that might be attributed to life.

Professor Seager is also involved in the search for exoplanets and her focus this year has been on two future space missions.

The first is the NASA "Probe-Class" Starshade study that Seager chaired for two years, ending in March 2015. The Starshade team comprised individuals from academia and NASA centers with a design team from NASA's Jet Propulsion Laboratory. The Starshade is a specially shaped screen, tens of meters in diameter, that would fly in space at distances of tens of thousands of kilometers from a space telescope with the goal of blocking starlight so that an orbiting plant would be visible in reflected light. The ultimate goal is to be able to image Earth-size planets orbiting Sun-size stars; a few such planets would be discoverable with a Starshade and a small telescope. The study has issued a final report.

Seager also co-chaired a two-year study that ended in July 2015 on the high definition space telescope. Such a telescope would come after the Starshade mission and would be the largest space telescope ever launched for astronomy, with an aperture diameter of 12 meters. The high-definition space telescope would be capable of searching hundreds of sun-like stars in a direct imaging search for planets of Earth's size or larger, with an anticipated yield of dozens of terrestrial planets and the revolutionary capability to observe down to a spatial scale of 100 parsecs at all distances. The study's report was initiated and sponsored by the Association of Universities for Research in Astronomy. Seager is also a leading co-investigator on the MIT-led NASA Mission Transiting Exoplanet Survey Satellite (TESS); the principal investigator is George Ricker of the MIT Kavli Institute for Astrophysics and Space Research. Mission TESS is scheduled for launch in 2017. Professor Seager's responsibility is to help plan and run the MIT TESS Science Center, which will deliver light curves to the community as well as to the TESS Team for assessment of the best planet candidates for follow-up mass and atmosphere measurements. Mission TESS, combined with the James Webb Space Telescope (scheduled for launch in 2018), will provide the first opportunity to search for life in the atmospheres of rocky exoplanets.

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Professor Seager's research group published several papers on exoplanets, habitability, and biosignature gases:

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- Kreidberg, L., J.L. Bean, J.M. Desert, B. Benneke, D. Deming, K.B. Stevenson, S. Seager, Z. Berta-Thompson, A. Seifahrt, and D. Homeier (2014), "Clouds in the Atmosphere of the Super-Earth Exoplanet GJ 1214b," Nature, 505 (7481):69–72, DOI: 10.1038/nature12888
- Seager, S. (2014), The future of spectroscopic life detection on exoplanets, Proceedings of the National Academy of Sciences of the United States of America, 111(35):12634–12640, DOI: 10.1073/pnas.1304213111

Susan Solomon

Susan Solomon and her research group focus on atmospheric chemistry and its interactions with climate change, as well as on particulate matter produced in air pollution.

A recent paper published in *Environmental Science and Technology* provided game-changing new results on how the sensitivity of aerosols smaller than 2.5 microns (PM2.5) to emissions of nitrogen and sulfur oxide pollution has changed since 2005. The group has shown that over much of the American Midwest, nitrogen oxide controls could now reduce PM2.5 much more effectively than before because of a regime shift in nonlinear chemical processes. PM2.5 is of particular importance because of its damaging effects on human health, including respiratory ailments and death (Holt et al., 2015).

Another recently published paper in *Geophysical Research Letters* has demonstrated that the influence of minor volcanic eruptions on climate change since 2000 has been greatly underestimated. This is because of the important role played by stratospheric particles at altitudes that are not generally sampled in the satellite data used to estimate their abundance. This paper is of special importance given the need to explain recent rates of change of atmospheric temperature, sometimes referred to as the "warming hiatus" (Ridley et al., 2015).

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Roger Summons

Members of Roger Summons's laboratory continued their studies of molecular and isotopic biosignatures from sediments, sedimentary rocks, environmental samples, and microbial cultures. The overall aim of this work is to discern clues about the nature of early life on the Earth and the environmental transitions that permitted the development of complex life.

MIT/WHOI Joint Program graduate student Katherine French completed her research on the search for hydrocarbon biomarkers from 2.7-billion-year-old sediments (French et al., 2015), disproving some of her advisor's prior work from 15 to 20 years ago. Ainara Sistiaga, a student visitor from the Universidad de La Laguna, La Laguna, Spain, successfully defended her thesis in the spring and published her work on the diet of Neanderthals, based on studies of faecal sterols (Sistiaga et al. 2014, 2015).

Summons co-chaired a NASA study panel that defined contamination requirements for the Mars 2020 mission and potential sample return (Summons et al., 2015). Summons will spend the 2016 academic year as Cox Visiting Professor at Stanford University in the Department of Earth System Science in the School of Earth, Energy and Environmental Sciences.

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Benjamin P. Weiss

Professor Weiss and his group are interested in the formation and evolution of terrestrial planets and small bodies, with particular focus on planetary differentiation, paleomagnetism, meteoritics, and habitability. In the past several years, they have been studying the history of the lunar dynamo (Weiss and Tikoo, 2014), the nature of planetesimals (Weiss and Elkins-Tanton, 2013), and nebular magnetism in the early solar system (Fu et al., 2014).

The group's most important work in the past year was to make the first determination of magnetic field strength in the planet-forming region of a protoplanetary disk (Fu et al., 2014). Obtaining such a measurement has been one of the defining goals of the field of extraterrestrial paleomagnetism since it was founded five decades ago; it has major implications for the formation of terrestrial planets in the universe. Using newly developed experimental techniques, the Weiss group demonstrated that chondrules in the Semarkona meteorite were magnetized in a substantial nebular magnetic field. Previous paleomagnetic experiments were unable to isolate nebular magnetization; current astronomical observations cannot constrain the magnetic fields in the midplane of protoplanetary disks within several tens of astronomical units of the star where planet formation occurs.

This work holds broad implications for diverse disciplines. For the astrophysical community, magnetic fields are widely believed to play a critical role in protoplanetary disk evolution; their presence may explain the rapid redistribution of mass and angular momentum, the presence of turbulence, and the observed ubiquity of planet-forming disks. The Weiss group's results offer, for the first time, direct constraints on the nebular field strength and therefore reinforce the importance of magnetic phenomena in protoplanetary disks. For the planetary science community, the group's identification of nebular magnetization in chondrules provides novel constraints on the mechanism and conditions of chondrule formation, a critical and poorly understood step in the evolution of solid bodies in planetary systems.

For the paleomagnetic community, the Weiss group's measurements represent the earliest recovered paleomagnetic record, the first paleomagnetic determination of nonplanetary magnetic fields, the first in-depth paleomagnetic study of a new class of planetary materials, and the development of a suite of new microsampling and high-sensitivity magnetometry techniques.

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Jack Wisdom

Professor Jack Wisdom has been studying the early evolution of the Earth-Moon system after the giant impact that is presumed to have formed the Moon. Isotopic similarities of the Earth and Moon suggest that the Moon-forming impact was more severe than previously thought, but this would leave the system with too much angular momentum. Professor Wisdom and graduate student Zhen Liang Tian have recently found that the Earth-Moon system can be captured into a limit cycle associated with the evection resonance that removes the excess angular momentum. More work remains to be done.

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