Department of Earth, Atmospheric and Planetary Sciences

The Department of Earth, Atmospheric and Planetary Sciences (EAPS) studies the Earth, planets, climate, and life and has broad intellectual horizons encompassing the solid Earth, its fluid envelopes, and its 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. In academic year 2018, the department's faculty comprised 42 members, including three with a primary appointment in the Department of Civil and Environmental Engineering (CEE), one with a primary appointment in the Institute for Data, Systems, and Society (IDSS), one with a primary appointment in the Department of Aeronautics and Astronautics (AeroAstro), and another with a primary appointment in the Department of Mathematics. There were also more than 310 research staff, postdoctoral associates, and visiting scholars.

EAPS is noted for its emphasis on interdisciplinary problems and is involved in numerous laboratories, centers, and programs that address broad questions in the Earth sciences, including those that are among the most pressing societal issues of our time: changes in the 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 Laurent Demanet) integrates faculty, staff, and students across disciplinary, departmental, 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 (under the co-directorship of Professors Kerry Emanuel and Daniel Rothman) aspires to be a climate think tank devoted to fundamental scientific inquiry. Furthermore, EAPS is MIT's largest participant in the MIT-Woods Hole Oceanographic Institution (MIT-WHOI) Joint Program for graduate education and research in ocean sciences and engineering.

Educational Activities

EAPS faculty is committed to the development and maintenance of vibrant education programs at both the undergraduate and graduate level. Student engagement with the education program is a continuing departmental goal. Graduate students meet with the department head and associate head at least once per term to discuss concerns and issues arising in their respective programs with the goal of sustaining active and open conversations 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 2017, the Committee on Graduate Programs approved a joint proposal from EAPS and the Woods Hole Oceanographic Institution (WHOI) to add biological oceanography as a thesis field in the department. This addition gave five students the ability to move from the Department of Biology at MIT to EAPS as their home department, which aligned their biology, ecology, and physiology research with an oceanographic focus. In fall 2017, EAPS had 140 graduate students (134 PhD students and six SM students) registered in the department, including 72 students in the MIT-WHOI Joint Program and three fifth-year master's degree students. Of these, 51% were women and 7% 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 their 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 the newcomers to EAPS, MIT, and 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 departmental Graduate Student Mentoring Program continues to be a well-received approach to providing peer support for new students.

EAPS awards an annual prize for excellence in teaching to highlight the superior work of its teaching assistants. During academic year 2018, Marjorie Cantine and Margaret Duffy were recognized for their contributions.

EAPS students were also recognized by MIT and their respective professional societies and outside organizations. Tom Beucler was a finalist for the Climate Changed Ideas Competition; he also received the Best Poster prize for Preparing MIT for 2050 Floodwaters at the MIT Water Night. Beucler was awarded an American Geophysical Union 2017 Editor's Citation for Excellence in Refereeing; is the recipient of a graduate research fellowship in the Program on Mathematical and Statistical Methods for Climate and the Earth System at the Statistical and Applied Mathematical Sciences Institute in North Carolina; and was a 2017 summer fellow at the Les Houches Summer School on "Fundamental Aspects of Turbulent Flows in Climate Dynamics." William Corlett received the Mark B. Bain Graduate Fellowship from the Hudson River Foundation. Zahra Essack received a motion of congratulations from the National Assembly of the Parliament of South Africa in recognition of her master's degree research in developing an algorithm to detect exoplanets in transit light curves. Manuel Florez Torres was honored by the Seismology Society of America for contributing one of the best student presentations at the society's 2017 annual meeting. Daniel Gilford and Clara Maurel received Outstanding Student Presentation Awards from the American Geophysical Union. Sam Goldberg was awarded a NASA Earth Systems Science graduate fellowship. Clara Maurel was awarded an Outstanding Student Presentation Award from the American Geophysical Union and the Amelia Earhart Fellowship from Zonta International. Maya Stokes was awarded a Hugh Hampton Young Fellowship and was named a Martin Family Sustainability Fellow.

Twenty doctoral students and seven master's degree students graduated from EAPS in AY2018.

Undergraduate Program

EAPS had 20 students who were undergraduate majors in AY2018. Of these, 60% were women and 30% percent were members of an underrepresented minority group.

The EAPS undergraduate population has always been small but student satisfaction is high. The department increased its efforts to have more students majoring in EAPS in AY2018. For example, EAPS launched new degree requirements for the major that offer students four concentration areas to choose from:

- Geoscience: geology, geochemistry, geophysics, and geobiology
- Atmospheres, oceans, and climate
- Planetary science and astronomy
- Environmental systems

This reorganization of the major has been well received by students who find the subject selection easier to navigate. Other activities include monthly lunch seminars for undergraduates that expose them to different resources at MIT (such as Global Education and Career Development, Mind Hand Heart, and so on), events for incoming freshmen, involvement through freshman advising and teaching beyond EAPS, widened use of social media, and increased visibility on campus.

The department maintains a strong presence in undergraduate education across MIT so that the general student body has ready access to education in geoscientific aspects of climate and environmental change, natural hazards, and natural energy resources. For example, Mick Follows co-taught an ecology class with CEE. Susan Solomon co-taught an environmental history course with the Department of History and an environmental governance class with the Sloan School of Management and IDSS.

EAPS faculty members with joint appointments (Kerri Cahoy, Noelle Selin, Collette Heald, Ruben Juanes, Dara Entekhabi, and Laurent Demanet) are also active in teaching undergraduates. The department supports and provides leadership for two major undergraduate programs at MIT: Terrascope (under the directorship of Professor David McGee) and the Experimental Studies Group (under the directorship of Professor Leigh Royden). EAPS also offers freshman advising seminars and freshmen pre-orientation programs. With the combined enrollment of Terrascope, the advising seminars, and the Experimental Studies Group, EAPS connected weekly with 10% of the students in the freshman class. Similarly, EAPS is an active participant in four interdisciplinary minor programs: the broadly based energy minor, the astronomy minor (with the Department of Physics), the atmospheric chemistry minor (with the Department of Chemistry, AeroAstro, CEE, and IDSS), and the newly launched environment and sustainability minor, which offers courses from 17 departments.

At the 2018 Student Awards and Recognition Dinner, the Goetze Prize was awarded to Elisabeth Boles (advised by Professor Andrew Babbin) in recognition of her outstanding senior thesis. Jonathon Hurowitz received the W. O. Crosby Award for Sustained Excellence, recognizing his achievement, both academic and intellectual, as well as general contributions to the department. Hurowitz was also inducted into the Xi chapter of Phi Beta Kappa. Jordan Benjamin was the recipient of the EAPS Achievement Award, which recognizes a rising senior from across the EAPS disciplines. The award is presented to a student who has distinguished herself or himself through a combination of high grade point average, focused course work, and leadership within EAPS. Lilian Dove received an American Meteorological Society graduate fellowship. Jade Fischer received the Origins of Life Summer Undergraduate Research Award.

Ten students graduated from EAPS with bachelor's degrees in AY2018.

Faculty

The department continues its efforts to hire the best young scientists and help them develop successful careers. For example, astrophysicist Katherine de Kleer will complete a postdoctoral assignment at the California Institute of Technology and join EAPS in July 2019.

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

Promotions

Associate Professor of Atmospheric Science Daniel Cziczo was promoted to the rank of associate professor with tenure, effective July 2018.

Communications

Academic year 2018 saw a number of major new initiatives from the EAPS Communications Office as well as some personnel changes.

EAPS Communications Officer Helen Hill stepped down in June to take a new role with the Simons Foundation Collaboration on Ocean Computational Biogeochemical Modeling of Marine Ecosystems, working with EAPS Professor Mick Follows. Jen Fentress, EAPS branding and communications coordinator, was promoted to communications officer to replace Helen. Fentress brings 25 years of experience in design and marketing to the role and will continue her work to develop the EAPS brand and its messaging while managing the department's news and social media coverage. EAPS is searching for a news and online communications assistant to report and write about EAPS science news and generate social media content.

Megan Jordan, education director, and Andrew Babbin, faculty representative, joined the Communications Committee, which was reorganized with a broader focus. Meeting monthly, the committee now seeks to include all administrators within EAPS who manage websites and social media for their research groups. The goal is to achieve strong brand consistency and coordinated campaigns while also identifying inefficiencies and establishing best practices. Part of this effort included deploying a standardized checklist for promoting events and initiating the drafting of a comprehensive editorial and design style guide and template library.

Jordan and Babbin were also instrumental in collaborating with Fentress to broaden the reach of the "Go Beyond" undergraduate recruitment campaign, with new brochures for students considering majoring and minoring in EAPS and expanded campus-wide advertising—for Course 12 in general as well as individual class offerings—including print posters and video slides on the Infinite Display system. A major poster campaign was also deployed after spring break, with posters blanketing the Green Building elevators and poster boards around campus, highlighting photographs from the spring field research classes sponsored by EAPS.

The "Go Beyond" campaign has attracted overwhelmingly positive feedback from students. It has also attracted the attention of administrative peers from across the Institute—several departments, laboratories, and centers have asked EAPS for advice on undergraduate recruitment, and the School of Science invited Fentriss to give a presentation to other communicators on how to create an effective student-focused campaign. In addition, Terrascope (the freshman learning community sponsored by EAPS and CEE) asked for help in revitalizing its promotional materials to bring them more closely in line with the EAPS brand, reflecting the complementary relationship of the EAPS and Terrascope educational missions and helping to boost student recruitment.

In the fall, Heather Queyrouze, EAPS communications coordinator, took the initiative to revive the dormant EAPS Instagram account by creating "takeover Fridays." A different graduate student each week is invited to "take over" the department's Instagram feed and post photographs and blurbs throughout the day, giving the audience a day-in-the-life snapshot of the student's work and life at MIT. This campaign has proven quite successful, more than doubling the department's Instagram follower count. A major part of that success has been the collaboration between Queyrouze and the two graduate students who volunteered to help shepherd the program and teach their peers valuable social media skills.

Beyond these initiatives, EAPS digital media efforts saw continued growth and efficacy, as shown in these figures:

- Website:
    - Increased traffic by 17.5% with 129,000 individual visitors
    - Increased visitor sessions by 16.4% with 204,000 individual sessions
    - Increased page views by 10.9% to 620,000
    - Increased visitor return rate by 20.7% from 19,000 to 23,000
    - Featured 205 news stories from EAPS research
- Facebook:
    - Increased followers by 15.2% to 8,186 with a total reach of more than 10,000
- Twitter:
    - Increased to an average of 40,000 tweet impressions and 3,906 direct followers

- Email campaigns:
  - EAPSpeaks, the monthly e-newsletter, grew in circulation to approximately 3,500 and maintained well-above-average open rates of approximately 40% (the industry average is 15.5%)
  - Email promotions for headline department events and seminars averaged open rates of more than 50%

Development

During fiscal year 2018, EAPS fundraising efforts were focused on the EAPS building campaign, fellowships, planned gifts, and research. New gifts and pledges to EAPS in FY2018 totaled $13.3 million—an increase of 25% from FY2017. The increase reflected some generous planned gifts, fellowships, and an upswing in private and foundation gifts for research.

Graduate student support remains a top development priority for EAPS. In FY2018, the department received a total of $1.43 million in major gifts toward graduate student fellowship funds, including contributions toward an endowed fellowship fund and five expendable fellowship funds. Major fellowship donors were thanked at the fourth annual EAPS Patrons Circle dinner in April. Patrons Circle members enjoyed a poster session and presentations from students.

EAPS succeeded in a $1 million fundraising campaign to acquire a telescope to enable MIT's participation in the international Search for Habitable Planets Eclipsing Ultra-cool Stars project, which will look near ultra-cool dwarf stars for planets that are worthy of further investigation. In FY2018, EAPS also received a generous $300,000 commitment to establish the mTerra Catalyst Fund, which will provide seed grants for innovative climate and Earth sciences research—an invaluable resource for faculty wishing to launch new research and to establish the proof of concept in new research that is needed for federal grant applications.

In October 2017, Professor Susan Solomon spoke to more than 200 guests on "A Brief History of Environmental Successes" at the seventh annual John H. Carlson climate science lecture at the New England Aquarium. Her talk was followed by a VIP dinner for donors and friends. Other donor-centric events included the William F. Brace Lecture, the MIT on Chaos and Climate Symposium that honored Ed Lorenz and Jule Charney, and annual receptions for EAPS alumni and friends in New Orleans and San Francisco. All donor outreach events offered valuable opportunities for faculty and staff to make connections with alumni and to share EAPS news and exciting Earth sciences discoveries with a broader audience. The senior development officer worked closely with faculty and colleagues across EAPS, the School of Science, the Office of Resource Development, and the MIT Alumni Association to highlight EAPS research and fundraising needs. These needs were addressed through annual appeals, communications materials (including a brochure and a video to present the Earth and Environment Pavilion campaign), presentations to Resource Development gift officers, grant proposals, stewardship reports, and faculty presentations at various MIT events. These tools and events all offered exposure and inspiration to alumni and potential donors, as well as to development colleagues from across MIT.

The department's senior development officer will continue to work closely with the head of department, faculty, staff, and students, the Office of Resource Development, and EAPS Visiting Committee members to raise $30 million to build an Earth and Environment Pavilion. The pavilion is intended to foster campus-wide collaboration on climate and environmental issues and to provide the core resources to support EAPS students and faculty in their search for knowledge about the Earth, planets, climate, and the origins and evolution of life.

Faculty Research Highlights

Andrew Babbin

Assistant Professor Andrew Babbin is a marine biogeochemist studying how life operates under low-oxygen conditions. Three recent research expeditions have been completed. One trip was to the Gardens of the Queen archipelago in Cuba to study the microbial metabolisms operating in pristine coral reefs; two were to the Eastern Tropical North Pacific oxygen minimum zone, a region of naturally anoxic water off the Mexican coast, to study microbial nitrogen cycling in climatically critical low-oxygen regions. These voyages incorporated significant public outreach, including the filming of two documentaries and six public lectures, collaborating with the Aquarium of the Pacific and the Smithsonian Museum of Natural History. Additionally, Babbin was awarded two Environmental Solutions Initiative grants, one for teaching development of a hands-on biogeochemistry course and one for research into microbial nitrogen pathways as they pertain to Earth's climate. The Babbin laboratory expanded in its second year, training two students in the Undergraduate Research Opportunities Program, hiring a research scientist, and bringing a new graduate student into the MIT-WHOI Joint Program.

Kristin Bergmann

Professor Bergmann's research group studies the interactions between ancient climate and early complex life. In particular, her group studies the nature of carbonate sedimentation through time and reconstructs temperature records from rocks from approximately 1 billion to 443.8 million years ago. The Bergmann laboratory uses a combination of approaches, including fieldwork, microanalytical methods (such as electron microprobe and synchrotron-based techniques), and carbonate clumped isotope geochemistry. The Bergmann group is synthesizing a wide range of observations about the Neoproterozoic to Ordovician time interval into a new model of Earth's early climate system and its importance for macroscopic life.

Bergmann's research and teaching begin in the field and this past year was a busy year for both. Three field expeditions were conducted—one to Svalbard, Norway, to sample strata from the Neoproterozoic era to the Ordovician period (541 million to 443.8 million years ago); one to the area outside Death Valley National Park in California and Nevada; and one to the Sultanate of Oman. During fall 2017, Bergmann taught an EAPS departmental field course in Newfoundland. In the spring of 2018, she taught 12.111B/12.465B Sedimentology in the Field, which culminated in a spring break research experience in Bermuda to study modern carbonate-producing environments.

Richard Binzel

Professor Richard Binzel and graduate student Alissa Earle completed a long-term climate analysis for the dwarf planet Pluto, including a study of the distribution of methane ice across its surface, using data returned from NASA's New Horizons mission. Professor Binzel was selected as a science co-investigator on two additional NASA missions (Lucy and Psyche) to study asteroids that are planned for launch in 2021 and 2022. In a project involving both EAPS and AeroAstro, Binzel is overseeing the in-flight calibration and testing of the regolith x-ray imaging spectrometer (REXIS) instrument aboard NASA's Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer (OSIRIS-REx) asteroid sample return mission. Binzel was awarded the NASA Silver Achievement Medal, NASA's second highest award that can be given to a nongovernment scientist, for exceptional contributions to the astronomical characterization of the OSIRIS-REx mission target asteroid Bennu.

Edward Boyle

Professor Edward Boyle's group has continued exploration of the marine geochemistry of chromium and chromium isotopes. Graduate student Tianyi Huang participated in a research expedition in the oxygen-deficient zone off the Mexican continental margin. Because of dynamically restricted ventilation and high surface productivity, the water column from 100 meters to 1,000 meters is virtually devoid of oxygen. Previous publications have shown that chromium is reduced from hexavalent chromate (a doubly charged anion that is toxic) to trivalent chromium (a triply charged aquo cation that is biologically functional) in this region. The group will analyze these samples for the concentrations of trivalent and hexavalent chromium and their isotopic composition (trivalent chromium preferentially incorporates chromium-52 over chromium-53). This data has implications for the geological history of atmospheric oxygen preserved in ancient sediments.

The Boyle group also collected deep profile samples from the Argentine Basin. A previous publication reported anomalously high chromium concentrations in this region—higher than anywhere else in the ocean. In contrast, they found that chromium concentrations were less than half those previously reported, which solves a major conundrum confounding the previously established paradigm for global chromium distribution.

Working with national colleagues, the group completed planning and cruise preparation for a major GEOTRACES section from Alaska to Tahiti in the fall of 2018. (GEOTRACES is an international study of the marine biogeochemical cycles of trace elements and their isotopes.) The team's role will be to analyze lead isotope ratios and chromium isotope ratios.

The Boyle laboratory researchers completed publication of a detailed section of lead and lead isotopes in the northern North Atlantic Ocean. The data from this section and a comparably detailed section in the eastern South Atlantic was publicly released in the GEOTRACES IDP 2017 database.

Timothy Cronin

Assistant Professor of Atmospheric Science Timothy Cronin continued to expand his group and develop his research program on climate, clouds, and atmospheric convection. The group now has two graduate students and two postdoctoral associates; a third PhD student, Martin Velez-Pardo, will join the group in the fall. Second-year PhD student Tristan Abbott passed his PhD qualifying examination; postdoctoral associate Nicholas Lutsko joined the group in September 2017. Cronin taught 12.003 Introduction to Atmospheres, Oceans, and Climate in fall 2017, and was awarded an Environmental Solutions Initiative curriculum grant to rework the class for inclusion in the environment and sustainability minor. Cronin also taught 12.815 Atmospheric Radiation and Convection in spring 2018. Cronin was awarded a National Science Foundation grant as co-principal investigator in an effort to understand and simulate rainfall over tropical islands and its effect on the tropical atmosphere. Cronin was awarded the three-year Kerr-McGee Career Development Chair and an Ally of Nature fund award. Notable publications from the group include a paper with Allison Wing of Florida State University on climate sensitivity in a convection-permitting model and a paper by James S. MacDonnell Foundation Postdoctoral Fellow Daniel Koll explaining why the radiative heat loss by the Earth tends to increase linearly over a wide range of surface temperatures.

Kerry Emanuel

During academic year 2018, Kerry Emanuel and his research group continued several lines of research and initiated several others. He published a paper showing that Hurricane Harvey's 840 millimeters of rainfall in Harris County, TX, was likely a 2,000-year event in the climate of the end of the 20th century—but if nothing is done to curb the increase in greenhouse gas concentrations, such events are likely to occur 10 times as often by the end of this century. Emanuel's graduate student Diamilet Perez-Betancourt wrapped up her thesis work on the dynamics of spiral rainbands in hurricanes. Emanuel worked with his graduate student Rohini Shivamoggi to study the physics of secondary eyewalls in tropical cyclones, and with graduate student Raphael Rousseau-Rizzi to show that the phenomenon of "superintensity" of tropical cyclones, about which much has been written, is largely illusory. Jonathan Lin just started working with Professor Emanuel on generating massive (more than 1,000) real-time numerical tropical cyclone ensembles as a basis for probabilistic hurricane forecasts at specific locations.

Professor Emanuel won the 2018 Friend of the Planet Award from the National Center for Science Education. He was also given an honorary degree from the University of Nanjing in China.

Raffaele Ferrari

Raffaele Ferrari's work this past year at MIT followed two major paths. He led the planning of a program to observe the rising of abyssal waters along a seamount, a process crucial in setting the division of carbon between the ocean and atmosphere. In the past few years, the Ferrari group has overturned the general understanding of the abyssal ocean circulation. It had been believed that the rise of carbon-rich waters from the abyss was driven by the mixing generated when internal waves break in the ocean interior. The group's work has shown that mixing drives waters toward the abyss, not the other way around; carbon-rich waters rise along seamounts and ridges. Ferrari laboratory researchers showed that the new paradigm results in a different residency time of waters in the abyssal ocean and affects climate variability on centennial (and longer) timescales. So far, the work has been based on theory and numerical simulations. In collaborations with colleagues at WHOI, the Scripps Institution of Oceanography, and the Southampton Oceanographic Center, the Ferrari group designed an observational program to observe this circulation in the Eastern North Atlantic. The project had not yet been funded at the end of academic year 2018.

Professor Ferrari's second line of work culminated in the creation of a multi-institutional climate initiative that has been funded through a consortium of private foundations and philanthropies. Climate change projections continue to be marred by large uncertainties. However, breakthroughs in their accuracy are within reach, thanks to recent advances in the computational and data sciences and in the availability of Earth observations from space and from the ground. An initiative led by the California Institute of Technology, in collaboration with the Ferrari group at MIT and Frank Giraldo's group at the Naval Postgraduate School, has been established to develop a new Earth system modeling platform to harness these advances. It will develop an Earth system model making use of global observations and targeted local high-resolution simulations of clouds, turbulence, ocean mixing, and other elements of the Earth system, harnessing developments in computation and machine learning. The group at MIT will develop the ocean component of the Earth system model, including subgrid-scale process models for the ocean (e.g., for boundary layer dynamics and deep convection) that are suitable for machine learning and data assimilation.

Glenn Flierl

Glenn Flierl and his students are investigating physical and biological dynamics in the ocean and other, more general problems in geophysical fluid dynamics. Recent publications include an examination of turbulence in a model of the flow above the ocean thermocline, a study of the role of sudden events in the extinction of populations, and the generation of planetary waves by flows around islands. Work on instabilities of flow around islands continues; the application of similar ideas to vortices over seamounts has been under way with a visiting student and a student at WHOI's Geophysical Fluid Dynamics Summer School.

Professor Flierl participated in many outreach events using the iGlobe spherical display at Hayden Library. These included an exhibit in the Hayden Library for the fall semester and Independent Activities Period, Girls Day at the MIT Museum, and the EAPS "One Sustainable World" event. He and his students also developed a web-based outreach tool that they used at these events.

Gregory Fournier

At the end of AY2018, the goals of Professor Gregory Fournier's laboratory included the publication of papers describing the completed research of several members who will leave the laboratory in fall 2018. These research projects included:

- Dating the evolutionary history of chitin-degrading enzymes within diverse microbial groups across marine and terrestrial environments, a major component of the PhD thesis of Danielle Gruen, an MIT-WHOI Joint Program chemical oceanography student in the Fournier laboratory;
- Mapping the evolution of carbon fixation proteins across marine cyanobacterial groups and sulfur bacteria, the master's thesis project of Makayla Betts, who graduated in spring 2018; and
- Reconstructing the evolutionary history of early sulfate- and nitrate-reducing microbial metabolisms, as facilitated by the discovery of new deep subsurface bacteria. This project was completed by Crosby Postdoctoral Fellow Lily Momper, who will leave MIT in fall 2018.

Professor Fournier's goals at the end of AY2018 also included completion of two major ongoing projects in research into the origin of life (supported by the Simons Foundation Collaboration on the Origins of Life) and completion of an automated pipeline for horizontal gene transfer detection from large genome data sets for use in molecular-clock studies (supported by the National Science Foundation). Another goal was further development of the fall semester subject 12.090/12.S492 The Phylogenomic Planetary Record.

Integrated across each of these projects, Fournier's research priority at the end of the academic year remained the same as in previous reports, but with an added focus. He is trying to establish a generalized approach to using gene transfers to inform the planetary record of microbial life, across all groups of the tree of life, and then to communicate these approaches and results, making tools available to the broader community in molecular evolution and microbiology.

Professor Fournier's accomplishments this year included several invited lectures at major research conferences, as well as poster presentations at several meetings by members of the laboratory, including at the Gordon Conference on the Origin of Life and the Gordon Geobiology Conference, the annual meeting of the Geological Society of America, the regional meeting of the American Society of Microbiology, and the annual Geobiology Society Conference, where he also held a panel debate on the origin of oxygen-producing cyanobacteria on the early Earth. He also co-chaired a session at a national workshop on Deep Time Data Driven Discovery and the Evolution of Earth at the Carnegie Institution for Science in Washington, DC.

Fournier's group also organized a highly successful local outreach activity this year in cooperation with Boston Public Schools and the Franklin Park Zoo. This activity was in celebration of Darwin Day, supported by a National Science Foundation grant to EAPS. The group worked with two Boston Public School science teachers from the Dorchester area of Boston, a school region with students from historically underrepresented minority groups and lower-income families. Over two months, with guidance from graduate students in the Fournier laboratory, 10 groups of seventh-grade students built interactive projects with activities designed to teach other students about the basic principles of selection, inheritance, and Darwinian evolution. On February 12 (Darwin's birthday), the students held an activity fair that was open to the public in the rainforest exhibit of the Franklin Park Zoo. More than 200 people attended the fair, which concluded with a public lecture on the diversity of life and how it relates to our understanding of evolutionary change over time. This successful outreach also established positive relationships between MIT, Boston Public Schools, and the Franklin Park Zoo, and created excitement about cooperating in organizing future events.

Within the laboratory, graduate student Sarah Schwartz received a major research fellowship to support the remainder of her graduate student career, the National Defense Science and Engineering Graduate Fellowship Award.

There were several changes in Fournier laboratory staff this year. Graduate student Makayla Betts graduated with an SM degree and left the laboratory, Luiz Thiberio Rangel joined the laboratory as a postdoctoral associate, and graduate Sarah Schwartz became a full member of the laboratory, with Professor Fournier as her sole advisor.

A significant change to teaching and the curriculum in EAPS this year was a new subject, The Phylogenomic Planetary Record. This subject is a modified and greatly expanded version of the evolution component of the microbial genetics and evolution subject that Fournier had taught for the previous two years in the Department of Biology. The subject matter in this course covers evolutionary theory, cladistics, and phylogenetics, with a focus on microbial evolution and its role in shaping planetary geochemistry across Earth's history. This course contains lecture and paper seminar components, as well as a bioinformatics computer laboratory component, illustrating current concepts in molecular evolution and teaching practical skills for using molecular evolution tools within the laboratory. This is the first time this material has been taught within EAPS.

During Independent Activities Period, Fournier also organized an Origin of Life Seminar Series, inviting five leaders in the origins community across several disciplines to visit with students at MIT, give seminars, and have informal discussions and interviews. Students then collaborated to produce a series of interview blogs highlighting the lectures and views on origins for each of the speakers; these were made available on the EAPS website.

Several research projects within the laboratory also continued, in collaboration with research groups at MIT and other institutions. These were supported by departmental startup funds, the NASA Astrobiology Institute Foundation of Complex Life team, the Simons Foundation Collaboration on the Origin of Life, and the National Science Foundation.

The first project could be called "dating the tree of life." Using computational techniques and genome sequence data, this project attempts to combine genomic, paleontological, physiological, and geological and geochemical evidence to calibrate the evolutionary histories of major groups of microbes, in order to estimate when they probably evolved and how their metabolisms influenced the planetary system. This year, researchers completed three major projects resulting in novel age estimates for different groups within the tree of life. The first project used horizontal gene transfer from an ancient group of methanogens to the ancestor of all cyanobacteria to get more accurate age estimates for the antiquity of methane-producing metabolic pathways on Earth. They showed that archaea with methanogenic metabolisms very likely had evolved by 3.5 billion years ago and may have been responsible for warmer temperatures during this time because of the greenhouse gas properties of atmospheric methane.

The second project was broader in scope: the culmination of a two-year project estimating ages across the bacterial tree of life, focusing on photosynthetic lineages and their relative ages. Using multiple fossil calibrations and horizontal gene transfer events, this study was able to make several predictions about the age of biogeochemically relevant microbial groups, independent of the geological record. The work included inferring that sulfide-utilizing green sulfur bacteria evolved approximately two billion years ago. At that same time, geochemistry predicts an increase in marine sulfidic conditions. The diversification of oxygen-producing cyanobacteria is thought to have taken place approximately 2.6 billion to 2.3 billion years ago, at the same time as the so-called Great Oxidation Event, as evidenced by geochemical proxies. Current work promises to improve the precision of these age estimates by incorporating more fossil calibrations and gene transfer constraints, in collaboration with the Tanja Bosak laboratory. This work will incorporate additional information from gene transfer events studied by graduate student Makayla Betts.

The third completed project was part of graduate student Danielle Gruen's PhD dissertation work, focusing on the close interplay of the evolution of microbial metabolisms, ecology, and animals during the early Phanerozoic Eon. Specifically, Gruen and colleagues investigated the environmental and taxonomic distribution of chitin-degrading genes to date multiple groups of bacteria that had had no informative age estimates. Because this gene was transferred from a fungal lineage to bacterial groups, fossil-calibrated age estimates of fungi can be used to constrain the ages of the bacterial recipients. The results of the group's molecular-clock analyses are especially exciting, as they show a striking convergence of the ages of three groups of chitinase genes inherited by different groups of terrestrial bacteria, all between 500 million and 350 million years ago. This same interval of time saw the terrestrialization of the major groups of arthropods, the primary source of chitin in the environment. This not only establishes the ages of several groups of microbes important in terrestrial and marine environments, such as Actinobacteria and Vibrio, but shows how substrate-specific enzymes, spread by gene transfer, can be "standard candles" for molecular-clock dating of groups without fossil records. Ongoing molecular-clock projects in the laboratory include a long-term project to date the diversification of Proteobacteria.

One of the major challenges in this work over the past year has been developing computational methods to make the most use of horizontal gene transfer events as a tool in dating phylogenetic trees. The group has investigated several ways of incorporating this information, with varying success based on the groups of organisms involved, the amount of sequence information within the transferred genes, and the types of calibrations. Through these efforts, they established a set of strict criteria for using gene transfer in molecular-clock analyses. Working with postdoctoral associate L. Thiberio Rangel, a new member of the group, researchers plan to finish an automated computational pipeline and online tool and database for these methods this year.

Other research efforts this year focused on major questions in the evolution of early life. Two of these efforts are particularly notable. The first project was a continuation of their investigation into the early evolution of aminoacyl-tRNA synthetase proteins, an ancient family of proteins responsible for determining the specificity of the genetic code, which evolved before the last common ancestor of all life. This work grew out of a collaboration with Jack Szostak's group at Harvard Medical School, investigating the earliest origins of the protein synthesis machinery by reconstructing ancestral sequences of families of proteins that load specific transfer RNA with their cognate amino acids. Previously, the deep evolutionary history of these proteins was not known because of their extreme sequence divergence, which confounded automated methods of sequence or structure alignment. To deal with this limitation, Professor Fournier performed a detailed, careful manually curated alignment of these ancient proteins, using expertise in protein structural chemistry and available three-dimensional protein structures. This approach enabled a high-quality alignment across most of these sequences, providing a new source of information for inferring their evolutionary origins. With this alignment, researchers can produce a phylogenetic tree that fully resolves the history of every one of these ancient proteins, a previously unrealized goal. Using this information, Fournier began making ancestral reconstructions of the earliest sequence ancestors of these proteins to probe the earliest evolution of protein synthesis.

The second project involves exploring the possibility of partial horizontal gene transfer, which occurs when genes within a genome have a chimeric ancestry, with one part being transferred from a separate donor lineage. If they are widespread, partial transfers can confound researchers' ability to make correct phylogenetic inferences based on sequence data. In academic year 2018, Fournier identified extensive partial gene transfer events within elongation factor proteins, important marker proteins for constructing the history of ancient microbial lineages. In addition, Fournier showed that these partial transfer events are the cause of conflicts within these lineages, and that, once they are detected and removed, the evolutionary signal becomes far more robust, even for a single gene. At the end of AY2018, he was in the final stages of testing these results. Future work will generalize the detection and impact of partial gene transfer across large protein data sets to test the extent to which this evolutionary process makes it more difficult to recover the true tree of life from sequence data.

Timothy Grove

Professor Tim Grove and former postdoctoral associate Bernard Charlier completed an experimental study that recreated the fractional crystallization processes during the differentiation of a lunar magma ocean. These were challenging experiments as the lunar magma ocean crystallized from the bottom up, they had to constantly change the pressure and temperature of each subsequent experiment and also the composition of the residual liquid. The results of this years-long study allowed Grove to set constraints on the depth of the magma ocean; it could have been approximately 600 km deep. Grove and Charlier ruled out a whole-moon ocean. They also predicted the thickness and composition of the magma ocean cumulate layers that were subsequently remelted to produce the mare basalts. An especially important unknown was the thickness of the layer that was melted to form the high-titanium mare basalts; it was found to be less than 10 km. They also confirmed that the observed composition of the anorthosite crust can be explained by crystallization of a lunar magma ocean. These questions had been unanswered since the presence of a moon-wide magma ocean was first postulated in 1970, immediately after the Apollo 11 samples were returned and examined.

Honors, Teaching, and Service to the Institute

Professor Grove was invited to participate in a high-level workshop at Corning at their Glass Summit: Glass Across Boundaries meeting on June 6–8, 2018.

Grove led the Discover Earth, Atmospheric and Planetary Science Yellowstone trip, one of two pre-freshman activities offered by the department; 35 people attended. In the fall, he taught two subjects, 12.486 Graduate Igneous Petrology and a freshman advising seminar, 12.A03 Meteorite from Mars Kills Dog. He also taught some substitute classes for 12.001 Introduction to Geology.

Professor Grove continued as associate department head. Along with other members of the department, he also stepped up activities directed to recruiting undergraduate major students by inviting those interested in this science area to a reception and following up again around the time of choice of major. The department met all departmental stakeholders and prepared for and successfully completed the MIT Visiting Committee evaluation. It also ran a very successful Open House for graduate student admissions. Through much of the year there were meetings about design and planning for the fourth floor of Building 4. Grove is the primary mentor for Matej Pec and served on the tenure committee for Dan Cziczo.

Other Service and Community Outreach

Professor Grove continued to serve on the Development Board of the American Geophysical Union and as chair of its Centennial Steering Committee. In September 2017, he served as a member of a NASA review panel for solar system workings.

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

Thomas Herring

Professor Thomas Herring is using global navigation satellite system (GNSS) data to develop geophysically based models of Earth deformations on global, regional, and local scales, and of changes in the rotation of the Earth. In AY018 there was a large software development project to include other GNSSs in the MIT geodetic processing software, GAMIT/GLOBK. This development allows data from the Russian global navigation satellite system (GLONASS), the European Galileo system, and the Chinese BeiDou system, as well as GPS, to be processed. Professor Herring 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 GNSS measurements in many different study areas, including much of the southern Eurasian plate boundary and the western US. They are investigating processes leading up to earthquakes on time scales of years, transient deformation signals lasting days or weeks or years, post-seismic deformation after earthquakes on time scales of a day to decades, surface wave propagation during earthquakes using high-rate GPS data, and ice dynamics. All of these measurements have precision of a submillimeter to a few millimeters. In collaboration with CEE, the group is also monitoring deformations of a tall building in the Middle East. Data from this building was able to capture the impact on the building of a distant large earthquake.

John Marshall

Professor John Marshall has ongoing projects in the Arctic, the Antarctic, the Southern Ocean, and the intertropical convergence zone, in particular a study exploring the role of the ocean in mediating shifts within the intertropical convergence zone. This study involves a collaboration with Professor David McGee and a PhD project by Brian Green. Marshall presented the work, which has a strong pedagogical element, at ICTP Summer School on Theory, Mechanisms and Hierarchical Modelling of Climate Dynamics: Multiple Equilibria in the Climate System and the 2nd WCRP Grand Challenge Meeting on Monsoons and Tropical Rain Belts, June 25-July 5, 2018, in Trieste, Italy.

Collaborations with postdoctoral associates Gianluca Meneghello and Ed Doddrige on the role of the ocean in mediating sea-ice cover in the Arctic (Meneghello) and the Antarctic (Doddridge) are yielding exciting results. In particular, the manner in which sea ice moderates the effect of the wind acting on the underlying ocean is a significant discovery; the mechanism has been dubbed the "ice-ocean governor."

Graduate students Brian Green and Mukund Gupta are progressing in their thesis work; Green expects to graduate in the summer of 2018. Professor Marshall's new student, Ali Ramadhan, is already contributing to the group's research.

Brent Minchew

Assistant Professor of Geophysics Brent Minchew continued research on the interactions between the climate, the cryosphere, and the solid Earth. Over the past year, most of his efforts were directed at understanding the mechanisms that govern the rate at which the West Antarctic Ice Sheet could contribute to sea level rise, work that will continue for the foreseeable future. Since joining the EAPS faculty in January 2018, Professor Minchew has continued his research in ice sheet dynamics, built a research group that now includes five PhD students researching a variety of topics, recruited a postdoctoral research associate (who will start in September 2018), secured research funding, developed a teaching plan that includes a new course in remote sensing, and initiated outreach efforts in the local area that entail a position as an advisor to the Boston Museum of Science.

Since January 2018, Professor Minchew and co-authors have published three journal articles on the thermomechanics and hydrology of lateral shear stresses in glacier shear margins. One article reported the first study to provide observational constraints on the relative contributions of various mechanisms that soften ice within lateral shear margins, a long-standing problem in glacier dynamics. This work built on observational techniques that had been developed by Professor Minchew and others. The main conclusion—that the observed downstream softening of ice over spatial scales on the order of 10 km is driven almost exclusively by viscous dissipation—provided the motivation and foundation for several ongoing projects. A second article published in 2018 focused on the processes that control deformation-induced melting of ice in shear margins; it reports the first continental-scale mapping of Antarctica that identifies areas where the observed deformation rates in the ice were sufficient to melt more than half of the ice column. The most important contribution of this work is to elucidate the balance between the rate of deformation-induced heating and the vertical advection of cold ice from the surface. A third paper undertook a more detailed study of one area, where deformation-induced melt was suspected, to better understand the hydromechanical coupling between meltwater generated through viscous dissipation in the ice and the shear strength of the bed. The main finding is that the production of meltwater in the shear margin strengthens the sediment beneath the shear margin by locally reducing the pore water pressure.

Professor Minchew and co-authors also investigated how fast-flowing glaciers in Antarctica respond to melting and ocean tidal uplift of their floating extensions, known as ice shelves. They forced a dynamical ice flow model with recent observations of thinning in Antarctica to estimate the response of outlet glaciers to ocean-induced thinning of the floating ice shelves. Model results were in close agreement with observations of glacier velocity and indicated that variations in snow accumulation in the area, rather than the dynamic response of glaciers to thinning of the ice shelves, is the most likely explanation for observed ice mass loss along the Bellingshausen Sea. Working with other colleagues, Minchew provided a simple physical explanation for the response of ice streams to ocean tidal forcing. Results from a simple viscoelastic model of ice streams forced by a combination of changes in the buttressing stresses from the floating ice shelf and hydrostatic pressure from the ocean showed a diverse range of responses in horizontal ice flow.

Paola Rizzoli

Professor Paola Rizzoli's 10-year-long Singapore-MIT program, the Center for Environmental Sensing and Modeling, ended on March 31, 2018. Many publications resulted from this collaboration between Professor Rizzoli and Professor Elfatih Eltahir of CEE.

In 2017, Rizzoli started an initiative in Venice, Italy, based on the collaboration between MIT, the Venice University of Architecture, the Venice Water Authority, and the Consorzio Venezia Nuova. The last is the conglomerate of companies in charge of the planning and construction of the Modulo Sperimentale Elettromeccanico (Experimental Electromechanical Module, MOSE) barriers for the protection of Venice and its lagoon from the Adriatic Sea storm surges.

The initiative is focused on teaching the science and technology know-how of more than 25 years of history of MOSE barriers to an audience of American and Italian students. Professor Rizzoli has a deep knowledge of the scientific aspects of the oceanographic problem and of the engineering alternatives that led to the choice of the MOSE barriers as the most protective solution to the problem.

A second summer school session was held on the island of Pellestrina, which separates the lagoon from the open sea, from June 11 to June 22, 2018. The island was almost completely destroyed during the flood of November 4, 1966, and it is there that the biggest MOSE barrier protecting Malamocco is being completed. Eleven MIT students, supported by the MIT International Science and Technology Initiatives (MISTI) MIT-Italy Program, attended both this session and the previous session, held in 2017. They were joined by an equal member of students from the Venice University of Architecture. About 15 faculty members from MIT, the Venice University of Architecture, the University of Padua, and the Ca'Foscari University of Venice constituted the teaching body and jointly supervised the students in the summer projects. The subject of the 2018 session was "Border, but not Marginalized, Territories: The Case of Pellestrina Island." A contract has been signed between MIT, the Venice University of Architecture, and the Venice Water Authority that ensures financial support for the next three years.

J. Taylor Perron

Associate Professor J. Taylor Perron and his group study the processes that shape landscapes on Earth and other planets. Their efforts are currently focused on the formation and evolution of river networks, climate's effects on erosion, and the landscapes of Mars and of Saturn's moon Titan.

Professor Perron was the Faculty Fellow in Archaeological Materials in the Department of Materials Science and Engineering during academic year 2018 and he delivered the Archaeological Materials Lecture there in spring 2018. He collaborated with faculty members in MIT's Center for Materials Research in Archaeology and Ethnology to investigate how plate tectonics, climate, and rivers influenced the rise of pre-Columbian agriculture in the Amazon region. Perron and his collaborators received a seed grant from the MIT Abdul Latif Jameel World Water and Food Security Lab to continue this research.

With PhD students Maya Stokes and Samuel Goldberg, Perron launched a new project to investigate how changes in the configuration of river networks alter topography and biodiversity. They are focusing their initial efforts on the effects of river capture—the abrupt, permanent diversion of rivers by natural processes. They recently published evidence that river capture is continually altering some of the world's largest river basins. In collaboration with biologists and molecular ecologists, they have been conducting fieldwork and constructing computational models to test whether frequent river captures helped create the exceptionally diverse fish populations of the southeastern US.

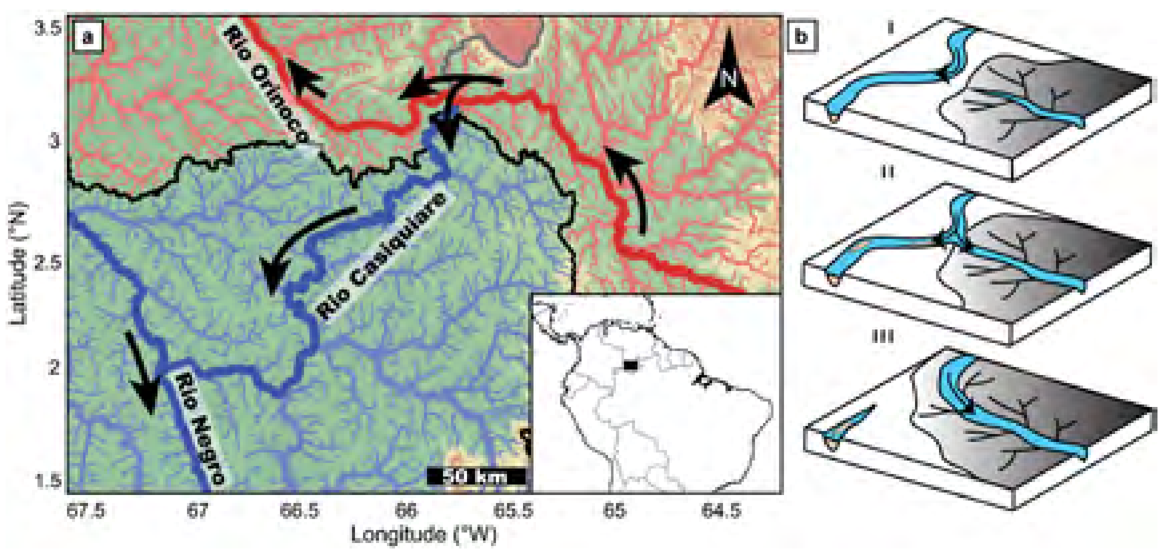

Figure 1: (a) Map of the Rio Casiquiare, a permanent water connection between the Orinoco and Amazon river basins, with rivers and flow directions indicated. The Rio Negro (a tributary of the Amazon) is in the process of capturing the upstream portion of the Orinoco. The black line is the present boundary of the Amazon basin; the gray line is the future boundary once the capture is complete. (b) Schematic representation of the hypothesized capture process: (I) pre-capture, (II) present flow bifurcation, and (III) future complete capture. Shading denotes the Amazon basin. Reproduced from Stokes, M.F., S.L. Goldberg and J.T. Perron (2018). Ongoing river capture in the Amazon. Geophysical Research Letters, 45, 5545-5552, https://doi.org/10.1029/2018GL078129.

Student Awards

PhD student Samuel Goldberg was awarded a NASA Earth and Space Sciences graduate fellowship. PhD student Maya Stokes was awarded a Hugh Hampton Young Graduate Fellowship by the MIT School of Science and was named a Martin Family Sustainability Graduate Fellow.

Daniel Rothman

Recent work by Professor Daniel Rothman focused on the stability of Earth's carbon cycle. By constructing and analyzing a database of past disturbances of the cycle, Professor Rothman's work identified critical rates and amplitudes beyond which the Earth system may become unstable. Physical and mathematical reasoning predict that the total carbon dioxide added by human activities to the oceans may cross a threshold leading to mass extinction sometime in the present century. A key methodological innovation of this work is to show how disturbances in the carbon cycle at geologic time scales can be quantitatively related to the stability of the cycle at human time scales. Continuing work seeks to express these ideas within the framework of dynamical systems.

Susan Solomon

Work in Professor Susan Solomon's laboratory is directed broadly to studies of atmospheric chemistry and its interactions with climate change, as well as environmental science and policy. The group studies atmospheric composition and chemical processes that affect it, the interactions between chemistry, radiation, and Earth's climate, and the use of scientific information in policy formulation.

Key accomplishments of the past year included the following:

- Completed a formal attribution study of upper- and lower-stratospheric ozone changes using observations together with simulations to quantify the zonal-mean response patterns ("fingerprints") to combined forcing by ozone-depleting substances and well-mixed greenhouse gases, as well as to the individual forcing by each factor, and to demonstrate the importance of using nonlinear signal detection.

- Used formal detection/attribution fingerprint methods to identify influences of greenhouse gases and ozone depletion on wind system changes in the troposphere and stratosphere, revealing and quantifying greenhouse gases' effects in both hemispheres from December to May, as well as significant effects of ozone in the Northern Hemisphere in March, April, and May. The study provides new and stronger evidence that both greenhouse gases and ozone changes have influenced patterns of global and hemispheric circulation patterns of both hemispheres over the past three decades.

- Analyzed atmospheric structure to reveal a special feature of the Western Pacific region with regard to tropical cyclones: the tropopause region thermal structure permits intense Western Pacific cyclones in every month of the year, which is important for coastal societies. This feature is unique to the Western Pacific.

- Identified a seasonal and vertical fingerprint of ozone recovery in the upper stratosphere and showed the importance of accounting for solar proton events as well as dynamical variability in the tropical lower stratosphere.

- Demonstrated that the timing of several small as well as larger volcanic eruptions played significant roles in recent ozone trends. In particular, the eruptions of El Chichon and Pinatubo accelerated global ozone losses during the depletion era (1979–1998). A novel result of the current study was the documentation of the role played by a series of relatively small volcanic eruptions after 2000 in delaying the recovery of ozone after 2000 or so, not only in the Antarctic but also globally. The paper also provided evidence that the Southern Hemisphere's mid-latitude and tropical ozone has recovered more than in those areas in the Northern Hemisphere, and that recovery and depletion signals from higher latitudes are transported to the subtropics and tropics, which emphasizes the importance of the Antarctic for ozone recovery across the hemisphere.

Robert D. van der Hilst

Professor Robert D. van der Hilst has been department head of EAPS since January 2012. His research continues to focus on regional tectonics in southeast Asia and North America, imaging of Earth's deep interior using dense seismograph arrays (in collaboration with Visiting Professors Maarten De Hoop from Rice University and Michel Campillo from the University of Grenoble, France, and colleagues at Imperial College London), and development of algorithms for high-resolution seismic imaging with natural earthquakes (in collaboration with De Hoop). Van der Hilst's team has developed a method for determining contrasts in mass density and seismic wave speed across interfaces deep in Earth's interior; from such measurements they estimated the composition and temperature beneath Hawaii and the Central Pacific at depths that are well outside the reach of direct observation and measurement. They also presented novel approaches to high-resolution imaging of the structure of Earth's crust, the rocky outer part of the Earth, and the upper mantle beneath North America. Further, they we demonstrated that one can use seismic waves to detect and quantify the deformation of a volcano caused by tides and changes in precipitation and atmospheric temperature.

Jack Wisdom

Professor Jack Wisdom worked on several projects, one of which was motivated by a lecture by EAPS Professor John Marshall. Proxies for climate variations on the Earth (more specifically, temperature variations on the Earth, and the extent of glaciations) exhibit periodicities that are similar to periodicities in the variation of the Earth's orbit and obliquity (the tilt of the spin axis). The association of climate variations with orbital forcing is generally termed the Milankovich theory. Although there are variations, the Milankovich theory assumes that the glacial extent is primarily affected by the insolation (heat energy from the sun) in the northern latitudes (specifically, 65 degrees north) during the summer. The trouble with this hypothesis is that the summer insolation at 65 degrees north shows little power at intervals of 100,000 years (100 Kyr), while the proxies for climate variation show dominant power at 100 Kyr intervals. (This is the so-called 100 Kyr problem.)

Wisdom proposed a different mechanism. He proposed that what is important is the total amount of energy getting into the system, not the insolation. Some of the incoming energy is immediately reflected to space. To compute this, he made a mode of the latitudinal variations of the Earth's albedo using modern satellite data. The albedo measures what portion of incoming insolation is reflected. He then computed the total heat input to the Earth system as a function of time, using the full chaotically evolving solar system (with the tidally evolving Moon). He found that the resulting time series of total heating showed strong variations at 100 Kyr—thus obtaining a tentative solution of the 100 Kyr problem. The computed time series was actually able to "predict" the last two major glaciations. However, the agreement is not perfect; there is more work to be done.

Robert D. van der Hilst
Head
Schlumberger Professor of Geosciences