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. EAPS also seeks to inform policy and create solutions, for example, concerning climate change and natural resource management. The department comprises 42 faculty members, including three with a primary appointment in the Department of Civil and Environmental Engineering, one with a primary appointment in the Institute for Data, Systems and Society, one with a primary appointment in the Department of Aeronautics and Astronautics, and another with a primary appointment in the Department of Mathematics. There are also more than 300 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 Laurent Demanet) 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 activities 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 enquiry. 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

The EAPS faculty is committed to the development and maintenance of vibrant educational 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 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 2018, the Committee on Graduate Programs approved the addition of a doctoral degree in Computational Earth, Atmospheric and Planetary Sciences in collaboration with the Computational Science and Engineering program. This addition has already provided one student the opportunity to move into this new collaborative degree program. In fall 2018, EAPS had 153 graduate students (148 doctoral students and seven master's degree students) registered in the department, including 66 students in the MIT-WHOI Joint Program and two fifth-year master's students. Women constituted 50% of the graduate student population; 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 and student life of the department. For example, current graduate students 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 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 the 2019 academic year, Kelsey Moore, Patrick Beaudry, and Maya Stokes were recognized for their contributions.

The department's students also received recognition from MIT, professional societies, and outside organizations. Joleen Heidrich, Sam Levang, Sebastian Essink, and Julie Jkoboski placed first at the 2019 EarthHack, and the team of Deepa Rao and Craig McLean placed third at the event. Tajana Schneiderman and Zhuchang Zhan were joined by undergraduate Sheila Baber on a team that placed third at the 2019 NASA Big Idea Challenge. Christine Chen received the MIT Larry G. Benedict Leadership Award. Jane Chui, Ziwei Li, Hannah Mark, and Meghan Jones were recognized with Outstanding Student Presentation Awards from the American Geological Union. Maya Stokes, Gabi Serrato Marks, and Christina Hernandez were recognized as MIT Graduate Women of Excellence. Clara Maurel received the Stephen E. Dwornik Planetary Geosciences Best Graduate Oral Presentation Award as well as the Amelia Earhart Fellowship from Zonta International. There were additional student awards for academic year 2018.

The Department of Earth, Atmospheric and Planetary Sciences graduated 23 doctoral students and five master's degree students in AY2019.

Undergraduate Program

EAPS had 25 undergraduate majors in AY2018, five more students than the previous year. Of the undergraduates, 72% were women and 32% were members of an underrepresented minority group. The EAPS undergraduate population has always been small, but satisfaction is high; the department continues its efforts to increase the number of students majoring in the department. Activities include monthly lunch seminars for undergraduates that expose them to different resources at MIT (such as Global Education and Career Development, MindHandHeart, and so on), events for incoming first-year students, involvement through first-year 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 MIT student body has ready access to education in geo-scientific aspects of climate and environmental change, natural hazards, and natural energy resources. Mick Follows co-taught an ecology subject with the Department of Civil and Environmental Engineering. 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 (directed by Professor David McGee) and the Experimental Studies Group (directed by Professor Leigh Royden). EAPS also offers first-year advising seminars and first-year pre-orientation programs. With the combined enrollment of Terrascope, the advising seminars, and the Experimental Studies Group, EAPS connected with 10% of the students in the first-year class on a weekly basis. Similarly, EAPS is an active participant in four interdisciplinary minor programs: the broad-based energy minor, the astronomy minor (with Physics), the atmospheric chemistry minor (with Chemistry, Aeronautics and Astronautics, Civil and Environmental Engineering, and the Institute for Data, Systems, and Society), and the environment and sustainability minor.

At the 2019 Student Awards and Recognition Dinner, the Goetze Prize was awarded to Emma Rutkowski (advised by Professor Noelle Selin) in recognition of her outstanding senior thesis. Apisada Chulakadabba received the W. O. Crosby Award for Sustained Excellence, recognizing her academic and intellectual achievements as well as general contributions to the department. Charlotte Minsky was the recipient of the EAPS Achievement Award, which recognizes a rising senior from across the EAPS disciplines. The award is presented to a student who has distinguished her- or himself through a combination of a high grade-point average, focused course work, and leadership within EAPS. Megan Goodell received an Undergraduate Teaching Assistant Award.

EAPS graduated five students with bachelor's degrees in AY2019.

Faculty

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

Camilla Cattania, a geophysicist working on understanding earthquake processes, will complete a postdoctoral program at Stanford University and join the department in July 2020.

EAPS is now halfway through the eighth 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 the department. Junior and senior faculty members alike are satisfied with the system, but feedback solicited from junior faculty will be used to make further improvements.

Promotions

Associate Professors Taylor Perron and Paul O'Gorman were promoted to the rank of full professor. Associate Professor David McGee was promoted to the rank of associate professor with tenure, all effective July 2019.

Communications

Academic year 2019 coincided with the first full year of Communications Officer Jennifer Fentress's tenure at EAPS. One of her first tasks was to complete the hiring of a news and online media coordinator to report and write about EAPS news and liaise with the MIT News Office, generate and manage social media content, and provide general assistance in maintaining the department website and executing Communications Office objectives. Lauren Hinkle, a former contract science writer and online media manager for the Program in Atmosphere, Oceans, and Climate, accepted the new position and started in September 2018.

The department's online presence has expanded since September 2018, with a 26% increase in news content production, including increased coverage of scientific papers. The department's website user traffic has maintained a steady growth trend, with more than 11,500 average monthly overall site users, of whom more than 10,800 are new users. On Twitter, EAPS has 67,000 average monthly impressions, with 2,500 average impressions per post, and more than 5,000 followers. On Facebook, EAPS has 50,000 average monthly impressions, with 1,250 average impressions per post, and more than 9,300 followers, with a total reach of 12,100 individuals.

The communications officer has been networking with communications peers across the Institute to research and begin to build policy recommendations and best practices for EAPS communications efforts. In addition, Fentress has been working to quantify (with analytics gathered by other Institute groups as well as analysis of EAPS website and social media traffic) which communications efforts yield the most fruit. In the near term, with limited manpower and resources and increasingly well-informed audiences, it will be crucial for EAPS to concentrate its efforts on only the most efficient and highest-return-on-investment activities and platforms. The department has made modest gains by streamlining the news pitch process as well as the website calendaring system, email campaign system, and digital media library. EAPS has also adopted the Asana team project management tool to help coordinate efforts and centralize information among headquarters stakeholders.

Finally, Fentress investigated and secured a partnership with the MIT Graduate Program in Science Writing to host a student from that program in a half-time research assistant position in EAPS for AY2020. Beginning in September, this student will work with the EAPS communication team to help write more feature stories and student profiles, and to create content for online media.

Development

During fiscal year 2019, new gifts and pledges to EAPS totaled $21.08 million. This very gratifying increase of 58.5% from FY2018 was fueled by a number of seven-figure commitments for the proposed addition to the Green Building (Building 54)—the Earth and Environment Pavilion—and associated improvements, including renovation of the large lecture hall. The upswing reflected very generous gifts made or facilitated by EAPS Visiting Committee leaders and MIT Corporation members. Having reached more than 50% of the department's $30 million goal for the Earth and Environment Pavilion (a "gated" project that can proceed only once the fundraising target is reached), selection of an architect can now proceed.

The proposed new Earth and Environment Pavilion will signal the dawn of greater collaboration between EAPS faculty and students and MIT's Environmental Solutions Initiative. The Environmental Solutions Initiative plans to join EAPS and the MIT-WHOI Joint Program for Oceanography in the new space to advance a shared mission for research and education in an era when understanding and acting upon environmental challenges such as climate change are becoming increasingly urgent.

The department's senior development officer worked closely with faculty, alumni, and colleagues in the School of Science and the Office of Resource Development to inspire several other significant gifts to EAPS in FY2019. These included the establishment of the new Maxwell-Hanrahan Fund for Education and Research, and the Gilman Exoplanet Research and Education Fund. EAPS was also grateful to receive several significant research grants from foundations, including the Heising-Simons Foundation and the Simons Foundation.

EAPS alumni rallied to help lead two other successful fundraising efforts in FY2019. Course XIX (Meteorology) alums joined forces to update the Charney Library on the 14th floor of the Green Building (much to the delight of the EAPS students who designed the new space), and geophysics alumni raised funds and helped organize a joyful 85th birthday celebration in honor of Emeritus Professor M. Nafi Toksöz, founder of the Earth Resources Laboratory at MIT. In May, more than 60 former students traveled from around the country to join Professor Toksöz and EAPS faculty in Cambridge for the festivities.

EAPS continues to organize regular outreach events each year so that faculty and students can connect with alumni and friends and share exciting Earth and planetary sciences discoveries with a broader audience. In FY2019, this included the John Carlson Annual Lecture and the Henry Kendall Lecture, both bearing a climate- or environment-oriented theme. EAPS also organized well-attended receptions at major scientific meetings, such as those of the American Geophysical Union and the Society of Exploration Geophysicists. The department also supported various events around the country that were hosted by the MIT Alumni Association and the Office of Resource Development and starred some of the most sought-after EAPS faculty speakers.

Fellowship gifts to EAPS dipped slightly in FY2019, due in part to the focus on capital fundraising. The department hopes to rebuild critical pipelines of student and faculty support in FY2020 and to continue to add to its endowment funds. EAPS remains most grateful to MIT alumni and friends for their commitment to the department's scientific mission.

Faculty Research Highlights

Andrew Babbin

The Babbin laboratory comprises biogeochemists, oceanographers, and microbial ecologists studying the interplay of chemistry and biology across spatial scales. Researchers focus on the interactions of microorganisms with their chemical environments in an effort to understand climate and the roles microbial communities have in setting marine biogeochemistry. They specifically investigate the cycling of marine nitrogen, the limiting nutrient for productivity and fertility across much of the global oceans, under reduced oxygen concentrations. Their approach is threefold: investigating in situ biogeochemistry through shipboard field work, designing laboratory-based systems to probe the underlying fundamentals for microbial community growth and function, and analyzing the implications of their observations with numerical simulations and modeling. Over this past year, they have made significant headway toward these goals. The lab participated in two research cruises to the eastern tropical North Pacific: one as a guest of Bess Ward (Princeton University) for five weeks in March and April, and the laboratory's own cruise for three weeks in June and July. Samples from these cruises are being analyzed for microbial rates and chemical concentrations in the EAPS laboratory, and—in collaboration with Bess Ward and Scott Wankel (WHOI)—will undergo mass spectrometry analyses.

Researchers in the Babbin laboratory are further isolating denitrifying bacteria to build a set of environmental isolates for the construction of mock communities to investigate fundamental controls on denitrification in the ocean. In the lab, they have completed construction of genetically engineered strains of bacteria for experiments investigating the impact that specialization of genetic metabolisms among separate microorganisms has on marine biogeochemistry and climate. They have complemented targeted field and laboratory work aimed at mechanistic controls with projects exploring distribution and interannual variability of ocean nitrous oxide from the atmospheric time series of the Advanced Global Atmospheric Gases Experiment network (Susan Solomon has been particularly supportive of this project), prebiotic nitrogen chemistry (with Sukrit Ranjan, a postdoctoral associate in Sara Seager's group), and hurricane mixing of oxygen minimum zones (with Daniel Gilford, former graduate student of Kerry Emanuel's).

Kristin Bergmann

The fossil record of life indicates that eukaryotes, unlike bacteria and archaea, evolved slowly and fitfully. First appearing approximately 1.8 billion years ago, eukaryotes took a billion years to establish microscopic complexity and another 250 million years to diversify as macroscopic organisms. Traditionally, the geobiological community has invoked a paucity of atmospheric oxygen to explain why complex life took so long to evolve. The Bergmann laboratory is actively testing a different explanation—that temperature changes controlled both the early evolution of complex life and oxygen availability. They are testing two ideas: long-term changes in carbonate sedimentation dampened Earth's climate fluctuations, and extreme temperature variability controlled both dissolved oxygen concentrations and the evolutionary patterns of early complex life.

A key step in testing these ideas is disentangling the importance of diagenesis, temperature, and the evolution of seawater's stable oxygen isotopic composition on the marine carbonate, chert, and apatite records. This decades-old problem is addressed in two of Bergmann's 2018 papers in *Geochimica et Cosmochimica Acta* and *Journal of Sedimentary Research*. A collection of her group's papers planned for submission in spring 2019 continued to flesh out and test these ideas. The first idea, that the carbonate record was a major factor in Earth's climate history, also features in a range of papers to be submitted in spring 2019. The Bergmann laboratory is testing hypotheses that, if accurate, will upend the way we view the evolutionary history of eukaryotes and how the selective pressures of that history shaped the genetic, functional, and structural characteristics of complex life. Additional papers report tests of the existing models for equatorial glaciation (the so-called Snowball Earth) with new temperature and seawater stable oxygen isotopic composition constraints.

Richard Binzel

The American Astronomical Society, Planetary Division, awarded the Urey Prize to Francesca DeMeo, a collaborator in the Planetary Spectroscopy group at MIT headed by Professor Richard Binzel.

Enceladus and the Icy Moons of Saturn, a volume in the University of Arizona Space Science Series, appeared in 2018. *Planetary Astrobiology*, another volume in the series, was in preparation during AY2019. Professor Binzel is general editor of the series.

Research

In a NASA spaceflight project spanning EAPS and the Department of Aeronautics and Astronautics, Professor Binzel has been overseeing the in-space operation of the Regolith X-ray Imaging Spectrometer (REXIS) instrument aboard NASA's OSIRIS-REx asteroid sample return mission. REXIS is an MIT student-built flight experiment that has involved more than 80 students to date. During the current year, REXIS acquired its scientific measurements of the mission target asteroid Bennu, seeking to use its x-ray radiation characteristics as a diagnostic tool for discerning the asteroid's composition.

Tanja Bosak

The Bosak laboratory uses experimental geobiology to investigate interactions between microbes, biogeochemical cycles, and sediments.

Mirna Daye, a former postdoctoral associate, demonstrated the occurrence of anaerobic manganese oxidation in photosynthetic cultures that lack oxygen. This process had been thought to be impossible in the absence of oxygen. Daye also demonstrated the formation of dolomite in these cultures, providing a plausible analogue for the anaerobic formation of this major sedimentary mineral in the Archean. She submitted two manuscripts describing this to *Nature* and *Geology*. Most students and postdoctoral associates in the laboratory explored fossilization processes in anaerobic and aerobic microbial systems, with implications for the early Earth and Mars. Kelsey Moore, a graduate student, enriched many cyanobacteria that had previously not been used to test new calibration points for molecular clock models, demonstrating that eukaryotic plastids evolved early and implying a date for the origin of cyanobacteria that predates the Great Oxidation Event by 0.6 billion to 0.3 billion years. Haitao Shang, a former undergraduate student in the lab, has shown that a common methane-producing archeon forms elemental iron in the presence of iron oxides. He is currently writing a manuscript to describe this surprising finding. Lily Momper, a former Crosby Fellow, sequenced, assembled, and annotated genomes of various cyanobacteria and submitted an article describing the genomes of modern cone-forming cyanobacteria that are used as analogues of Archean cone-forming organisms. Sharon Newman, a former graduate student, characterized microbial processes that promote early fossilization of soft tissues, with implications for the preservation of the earliest animal fossils.

Edward Boyle

Professor Edward Boyle's group has extended its exploration of the marine geochemistry of chromium (Cr) and chromium isotopes. Geologists use these properties to infer aspects of oxygen in past environments, but there has been very little direct process investigation in the modern environment. The group's foci have been on the Eastern Tropical North Pacific oxygen deficient zone and the Alaskan Arctic continental shelf . They have also begun the analysis of lead (Pb) and lead isotopes on a long ocean transect from the Bering Sea to Tahiti.

Graduate student Tianyi Huang has analyzed samples she collected on a cruise in April 2018 for the two redox species of chromium [Cr(III) and Cr(VI)] and their isotope ratios. She found that Cr(III) is −1.5 parts per thousand (‰) lighter than the Cr(VI) that it is formed from. In the core of the oxygen-deficient zone, after the conversion of 83% of Cr(VI) to Cr(III), the isotopic composition of the residual Cr(VI) is 2.7‰ heavier in the $^{53}Cr/^{52}Cr$ ratio than the initial chromium. Sixty-four percent of the Cr(III) is scavenging onto the surfaces of sinking particles and is removed from the oxygen-deficient zone, leaving the residual total Cr lighter by 0.66‰.

Following up on the thesis work of former graduate student Simone Moos, researchers in Boyle's laboratory analyzed chromium and chromium isotopes at four stations on the Alaskan Arctic continental shelf and at a station in the Bering Sea that is the source of water for the Alaskan shelf. They find depleted chromium concentrations and extraordinarily enriched total dissolved chromium isotope values in the eight deepest samples nearest the shelf sediment, reaching values up to 3‰ heavier than the source water. They attribute this finding to the diffusion of reduced iron [Fe(II)] from the organic-rich reducing sediments of the Alaskan shelf, and its well-known reduction of Cr(VI) with an isotopic fractionation factor of −4.2‰, followed by strong scavenging onto the turbid, particle-rich, near-bottom waters. Particulate chromium data show a strong enrichment in the near-bottom waters, supporting this interpretation.

Visiting student Shuo Jiang has begun the analysis of samples from the Bering Sea to Tahiti (Pacific Meridional) transect provided to EAPS by the US GEOTRACES program (US GEOTRACES section GP15). A profile to the northeast of Hawaii shows an excellent profile rising from low values near the surface to a maximum at a depth of 200–300 meters (due to the subduction of northerly surface waters downwind of Chinese industrial emissions), and then a gradual decrease to very low values (5 picomoles per kilogram) near the bottom. The $^{206}Pb/^{207}Pb$ profile shows an increase from approximately

1.16 near the surface (reflecting recent Chinese lead emissions) to approximately 1.18 near the bottom (reflecting ancient natural lead). The $^{208}Pb/^{207}Pb$ profile shows a strong decrease near the bottom, attributed to the advection of Pacific bottom water through the deep passage south of the Horizon Guyot.

Timothy Cronin

Professor Timothy Cronin continued to develop his research program on climate, clouds, and atmospheric convection. Doctoral student Tom Beucler, whom Cronin co-advised with Kerry Emanuel, defended his thesis in fall 2018 and graduated in February 2019; first-year PhD student Martin Velez-Pardo joined the group in fall 2018. Third-year PhD student Tristan Abbott attended a field campaign on extreme thunderstorms in Argentina, which complemented his dissertation work on precipitation extremes, and won an outstanding student poster award at the American Meteorological Society conference on atmosphere and ocean fluid dynamics in June 2019. Cronin taught 12.003 Introduction to Atmospheres, Oceans, and Climate in fall 2018, helped design a course for all first-year graduate students in EAPS (also in fall 2018), and taught 12.815/12.315 Atmospheric Radiation and Convection in spring 2019. Cronin organized the 9th Northeast Tropical Meteorology Workshop, which was held in Dedham at Endicott House in June 2019. Notable publications from the group included a paper written with Daniel Chavas of Purdue University on dry and semi-dry hurricanes and a paper by postdoctoral associate Nicholas Lutsko about why precipitation efficiency is likely to increase in a warmer climate.

Julien de Wit

The scope of Professor de Wit's research is to build a platform to maximize the odds of identifying signs of habitability or life with the upcoming generation of observatories. This platform requires the development of hardware components at the beginning of the chain and development of software at its current end. The hardware component relates to building additional telescopes for the Search for Habitable Planets Eclipsing Ultra-cool Stars (SPECULOOS) project to identify as soon as possible the planetary systems around ultra-cool dwarf stars. The Transiting Planets and Planetesimals Small Telescope (TRAPPIST) has found one such system, known as such as TRAPPIST-1, whose temperate Earth-sized planets are amenable to in-depth atmospheric studies with upcoming telescopes. No other existing observatory is designed to find such planets. The software component relates to developing the tools to reduce, analyze, and interpret upcoming data sets. Preparing for their interpretation requires a particular effort in improving spectroscopy line lists and mitigating stellar contamination. Over the past year, de Wit's work has mostly been related to managing the various work leading to the installation of MIT's SPECULOOS telescope in Tenerife, supervising students, and preparing classes.

Kerry Emanuel

During 2018, Professor Kerry Emanuel's attention was focused in several directions. From a strictly research standpoint, Professor Emanuel thinks he finally arrived at an understanding of the physics behind the Madden-Julian Oscillation, one of the strongest signals observed in the tropical atmosphere, consisting of a single wave trapped at the equator and traveling eastward with a 30–60 day period. This has been something of a holy grail in theoretical atmospheric science since the Madden-Julian Oscillation was discovered in the mid-1970s. This understanding resulted in a paper with colleague Marat Khairoutdinov at the State University of New York at Stony Brook in which Professor Emanuel's theoretical model was tested with advanced numerical simulations.

Much of Emanuel's time in the spring of AY2018 was occupied in writing a major review of tropical cyclones that was published in the American Meteorological Society's *Meteorological Monographs* in honor of the organization's 100th anniversary in December 2018. The paper is 68 journal pages long with more than 200 references. During his leave of absence in the fall, Emanuel was able to make good progress on a number of projects and start a few new ones. With an intern's help, he was able to polish up a detailed observational test of a tropical cyclone rainfall algorithm he had developed over the past few years. Emanuel believes his work is the first physical risk model of tropical cyclone flooding ever developed, and as the private sector absorbs the task of insuring floods in the US, and as the federal government abandons that task, he should be in a good position to help assess risks accurately.

Raffaele Ferrari

The Ferrari group's research is focused on the role of ocean circulation on climate. The group approaches the question with a combination of theory, observational campaigns, and numerical models.

This past year, the group made key progress on three lines of research. They have shown that the expansion and retreat of sea ice around Antarctica played a key role in driving the ice ages. When Antarctic sea ice expands at the beginning of an ice age, it traps more carbon in the ocean, plummeting the Earth into a full-fledged ice age rather than a minor cold spell. The partitioning of carbon between the ocean and atmosphere is controlled by the rate at which it can be stored in the abyssal ocean. The Ferrari group's new theory suggests that carbon flows rapidly in and out of the abyssal ocean along ridges and seamounts. They verified the theory with numerical simulations over the past year. Professor Ferrari is now the principal investigator of a large observational campaign in the Rockall Trough funded to test the theory in the ocean over the next three years.

In collaboration with the California Institute of Technology, researchers in Ferrari's lab started writing a new climate model that uses nested high-resolution simulations to improve the representation of subgrid-scale physics. The goal is to write the ocean component of the model from scratch in the next three years and then couple it with the atmospheric component in the following two years. The project is sponsored by a consortium of philanthropies led by Eric and Wendy Schmidt and by the National Science Foundation.

Michael Follows

Professor Michael Follows's group seeks to map and understand the biogeography and biogeochemical role of marine microbes. He uses theory, data analysis, and numerical simulations to this end. Although the significance of microbial activity for global biogeochemical cycles is clear, the group does not yet have a comprehensive mapping of such activities, nor a clear theoretical framework with which to describe and interpret them. The work lies at the interface of ecology, biogeochemical cycles, and oceanography.

In the past year, enabled by his role in larger collaborative efforts, Professor Follows has seen significant progress toward one of his long-standing research goals. The elemental composition (i.e., the ratio of carbon, nitrogen, and phosphorus) of sinking marine particulate profoundly regulates the ocean's role in controlling atmospheric carbon dioxide. In turn, elemental composition is strongly affected by the physiological state and macromolecular composition (i.e., the ratio of protein, carbohydrate, lipid, and ribonucleic acid) of marine phytoplankton. Models rooted in this notion can help interpret the patterns and flows of elements in the ocean and make dynamic, mechanistic simulations of microbial controls on the carbon cycle and climate. However, because of the focus on gene-level tools and research in the oceanographic community in recent decades, this potentially fruitful approach has not been pursued. Over the past several years, through collaborative efforts supported by the Gordon and Betty Moore Foundation and the Simons Foundation, Follows has pursued the characterization of the relationships between macromolecular and elemental composition in laboratory cultures, developed mechanistic modeling frameworks rooted in these data, collected field data on the macromolecular composition of surface ocean particulate, and interpreted and simulated these data with ocean models. This decade-long effort has started to come to fruition with manuscripts now submitted on modeling and laboratory work and several more in preparation.

Gregory Fournier

The general scope of Gregory Fournier's lab's research is using genome sequence data and phylogenetic trees to inform the understanding of planetary history. Researchers do this by mapping the evolutionary history of genes and metabolisms that are relevant to major biogeochemical processes on Earth. Detecting horizontal gene transfer events between groups and applying molecular clocks for absolute dating of these events permits the use of genome data as a record of planetary history, one largely independent of the geological record. Researchers use these same approaches to reconstruct the very earliest history of life on Earth as it is preserved in genome signatures, developing new techniques to make the most of this scant, highly altered signal.

The lab's most important work in the past year was to successfully complete a bioinformatics pipeline for automatically detecting sets of gene transfers between groups of organisms that have the greatest potential for constraining their relative ages. While automated gene transfer pipelines have existed for some time, these tend to be catch-all approaches that recover large numbers of candidate gene transfers that often have uncertain donors and recipients, or multiple possible alternative gene transfer scenarios. These pipelines are also highly sensitive to the "rooting" of individual gene trees. Work in Fournier's laboratory has shown that these rootings are often incorrect and that inferred gene transfers are highly sensitive to the initial rooting assumption. Using improved rooting methods and a series of stringent criteria, the group has isolated the approximately 1% of gene transfers that are likely highly reliable for constraining ages within molecular clocks—so-called index transfers. Researchers are currently testing this approach against several data sets with known transfer histories, as well as mapping the landscape of types of transfers that can be identified (e.g., shallow, recent transfers, as opposed to deep, ancient events). These results are significant because they represent the first application of well-established biostratigraphic principles to gene transfer as a dating method, generating a standard database of index transfers for dating in the same way that paleontologists use a standard set of index fossils for dating. This promises to be a great improvement over other transfer-based dating pipelines which use far larger sets of inferred transfers in an approach that averages across a large, weak signal, instead of relying on a set of carefully vetted individual observations.

Timothy Grove

Professor Timothy Grove and former student Christy Till completed an experimental study that recreated the mantle melting processes that occur when water is added to mantle lherzolite in a subduction zone environment. The experiments were carried out at pressure and temperature conditions analogous to those that are encountered at the base of the mantle wedge just above the subducted ocean lithosphere. From their experimental results, they hypothesize that mantle wedge melting occurs over a range of depths, beginning at the base of the mantle wedge and ending at shallow mantle depths. These water-bearing mantle melts ascend and remain isolated until they mix in the shallow, hottest part of the mantle wedge. These are the first experiments to show how the compositions of hydrous mantle melts change with depth in the mantle wedge. An additional important finding of the work is that the metasomatic “slab melt” contribution to the magmas has to be small (approximately 5% by weight). However, its effect on the alkali, rare-earth element, and incompatible trace element budget of arc magmas is large. Grove and Till’s results reproduce the trace elemental characteristics of the primitive andesites found globally in arcs.

Thomas Herring

Professor Thomas Herring is using primarily 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. Development has continued on the MIT geodetic processing software GAMIT/GLOBK, as well as modeling improvements for the analysis of data from global navigation satellite systems. These developments allow data to be processed from the Russian Globalnaya Navigazionnaya Sputnikovaya Sistema (global navigation satellite system, GLONASS), the European Galileo satellite navigation system, the Chinese BeiDou navigation satellite system, and the US Global Positioning System. This past year, a new global-scale reprocessing of GNSS data collected since 1996 will begin. The results from this reprocessing will be used internationally for studying geophysical processes. This effort is being coordinated by the International GNSS Service. Professor Herring and Michele Moore from Geoscience Australia are the analysis center coordinators. Herring is also using interferometric synthetic aperture radar (InSAR) to study small surface deformations and he is developing new analysis methods for the interpretation of InSAR results. His group is using high-precision GNSS measurements in many different study areas, including over much of the southern Eurasian plate boundary and the western United States. The group is investigating processes on time scales of years leading up to earthquakes, transient deformation signals lasting days to weeks to years, post-seismic deformation after earthquakes on time scales of a day to decades, and surface wave propagation during earthquakes using high-rate GPS data. All of these measurements have sub-millimeter to a few millimeters precision.

John Marshall

John Marshall, Cecil and Ida Green Professor of Oceanography, studies the circulation of the ocean, its coupling to the atmosphere, and the role of the oceans in climate. This past year he has been working on the role of the ocean in modulating inter-hemispheric asymmetries in climate and the movement of the intertropical convergence zone. This involves a collaboration with Associate Professor David McGee. Professor Marshall has also been working on the dynamics of the Beaufort Gyre in the Arctic, a collaborative project with Professor Mary-Louise Timmermans of Yale University, and on the response of the southern ocean and sea ice to westerly wind trends induced by the ozone hole, a collaboration with Susan Solomon, the Lee and Geraldine Martin Professor of Environmental Studies at MIT.

Brent Minchew

Professor Brent Minchew's research lies at the interface of geophysics and climate science, and focuses on the connections between ice sheets, the climate system, and the solid Earth. This work has important implications for understanding past and future sea level rise, ocean circulation, Earth surface processes, and the global carbon cycle. To make progress on these broader questions, he studies the dynamic response of modern ice sheets to internal variability and external forcing, taking a data-intensive approach to understanding the fundamental mechanics of slip at the ice-bed interface and the deformation and fracturing of ice. Over the past year, Professor Minchew's group has done important work on two distinct themes in glacier dynamics: the mechanics of deforming glacier beds and the thermo-mechanics of glacier shear margins. The mechanics of glacier beds are poorly understood, which has long been recognized as one of the most important gaps in our understanding of ice sheet evolution. This year, they used a first-of-its-kind data set and a new model to constrain the mechanical properties of the ice–bed interface in a typical Antarctic outlet glacier. These results are unique and highlight a powerful approach to using newly available data to make progress on fundamental questions concerning the mechanics of fast-flowing glaciers. The group published three papers on the thermo-mechanics of shear margins. Perhaps the two most important contributions in these papers were the location of where in Antarctica the deformation rates are likely sufficient to melt the ice and quantification of the roles of various mechanisms in changing ice rheology in areas of rapid deformation. This second result presents a novel approach to addressing long-standing, fundamental questions related to the relative influence on ice viscosity of ice temperature and the crystalline structure of glacier ice.

F. Dale Morgan

Professor F. Dale Morgan's major focus is AY2019 was to re-engage in preparing work for publication. These efforts included the following:

- Alali, A. M., J. Ogunbo, and F. D. Morgan. Novel approach toward 1d resistivity inversion using the systematically determined optimum number of layers. Submitted to *Geophysics*.
- Morgan, Frank D. and R. Jerry. Investigations into the groundwater flow toward a spring in the Sapphire area, Soufriere, St. Lucia, West Indies. Submitted to *The Leading Edge*.

- Al Nasser, Saleh M., J. Ogunbo, and F. D. Morgan. An inversion approach toward a reduction of fluid flow model parameters. Submitted to *Journal of Geophysical Research*; reviewed manuscript and submitted to *Hydrology*.
- Al Ismail, M. and Morgan, F. D. 2018. The relationship between the compressional wave velocity of saturated porous carbonate rocks and density: theory and application. Presented at the American Association of Petroleum Geologists International Conference and Exhibition, Cape Town, South Africa, 4–7 November.

Research

Professor Morgan works in all areas of applied geophysics and in earthquake prediction. All finite difference tomograms suffer from the problem of too many pixels (in two dimensions) or voxels (in three dimensions). One useful approach is to apply some form of smoothing or regularization. With student Saleh Al Nasser, Morgan is using inversion to investigate the reduction of the large number of elements used in the forward modeling of fluid flow. The results are fascinating and encouraging. They intend to continue the research for Saleh's PhD by doing three-dimensional problems, and also applying the method to other areas of geophysics, such as resistivity and seismic problems.

Morgan's PhD student Ammar Alali's paper on automating one-dimensional resistivity inversion is to be published in *Geophysics*. Alali's main interest, however, is in artificial intelligence. He and Morgan intend to work on three or four problems by both conventional and artificial intelligence methods and to compare these critically.

Lubna Barghouty, another of Morgan's PhD students, will work on optimal experimental design. Morgan predicts that all field geophysics will be done in an iterative fashion—that is, a spatially uniform measurement system will first be used and then—with the results of a quick inversion—the data acquisition will be done again with different source–receiver positions. The point is that all data are not equally important to the accuracy of the inversion, and if too many of the poor (sensitivity) data are added to the inversion, the result can actually be less accurate. For some types of geophysical methods such as resistivity, the iteration of the data collection will be done automatically in the field.

Paul O'Gorman

The general scope of research done by Professor Paul O'Gorman group covers the behavior of the atmosphere in different climates, with a focus on the role of water vapor and precipitation. The group's recent research addresses three broad questions:

- How do the characteristics of precipitation (including spatial, temporal, and intensity distributions) change in respond to climate warming?
- How does latent heating related to phase changes of water affect the general circulation and behavior of extratropical cyclones?
- How does atmospheric convection behave in different models and how can it best be modeled as a subgrid process in climate models?

Changes in surface temperature and humidity over land are important for the effects of climate change on humans and ecosystems. In their most significant paper last year, O'Gorman's group showed how trends in land humidity and temperature in recent decades are linked to ocean warming. While changes in temperature and humidity have been different over land and ocean, they have combined to give equal changes in the moist static energy of the air over land and ocean. Byrne and O'Gorman used this dynamical constraint, and an additional constraint based on moisture transport, to estimate land climate changes given the ocean's warming. Land surfaces are notoriously complex to understand and model, yet their results show a remarkably simple behavior of the climate system that emerges at large scales.

Shuhei Ono

Associate Professor Shuhei Ono's group continues to apply their novel spectroscopy method to precisely determine the abundance of a rare isotopologue of methane—the doubly substituted isotopologue $^{13}CH_3D$—to gauge its formation temperature in a range of geologic settings. One of the group's major goals is to define the limit of life in a deep subsurface environment (e.g., at how high a temperature can life survive), as microbial methanogenesis is usually the terminal biological process in deep sedimentary environments. They worked with industry to measure mud gas logging samples from deep drilling and also participated in the International Ocean Discovery Program. So far, it appears that temperature has the most critical effect on the survival of microbial life in energy-starved environments. Their research has significant applications for oil and gas exploration. To understand microbial physiology and isotope fractionation at the thermodynamic limit, they started experimenting with electrochemical techniques to culture methanogenic microbes. The results of this project can be applied to develop efficient microbial fuel cells and to understand microbial physiology in nature. The ultra-sensitive optode oxygen sensor developed in Ono's laboratory has been very useful in culturing anaerobic microbes. They have also developed a new spectroscopy instrument to measure a doubly deuterated methane isotopologue with good precision, and this new tool will be used for future studies. They continued their study on the origin of Archean sulfur mass-independent isotope fractionation and its implications for the early Earth's anoxic atmosphere. In the group's work with Professor Robert Field of the Department of Chemistry and graduate student Alexander Hull, made a comprehensive spectroscopic model of the disulfur molecule was made. Ono expects this will be a huge step toward understanding the unique isotope's effect and its full geochemical implications.

Matej Pec

Assistant Professor Matěj Peč's research focuses on understanding the rheological properties of the lithosphere with two main topics being pursued in his group: the interaction between fracturing and viscous flow of rocks, and the influence of stress on melt segregation in partially molten rocks.

The interaction between fracturing and viscous flow of rocks is one of the outstanding challenges in Earth sciences. Constraining the mechanisms responsible for the brittle-viscous transition is critical for improving the understanding of the seismic cycle. In the past year, Professor Peč and his group have made significant advances in integrating an acoustic emission recording system into an experimental deformation apparatus. Currently, they have improved the sensitivity of the system by an order of magnitude and record about 4,000 events per experiment on quartzite. They have recently managed to add two sensors that allow the basic localization of events at pressures of up to 2 gigapascal. Acoustic emissions are important proxies for fracture events. The change in character of acoustic emissions with changes in pressure-temperature conditions will yield new insights into the brittle-viscous transition of rocks.

Melting and deformation go hand in hand in nature, yet most of our understanding of melt network geometry is based on hydrostatic experiments. Peč's group has begun to explore the influence of stress on grain-scale melt alignment at high pressures (greater than 300 megapascal). The goal is to quantify the development of melt preferred orientation and crystallographic preferred orientation and quantify their combined effect on the viscous and elastic anisotropy of partially molten aggregates over a range of pressures. The experiments are challenging. Peč's doctoral student Cassandra Seltzer is tackling the experimental problem and is making good progress.

J. Taylor Perron

Professor J. Taylor Perron's group works to discover and quantify the processes that shape landscapes on Earth and other planets. Their goal is to reveal how a planet's geologic, climatic, and biological histories are recorded in its surface topography, and how that topography in turn shapes a planet's history.

In the past year, Professor Perron's group expanded their focus on dynamic river networks. They discovered evidence of a major, ongoing change that corroborates their previous work: the Amazon (the largest river in the world) is in the process of capturing the headwaters of the Orinoco (the fourth largest river in the world). Doctoral student Maya Stokes and Perron collaborated with fish biologists to explore how such changes in river networks affect the evolution of aquatic species and regional biodiversity.

Zooming in to river networks at a much finer scale, postdoctoral associate Eric Deal, PhD student Santiago Benavides, and Perron collaborated with Professor Ken Kamrin's group in Mechanical Engineering to study the granular physics of sediment motion in turbulent rivers. They aim to improve predictions of gravel and sand transport rates, especially in human-impacted systems such as dam-removal sites and engineered channels.

On the planetary side, Perron led a collaboration with EAPS research scientist Jason Soderblom, WHOI's Andrew Ashton, and MIT-WHOI Joint Program doctoral student Rose Palermo to study the coastlines of hydrocarbon lakes and seas on Saturn's moon Titan—the only known standing bodies of liquid not on Earth. One of their goals is to determine if there are waves on Titan's seas, in anticipation of an eventual lander mission.

Daniel Rothman

Recent work by Professor Daniel Rothman has established a relation between the great environmental disruptions of the geologic past and modern environmental changes. Professor Rothman's work focuses on the carbon cycle. Earth scientists know that levels of carbon are now growing much faster than they did during the worst disruptions of the past, including those associated with mass extinction. However, modern changes are occurring over centuries, whereas ancient changes occurred over tens of thousands of years or more. Rothman's work predicts that catastrophic changes are possible if the influx of carbon dioxide to the oceans exceeds a threshold. Because the threshold increases inversely with the duration of forcing, the modern perturbation of the carbon cycle turns out to be roughly equivalent, in terms of its potential to excite a major disruption, to the relatively weak but longer-lived perturbations of the past.

Leigh Royden

Professor Leigh Royden works in the area of regional geology and geophysics and the mechanics of large-scale continental deformation, contributing to the study of geologic processes through quantitative geophysical modeling. Currently serving as the director of MIT's Experimental Study Group, Professor Royden has been on the faculty at MIT since 1988.

Royden has considerable supervisory responsibilities. She supervises 13 staff members (mainly instructors) teaching General Institute Requirement courses, more than 50 first-year students, and 40 teaching assistants in the junior and senior years. She also supervises the department's alumni relations efforts as well as fundraising (where she raised an endowment of approximately $1.2 million for the Experimental Studies Group). Professor Royden oversaw the making of a feature-length documentary film about the Experimental Studies Group at MIT.

Roger Summons

Members of Professor Roger Summons's geobiology laboratory continue to query geochemical records concerning early life and the evolution of planet Earth. Collaborating with other researchers interested in these topics, they continue to advance knowledge about the environmental controls on the production of diagnostic lipids in modern organisms and settings and their meaning for interpreting ancient fossilized counterparts. A signature result was a publication in *Science* by the team working the sample analysis on Mars instrument suite onboard the Curiosity Rover that reported the discovery of complex organic matter in the regolith of Mars.

Members of the laboratory are active in retrieving and interpreting molecular fossils pertinent to the evolution of animals during the Ediacaran period. One key was the paper in *Nature Ecology and Evolution* on a new sponge biomarker lipid that has been listed as one of three denoted as runner-up research in *Science* Breakthroughs of 2018.

Collaborating with colleagues at Stanford University, the University of Oklahoma, and the University of Cambridge, researchers in Summons's laboratory have conducted studies that have refined the chemical structures of the complex membrane spanning ether lipids in archaea and aspects of their biosynthesis. This research is funded by grants from NASA, the Simons Foundation Collaboration on the Origins of Life, and Shell.

Robert D. van der Hilst

Professor Robert D. van der Hilst has been head of the Department of Earth, Atmospheric and Planetary Sciences 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 of the University of

Grenoble and colleagues at Imperial College London), and development of algorithms for high-resolution seismic imaging with natural earthquakes (in collaboration with de Hoop). In recent years, van der Hilst's team developed a method for determining contrasts in mass density and seismic wave speed across interfaces deep in Earth's interior. From such measurements, the team estimated the composition and temperature beneath the Hawaiian Central Pacific at depths that are well outside the reach of direct observation and measurement. They presented novel approaches to the imaging of the structure of Earth's crust and the upper mantle beneath North America. They also demonstrated that one can use seismic waves to detect and quantify deformation of a volcano caused by tides and changes in precipitation and atmospheric temperature. The team's work resulted in a number of papers, including the following:

- Yu, C.-Q, E. A. Day, M. V. de Hoop, M. Campillo, S. Goes, R. A. Blythe, and R. D. van der Hilst. 2018. Compositional heterogeneity near the base of the mantle transition zone beneath Hawaii. *Nature Communications*
- Golos, E. M., H. Fang, H. Yao, H. Zhang, S. Burdick, F. Vernon, A. Schaeffer, S. Lebedev, and R. D. Van der Hilst. 2018. Shear wave tomography beneath the United States using a joint inversion of surface and body waves. *Journal of Geophysical Research: Solid Earth*, 123: 5169–5189
- Boyce, A., I. D. Bastow, E. M. Golos, S. Rondenay, and R. D. van der Hilst. 2019. Variable modification of continental lithosphere during the Proterozoic Grenville orogeny: Evidence from teleseismic P-wave tomography. *Earth and Planetary Sciences Letters*, Vol. 525
- Mao, S.-J., M. Campillo, R. D. Van der Hilst, F. Brenguier, L. Stehly, G. Hillers. 2019. High temporal resolution monitoring of small variations in crustal strain by dense seismic arrays. *Geophysical Research Letters*

Benjamin Weiss

Professor Benjamin Weiss studies the formation, evolution, and history of planets and small bodies, with a particular focus on paleomagnetism and geomagnetism, planetary geophysics, meteoritics, planet formation, and planetary paleoclimate and habitability. He analyzes planetary samples and conducts in situ spacecraft exploration of solar system bodies to understand the history of these geophysical and geochemical processes.

Researchers in Professor Weiss's group had four major achievements in the past year. First, they showed that the lunar dynamo ceased about a billion years ago. It had been shown that the Moon generated a dynamo magnetic field lasting from at least 4.2 billion years ago to as late as 1 billion years ago. However, it has been unclear when the dynamo ceased. They conducted new paleomagnetic and argon–argon dating studies showing that two lunar breccias cooled in a near-zero magnetic field at approximately 0.4 billion years and 0.9 billion years ago, respectively. Combined with previous paleointensity estimates, this indicates that the lunar dynamo likely ceased sometime between approximately 1.0 and 0.9 billion years ago. The protracted lifetime of the lunar magnetic field indicates that the late dynamo was likely powered by crystallization of the lunar core.

Second, they demonstrated that, contrary to recent claims by another group, zircons do not contain evidence for the existence of the geodynamo prior to the oldest known rock record at 3.5 billion years ago. They conducted the first detailed rock magnetic and mineralogical analyses of Hadean zircons, combining high-resolution magnetic field imaging, ultra-high sensitivity moment magnetometry, and transmission electron microscopy imaging. The results indicate that Jack Hills zircons likely were substantially remagnetized long after they formed.

Third, they developed a thermodynamic model for understanding the formation of the cloudy zone in meteorites that enabled two powerful new applications. First, they used the model to develop the first new metallographic cooling rate indicator for meteorites since the classic Widmanstatten technique was developed in the early 1960s. Second, they used the model to obtain quantitative estimates of ancient magnetic field intensities to be derived from synchrotron measurements iron meteorites. Despite the fact that they are samples of planetary cores, iron meteorites have heretofore been largely inaccessible to paleomagnetic analyses.

Fourth, they identified unambiguous new evidence for the existence of partially differentiated planetary bodies. Meteorites are classified into two principal lithographic types: chondrites, which are aggregates of primitive nebular material that remained unmelted on their parent planetesimals, and achondrites, which are the products of planetesimal melting processes. It has long been thought that no single parent body is the source of more than one of these two meteorite lithologies, meaning that early planetesimals evolved into a bimodal distribution of either undifferentiated or fully differentiated bodies. They have now found such evidence for such a body in a group of iron meteorites that consist of an iron matrix containing silicate inclusions (the iron meteorites). The silicates exhibit almost the full range of igneous differentiates—silicate partial melts, partially melted silicates, and an unmelted chondritic crust—expected for a partially differentiated planetesimal. Moreover, the group's cloudy zone paleomagnetic study of two IIE meteorites found evidence for a core dynamo, indicating the body also contains a large metallic core.

Robert D. van der Hilst
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