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 and inform policy and solutions in areas such as climate change and natural resource management. The department comprises 43 faculty, 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 one with a primary appointment in the Department of Mathematics. In addition, EAPS has more than 300 students, research staff, postdoctoral associates, and visiting scholars.

EAPS is notable for addressing problems that benefit from (or require) interdisciplinary approaches and is involved in numerous laboratories, centers, and programs that address broad questions in the Earth sciences, including those that are related to the most pressing societal issues of our time: changes in climate and environment, responsible use of natural resources, understanding and forecasting natural hazards, and understanding the origin and evolution of life on Earth and, perhaps, discovering signs of life 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 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 the Institute's largest participant in the MIT/Woods Hole Oceanographic Institution (WHOI) Joint Program, supporting its mission of graduate education and research in ocean sciences and engineering.

Educational Activities

The EAPS faculty is committed to the development and maintenance of vibrant education programs at both the undergraduate and graduate levels. 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 programs, with the aim of sustaining active and open conversations around educational issues.

During the past year the EAPS Task Force 2023 engaged students in a variety of surveys and focus groups in addition to hosting a two-day retreat. The goal of the task force was to take a broad look at the department and assess the status quo, explore what can be improved, and make recommendations for change. Students were engaged in discussions of curricula, research, community, and student funding, to name a few.

These conversations were robust and helped form recommendations for improvements in the overall educational program at the graduate as well as the undergraduate level. Recommendations for change were viewed as both short-term goals (such as changes to the general exam process for graduate students) and long-term goals (such as a deep look at the undergraduate curriculum tracks that help define career paths).

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, EAPS had 160 registered graduate students (152 PhD students, eight SM students), including 82 students in the MIT/WHOI Joint Program and two fifth-year master's students. Women constituted 51% of the graduate student population; 6% were members of an underrepresented minority group.

The excellence of the EAPS graduate program is built not only on the strength of teaching and supervision by the faculty but also on the involvement of EAPS graduate students in departmental activities. Students develop formal and informal ways of improving the educational experience as well as the student life of the department. For example, the department's graduate students continue to take responsibility for an expanded orientation program for incoming graduate students. They plan a number of social events to introduce the newcomers to EAPS, MIT, and the Cambridge area. The graduate students are well organized and meet regularly, with students presenting their research to the student body at various seminars such as the Graduate Student Seminar and the EAPS Active Talk Series. 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 2020 academic year, Craig Martin, Christopher Parsons, and Samuel Goldberg were recognized for their contributions.

EAPS students were also recognized by MIT and by professional societies and outside organizations. Christine Chen received the California Institute of Technology (Caltech) O.K. Earl and Texaco Postdoctoral Fellowship in Geological and Planetary Sciences. American Geophysical Union (AGU) Outstanding Student Presentation Awards went to James Bramante, Megan Lickley, and Julia Wilcots. Kalina Grabb was awarded an Association for the Sciences of Limnology and Oceanography (ASLO) Limnology and Oceanography Research Exchange (LOREX) Fellowship to conduct research during an exchange program in Australia. Charles Gertler won the Geological Society of America Congressional Science Fellowship, awarded as part of the American Association for the Advancement of Science (AAAS) Science and Technology Policy Fellowships program. Megan Lickley also received the Martin Fellowship. Zac Tobias was awarded the National Defense Science and Engineering Graduate Fellowship. Arianna Krinos was awarded a Department of Energy Computational Science Graduate Fellowship. Mallory Ringham was awarded an ASLO LOREX Fellowship to conduct research during an exchange program in Israel, and Katie Holloran was awarded a National Defense Science and Engineering Graduate Fellowship. Details on other AY2020 student awards are available on the EAPS website.

Twenty doctoral students and five master's students graduated from EAPS in AY2020.

Undergraduate Program

EAPS had 22 undergraduate majors in AY2020, 74% of whom were women and 30% of whom were members of an underrepresented minority group. Although the EAPS undergraduate population has always been small, the students are very active in the department and are interested in promoting it to help increase undergraduate enrollment. Activities include monthly lunch seminars for undergraduates that expose them to different resources at MIT (e.g., Global Education and Career Development, MindHandHeart), events for incoming first-year students, and involvement through first-year advising and teaching beyond EAPS. The department has prioritized providing summer Undergraduate Research Opportunities Program (UROP) opportunities for undergraduates, which has resulted in over 90 UROP students in the department. The School of Science helped the department with funding UROP students who could not be funded directly by the UROP office. A summer research program was developed to expose the summer UROP students to research being conducted by professors and graduate students in the department while also giving them an opportunity to showcase their research projects and present them to an audience.

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 class with CEE. Our 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 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 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 environment and sustainability minor (a collaboration of courses from 17 departments).

The 2020 student awards ceremony was moved online due to the COVID-19 pandemic. The Goetze Prize was awarded to Kyle Morgenstein (advised by Professor Tanja Bosak) in recognition of his outstanding senior thesis. Ruth Tweedy received the W.O. Crosby Award for Sustained Excellence, recognizing her academic and intellectual achievements and her general contributions to the department. Sarah Weidman 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 Award for Excellence in Teaching for her work as a teaching assistant. Seven students earned bachelor's degrees from EAPS in AY2020.

Faculty

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

Camilla Cattania, a geophysicist working on understanding earthquake processes, will join the department in July 2020.

William Frank, a geophysicist who examines physical mechanisms that control deformation within the Earth's crust, also will join the department in July.

The department is now halfway through the ninth year of the junior faculty mentorship program introduced in January 2012. Each junior faculty is assigned a mentor team comprising a primary mentor (often a close colleague) and two senior faculty members from outside the candidate's disciplinary group. They meet as a group once a semester and report to the head of 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.

Tanja Bosak has been promoted to the rank of full professor (effective July 2020).

Communications

AY2020 was a busy and fruitful year for the Communications Office due to the activities surrounding the EAPS Task Force 2023. Our communications officer co-led Working Group 1: Visibility and Image. Through the research and analysis done in the project, which spanned approximately seven months, paired with community input and the findings of the other working groups (Research Synergies, Departmental Organization and Cohesion) presented and deliberated on at the January retreat, EAPS now has good data and a solid blueprint for messaging themes and marketing strategies as we pursue hiring a branding agency to redesign our website and online presence—a long overdue project that recently received generous donor support for the coming year.

On the heels of the successful Task Force 2023 retreat and Visiting Committee meetings, EAPS Communications was met with the challenges posed by the current coronavirus pandemic. In an all-hands-on-deck situation, the Communications Office was instrumental in not only disseminating rapidly changing information to our constituents and launching the department-wide Slack channel (for more nimble communications and a virtual conversation spot) but also researching and implementing technological best practices for the rapid ramp-up to remote teaching and helping to coach faculty on new tools. Communications also helped to keep a sense of community by sharing profiles and first-person accounts from students and researchers of their pandemic experiences. As the semester came to a close, the office took the lead in creating a remote commencement experience through a weeklong series of video messages from staff, students, researchers, and faculty, culminating with a virtual hooding and the traditional reading of the graduates' names by the department head and associate department head.

As for day-to-day operations, EAPS has had continued success in earning MIT News coverage of scientific papers, with an average rate surpassing larger School of Science departments. Our website user traffic has held steady on an annual basis despite a downturn during the months of the COVID-19 shutdown (11,300 average monthly overall site users, 11,200 of whom are new users). At the same time, the EAPS Twitter and Instagram accounts have taken off due to closer coordination with communications peers across the School of Science (and the MIT communications cohort generally) in addition to a more regular schedule and a strategic approach to promoting news, events, and personal spotlights. In line with trends across social media, Facebook growth has fallen off; Facebook has recently changed its algorithms, and users are drifting to other platforms.

The department's Twitter account has seen a 9% increase in average monthly impressions (to 72,000), a 62% increase in impressions per post (to 4,000), and a 20% increase in followers (to 6,000), while the Instagram account has seen a 98% increase in followers (to 1,900) and now has an average reach per post of approximately 700. Meanwhile, the Facebook account has seen a 20% decrease in average impressions per post (to approximately 800) and a 3% increase in followers (to approximately 9,600).

Our partnership with the MIT Graduate Program in Science Writing to host a student from the program in a half-time research assistant position during AY2020 was a huge benefit to the department. The student was able to contribute many stories for *EAPS Scope* and our regular news feed that we otherwise would not have had time to cover. She was also able to make considerable headway populating the EAPS space on the new MIT Climate Portal website with dozens of climate-related news stories from our library. Finally, she secured media credentials to attend the National Aeronautics and Space Administration (NASA) Mars 2020 launch as an EAPS correspondent. While the pandemic prevented her from attending, we were able to transfer those credentials to another writer to attend and report for us live from the launch—a first for EAPS. We look forward to continuing with this program and welcoming our next research assistant in September.

Resource Development

In FY2020, new gifts and pledges to EAPS totaled $18.63 million, including a generous $10 million commitment for the Earth and Environment Pavilion. Our total raised for the pavilion is now $26 million, which is just $5 million short of our fundraising goal to create this exciting new hub for climate and environmental science research and programming adjacent to the Green Building.

Other notable major gifts included a capital gift of $1.2 million for the Rasmussen Laboratory (currently under construction in Building 4), where the focus will be on climate-related research, and a $2.5 million pledge for a new career development professorship in EAPS.

New funds created by EAPS major donors in FY2020 included the EAPS Endowed Fund, the EAPS Strategic Communications Fund, the Charles E. Kolb Lectureship Fund, and the Donald L. Paul Observational Astronomy Fund. EAPS also worked in partnership with the Radio Society to raise over $200,000 to renovate program space on the roof of the Green Building.

EAPS is grateful to its Visiting Committee members and many generous alumni and friends for their philanthropic support and to foundations such as the Simons Foundation, the Heising-Simons Foundation, and the Change Happens Foundation for supporting EAPS faculty and students in their innovative research endeavors.

Faculty Research Highlights

Andrew Babbin

The research performed in the BabLab (Bacteriology and Aquatic Biogeochemistry laboratory) focuses on the nitrogen cycle and the microbial process of denitrification, a pathway that supplants aerobic respiration as the major remineralization metabolism when oxygen levels are low. Headed by Assistant Professor Andrew Babbin, the group investigates how denitrification develops. For example, combining in situ ocean data collection with targeted laboratory experiments using model organism cultures, the group identifies the chemical controls on denitrification and uses this metabolic framework as a lens for understanding microbial community development, metabolic partitioning, and evolution. Over the past year, progress has been made on multiple fronts. In coordination with postdoctoral research fellow Sukrit Ranjan, the group has identified probable pre-biotic nitrogen chemistry on Earth as a method for constraining the likelihood of the development of life on the planet, finding shallow terrestrial ponds much more likely than open ocean/hydrothermal vents due to their ability to amass large quantities of fixed nitrogen. In a similar vein, regarding the diversity of chemical pathways existing on Earth, the group has identified the major metabolisms occurring within the modern ocean's anaerobic oxygen-deficient zones, including the dominance of nitrite oxidation, to resolve the disparate observations previously reported by a number of researchers. The group, including numerous MIT students (Elisabeth Boles '18, Susan Mullen '18, Jarek Kwiecinski, Martin Wolf PhD '20), further identified the role of water mass intrusions in setting the chemistry of the Eastern Tropical North Pacific, as measured on a cruise led by Babbin in summer 2018. As part of the master's thesis of Tyler Tamasi, the group has discovered prevalent denitrification and other anaerobic metabolisms among tropical coral tissue, occurrences not previously reported. Finally, the senior thesis of Elisabeth Boles'18 showed that the ocean's oxygen-deficient zones are hot spots of nitrous oxide production subject to variability induced by the El Niño and La Niña climate states.

Kristin Bergmann

Professor Bergmann's research group studies the interactions between ancient climates and early complex life. In particular, her group studies the nature of carbonate sedimentation through time and reconstructs temperature records from rocks approximately 443 million to 1 billion years old. The Bergmann lab uses a combination of approaches including fieldwork, micro-analytical methods (e.g., electron microprobes and synchrotron-based techniques), and carbonate clumped isotope geochemistry. The lab 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.

During the 2020 academic year, Professor Bergmann was on maternity leave.

Richard Binzel

After 10 years of development and three years of flight, the Regolith X-ray Imaging Spectrometer (REXIS) instrument aboard NASA's OSIRIS-REx asteroid sample return mission delivered its data in July and November 2019. Led by Professor Binzel, nearly 100 students participated in designing, building, and operating MIT's farthest flown student experiment.

Edward Boyle

Professor Boyle and his group extended their exploration of the marine geochemistry of chromium (Cr) and chromium isotopes. These properties are being used by geologists to infer aspects of oxygen in past environments, but so far there has been very little direct process investigation in the modern environment. Boyle's focus has been on the Eastern Tropical North Pacific Oxygen Deficient Zone (ETNP ODZ). In unrelated work, the group also completed half of the analyses of lead (Pb) and Pb isotopes on a long ocean transect from the Bering Sea to Tahiti, and a century-long record of Pb and Pb isotopes from a cold water coral off the Iberian Margin.

Graduate student Tianyi Huang analyzed samples of the two redox species of Cr—Cr(III) and Cr(VI)—she collected on a research cruise in the ETNP ODZ in October 2019 and assessed their isotope ratios. She found significant spatial variability within the ODZ (similar to that seen in the related redox trace nitrite ion), but at seawater potential densities below 27% all of the samples showed depleted Cr concentrations and enriched d^{53}Cr values relative to a completely oxic station outside of the ODZ. For one station just outside of the ODZ (station 23), data showed that reduced Cr(III) and Cr isotope anomalies advected/diffused out of the zone. Performing an in situ incubation experiment, she found that nanomolar reduced Fe(II) at a level as low as five reduces Cr(VI) to Cr(III) at measurable rates over several days.

Visiting student Shuo Jiang has analyzed half of the samples provided to the Boyle group by the US GEOTRACES GP15 transect from the Bering Sea to Tahiti. In addition to features noted in last year's report, the group found a strong plume of Australian-type Pb (low ^{206}Pb/^{207}Pb) moving northward at a depth of 300 to 700 meters in stations at 20°S and 10.5°S. In the deep waters at those stations, ^{206}Pb/^{207}Pb is high, reflecting either South American anthropogenic lead (Peru, Chile) transported on sinking particles or glacially eroded crustal lead from the Antarctic continent transported northward in Antarctic bottom water. In stations north of 10.5°N at least to 47°N, upper ocean waters show high ^{208}Pb/^{206}Pb ratios indicative of Chinese anthropogenic emissions. The group is also completing revisions on a manuscript on Pb and Pb isotopes in the Peru to Tahiti Eastern Pacific Zonal Transect, another area in which there is Chinese Pb in the upper waters.

As part of their MIT-Portugal project with Lélia Matos (Instituto Português do Mar e da Atmosfera, Lisbon), the group analyzed Pb and Pb isotopes from a 200-year-old cold-water coral collected off of the Iberian Peninsula at a depth of 1,400 meters. They found increased Pb concentrations and lower ^{208}Pb/^{207}Pb in samples from the past few decades, reflecting the outflow of dense salty water from the Mediterranean Sea.

Julien de Wit

The research of Professor de Wit's group focuses on building a platform to maximize our odds of identifying signs of habitability and/or life with the upcoming generation of observatories, notably the James Webb Space Telescope (JWST). To do so, they completed the installation of the first SPECULOOS telescope in the Northern Hemisphere (called ARTEMIS) and developed new tools to mine the collected data with the goal of revealing other planets such as TRAPPIST-1 (to date, the only exoplanet known to be terrestrial, temperate, and amenable for immediate atmospheric study). The group recently applied these new planet-finding tools to archival data and found "pi-Earth," a terrestrial planet on a 3.14-day orbit that may be one of the few terrestrial planets accessible with the JWST. The planet was confirmed with ARTEMIS, and the discovery paper led by graduate student Prajwal Niraula was recently accepted for publication.

In parallel with their efforts to detect the few terrestrial planetary systems of high impact for the decade to come, the team has pushed forward the development of tools for exoplanet characterization to optimize the scientific return of observatories. The goal is to provide the group with a significant competitive advantage when writing observational proposals. This effort requires a wide range of expertise and is supported by an integrated effort involving two postdoctoral members, four graduate students, and seven UROP students.

Kerry Emanuel

Professor Emanuel continued working with his four graduate students on a variety of problems related to climate and to tropical cyclones. With his student Raphael Rousseau-Rizzi, he pursued the hypothesis that the Atlantic hurricane drought of the 1970s and 1980s was caused by sulfate aerosol pollution originating in northern Europe. With graduate student Jonathan Lin, Emanuel made semi-operational a 1,000-member ensemble of real-time hurricane forecasts designed to make accurate pointwise probabilistic predictions of hurricane conditions. With Rohini Shivamoggi, Emanuel continued to investigate how secondary eyewalls develop in tropical cyclones, focusing on the physical mechanisms at work. Finally, with Sydney Sroka, a Mechanical Engineering PhD student under his supervision, Emanuel continued highly advanced two-phase flow computations of the formation and effects of sea spray under very high wind conditions.

During January and February Emanuel participated in a field campaign called EUREK4A, headquartered in Barbados. The goal of the project is to understand the properties of shallow moist convective boundary layers, which are poorly understood and which exert strong climate effects.

On the service side, Emanuel was appointed by Provost Martin Schmidt to lead a group of 12 MIT School of Science faculty in a search for a new dean of science. The group met extensively beginning in mid-March and conducted numerous interviews with both stakeholders and potential candidates. The search committee submitted its final report to the provost on June 17.

This year Professor Emanuel won the BBVA Foundation Frontiers of Knowledge Award in the Climate Change category and was elected a foreign member of the Royal Society.

Raffaele Ferrari

The Ferrari group focused on two large research projects during the past year: the Climate Modelling Alliance (CliMA) and the Boundary Layer Turbulence Experiment (BLT). The goal of CliMA is to build a new climate model, the Climate Machine, that leverages recent advances in the computational and data sciences to learn directly from observations and high-resolution numerical simulations as a means of improving the representation of small-scale processes that cannot be explicitly resolved in global climate models (clouds, atmospheric and ocean turbulence). This past year at MIT, the group developed the core of the ocean component of the Climate Machine. The code is written in Julia, a computer language spearheaded by colleague Alan Edelman that allows the model to run on emerging computer architectures such as graphics processing units, thus achieving performance above most existing ocean codes. The model relies on discrete Galerkin numerics, thereby closing the gap between state-of-the-art computational fluid dynamics and climate modeling. The group also developed new algorithms to represent sub-grid-scale turbulent processes in the ocean model and machine trained them with high-resolution simulations that explicitly resolved these processes.

The BLT project consists of a one-year field campaign in the North Atlantic to test the group's recent hypothesis that the heat and carbon that sink into the abyssal ocean at high latitudes come back toward the surface along the slopes of ridges and seamounts. While the field campaign has been postponed to next year, the group has been able to make progress on the theory by relying on available historical observations and high-resolution numerical simulations. For example, they have demonstrated that the flows that develop along the rugged slopes of the abyssal ocean control not only the rate at which waters rise toward the surface, and thus the global overturning circulation, but also abyssal ocean stratification.

In an attempt to diversify the group and engage with undergraduate students during these difficult times, the group recently welcomed two SuperUROP students working on CliMA and four UROP students studying the evolution of the COVID epidemic using statistical network models. The group has succeeded in both goals. The UROP group is remarkably diverse and engaged and has been incredibly productive.

Glenn Flierl

Professor Flierl and his students are investigating ocean physical and biological dynamics and other more general problems in geophysical fluid dynamics. Recent publications include an analysis of vortex structures in back-and-forth flows with applications to Jupiter's Great Red Spot, an exploration of a non-local formulation of turbulent mixing in the ocean surface layer, and an examination of the interaction and stability of vortices over seamounts or flow around islands. Madeleine Youngs defended her thesis work on the ways in which topography in the Southern Ocean affects the location of exchanges of heat and carbon with the atmosphere. Students in the group have also been studying how phytoplankton growth can occur even in winter and how eddies alter patterns of chlorophyll on the ocean surface. Collaborators have presented talks or posters at the American Physical Society, American Geophysical Union, and Ocean Sciences meetings as well as in seminars.

Professor Flierl has participated in many outreach events and forums using the iGlobe spherical display and the newly developed Environmental Science Globe; examples include Girls' Day at the MIT Museum, the Carleson Lecture, and the World Organization for Sustainability Leadership, which trains high school students to become "junior ambassadors" for the United Nations Sustainable Development Goals and Sustainable Energy for All initiatives.

Gregory Fournier

Over the past year, one of the objectives of the Fournier lab was to publish research completed during 2019, including (1) a new molecular clock age estimate for the origin of cyanobacteria and oxygenic photosynthesis during the Mesoarchean, long before the great oxygenation event, using integrated dating techniques such as fossil calibration and horizontal gene transfer constraints; (2) reconstruction of the evolutionary history and novel enzymatic organization of early nitrate-reducing microbial metabolisms as facilitated by the discovery of new deep subsurface bacteria, a project completed by Crosby Postdoctoral Fellow Lily Momper; and (3) a computational analysis of the impact of site rates within modeling sequence evolution showing that the often-discarded "fast-evolving" sites within conserved protein alignments inform, rather than obfuscate, the phylogenetic signals needed to accurately resolve the deepest branches in the tree of life. Also, the group completed the primary objective of their research supported by a National Science Foundation Integrated Earth Sciences Award and a Simons Collaboration on the Origins of Life Award. That work involved implementing the group's completed pipeline for detecting "index" horizontal gene transfers across the tree of life that are informative in terms of establishing the relative ages of tree of life groups. Using these detected transfers, they will map the relative ages of every major group of microbes on the tree and obtain an entirely novel set of absolute ages calibrated by fossil records.

Professor Fournier's accomplishments this year included giving invited lectures on astrobiology and evolutionary microbiology at Johns Hopkins University's Space Telescope Science Institute and the annual meeting of the Geological Society of America. He also served as a panel chief for the NASA Interdisciplinary Consortia for Astrobiology Research program. His lab ran their second Darwin Day outreach initiative together with the Boston Public Schools and the Franklin Park Zoo in Dorchester. Fournier's initiative works with middle school students from Boston Public School districts that primarily serve students from less privileged and underrepresented backgrounds. With guidance from the lab's members, these students work with their teachers to create and staff interactive exhibits for public engagement at the zoo during Darwin Day, celebrating Charles Darwin's birthday.

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

Timothy Grove

Professor Grove and recent PhD student Max Collinet completed an experimental study that re-creates what happens when planetesimals that formed during the first few million years of solar system history start to heat up and melt. Collinet designed a series of experiments at elevated pressures and temperatures similar to those occurring in the interiors of these bodies and demonstrated the first melt compositions. Surprisingly, there were already meteorites that had been found and described that matched these melt compositions—and nobody knew how these meteorites formed. Now this information is available: these mystery meteorites are very rich in SiO_2 and alkali elements (Na_2O and K_2O), not unlike the common granites that make up the Earth's crust.

There are two general classes of meteorites, chondrites and achondrites. Chondrites are made up of the first solids that condense from a gas of solar nebula composition, and they form bodies 100 to 200 kilometers in size that then heat up and melt. Meteorites sampled from these bodies that have undergone melting and subsequent chemical differentiation are called achondrites.

The conventional thinking was that the first melts of chondrites should be similar to the common basalt magmas found on Earth that form from melting of the Earth's mantle. But this assumption had never been tested. The experiments on chondrites (which have a very different chemical composition than the Earth's mantle) produced a partial melt that is much more similar to these mystery meteorites that are very rich in SiO_2 and alkali elements (Na_2O and K_2O). They are called trachyandesites.

Collinet's experimental results also provide new insights into how the terrestrial planets (Mars, Earth, Venus, Mercury) formed. These planets are variably depleted in alkali elements (Na_2O and K_2O). It had previously been assumed that this variable depletion occurred during condensation of solids from solar nebular gas under differing conditions, leading to variable incorporation of alkalis in the solids that condensed. This assumption was made in spite of the fact that no chondrites show this type of variability in these elements. Collinet's work shows that there is a process that can lead to variable alkali depletion—early melting of small planetesimals—and that this process can be used to show what types of chondrites melted to form the inner terrestrial planets and what types of chondrites could not have melted.

Professor Grove is the chair of Matej Pec's mentoring committee and continues to serve on AGU's development board. In addition, he continues as executive editor of *Contributions to Mineralogy and Petrology* and serves as an editor for the *Proceedings of the National Academy of Sciences*.

From August 17 to 24, Professor Grove led the Discover Earth, Atmospheric and Planetary Sciences (DEAPS) Yellowstone trip with 35 people attending. He taught two classes in the fall, 12.109 Petrology and a first-year advising seminar, 12.A03 Meteorite from Mars Kills Dog. In the spring, he was on sabbatical leave.

Bradford H. Hager

There is growing concern about seismicity triggered by human activities, wherein small stress increases cause tectonically stressed faults to fail, resulting in significantly greater stress release. Examples include mining, impoundment of water, stimulation of geothermal fields, extraction of hydrocarbons and water, and injection of water, carbon dioxide, and methane into subsurface reservoirs. In the absence of sufficient information to understand and manage the processes triggering earthquakes, authorities have set up empirical or statistical regulatory monitoring–based frameworks with varying success. Hager's group has a paper under review in *Nature* in which they report on the development, testing, and implementation of a new methodology for managing triggered seismicity using unusually detailed data about the subsurface, including data on hydrocarbon production and water injection, to inform geomechanical and earthquake source physics models. They employed their approach in the Val d'Agri oil field in southern Italy, providing the first documented case of successful management of triggered seismicity built on a process-based method applied to a hydrocarbon-producing field. Applying their approach elsewhere could help to manage and mitigate triggered seismicity.

Hager's second significant contribution, which represents a new direction for his research, grew out of teaching 12.021 Earth Science, Energy, and the Environment, a core science course for the undergraduate energy minor in which students examine the costs and benefits of various energy sources. In preparing his lecture on hydropower, he became aware of its sometimes surprisingly large greenhouse gas footprint. Because Hydro-Québec (HQ) power features prominently in Massachusetts' effort to decarbonize its electricity supply, Hager used HQ as an illustrative example. This led him to a detailed analysis and synthesis of the literature, allowing him to assemble and improve estimates of HQ's greenhouse gas footprint. HQ claims that its emissions are comparable to those of wind power, but Hager found that they are an order of magnitude higher and are a significant fraction of those produced by modern natural gas plants. He has provided written and oral testimony to the US Army Corps of Engineers for consideration in its permitting of the New England Clean Energy Connect, given lectures to the Sierra Club and others, and published an op-ed in the *Portland Press Herald*.

Thomas Herring

Professor Herring is using primarily global navigation satellite system (GNSS) data to develop geophysically based models of Earth deformations on global, regional, and local scales as well as changes in the rotation of the Earth. His group has continued to reprocess GNSS data collected for the past 24 years. This reprocessing includes data from the Russian GLONASS and European GALILEO systems along with the US GPS system. The results from the reprocessing will be used internationally for studying geophysical processes. This effort is being coordinated by the International GNSS Service (IGS). Professor Herring and Michele Moore from Geosciences Australia are the IGS analysis center coordinators. The 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. In addition, they are investigating processes on time scales of years leading up to earthquakes, transient deformation signals lasting days to years, postseismic deformation after earthquakes on time scales of days to decades, and surface wave propagation during earthquakes using high-rate GPS data. All of these measurements have sub-millimeter to low-millimeter levels of precision, and the group works actively in developing stochastic models to explain the noise characteristics in the data while being cautious about maintaining novel signals.

John Marshall

Professor Marshall and his research group continued several lines of research. They have ongoing projects on icy moons (Enceladus and Europa), the interaction of oceans and ice in Antarctica and the Arctic, and the dynamics of the Inter-Tropical Convergence Zone (ITCZ). Marshall is particularly excited by the group's studies of icy moons with postdocs Suyash Bire and Wanying Kang. This is new territory with many opportunities.

Graduate student Brian Green was awarded the Rossby Prize for the best graduate thesis in the Program in Atmospheres, Oceans and Climate. His work explored the coupling of the ITCZ with ocean circulation and will become textbook material. Mukund Gupta completed his PhD and is taking a postdoctoral position at Caltech. Graduate student Faye Elgart joined the group last fall, and a new graduate student, PJ Tuckman, will join this upcoming fall.

The group also worked with the Department of Physics in developing and trying out for the first time (in fall 2019) a sequence on non-inertial frames of reference (e.g., Coriolis forces) in 8.01 Physics I, the introductory physics class that most undergraduates take in their first year.

Brent Minchew

Assistant Professor Brent Minchew continued research on the interactions among the climate, the cryosphere, and the solid Earth. Over the past year, most of his efforts have been 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 on ice sheet dynamics, building a research group that currently includes 12 UROP students, seven PhD students, one postdoctoral research associate, and one research scientist. In addition, over the past year he has secured research funding, developed and taught two new courses in continuum mechanics, continued as an editor at a leading journal in his field (*Journal of Geophysical Research: Earth Surface*), and expanded outreach efforts that entail engaging with middle school students from underrepresented minority groups and serving as an advisor to the Boston Museum of Science.

In AY2020, Minchew and his group published four papers in scholarly journals and submitted three other manuscripts for peer review. The published papers focused on the mechanics of glacier beds composed of water-saturated sediment and the tensile strength of natural glacier ice. These studies were largely based on theory, although the paper focused on the tensile strength of ice contained a significant observational component built on optical satellite imagery. The papers under review are broadly focused on the mechanics of glacier beds and the thermomechanics of glacier (lateral) shear margins, which separate fast-flowing ice from stagnant ice or rock. These studies encompass a range of tools and approaches, from theory and experimentation to sophisticated time-series analysis and inverse methods. In the coming year, the group expects to build on all of the published and submitted work to address the broader issue of the stability of continental ice sheets.

Shuhei Ono

Associate Professor Shuhei Ono's group studies how microbes catalyze chemical reactions that shape the chemistry of our atmosphere and oceans. In particular, the group has investigated the early evolution of atmospheric oxygen using stable sulfur isotope systems and developed a novel tool to pinpoint the origin of methane, a significant long-lived greenhouse gas and a key biosignature gas for space exploration.

Postdoc Yenny Gonzalez-Ramos reported the development of the group's novel laser spectrometry instrument to measure the doubly deuterated isotopologue of methane ($^{12}CH_2D_2$). Jeemin Rhim G successfully defended her PhD dissertation ("Experimental Investigation of Isotopologue Fractionation during Microbial Methanogenesis"), which reported on her experimental investigation of isotopologue fractionation by methanogenic microbes cultured using a flow-through reactor and a novel electrochemical device. Ellen Lalk G measures methane from deep ocean drill core samples to investigate the temperature limits of microbial life on the seafloor. Patrick Beaudry G studies the abiotic formation of methane in volcanic fumaroles in Greece and Iceland.

Taylor Perron

Professor 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 effects on erosion, landscapes, and the human past; and the landscapes of Mars and Saturn's moon Titan.

Among the highlights from the 2020 academic year were two research directions in which natural laboratories were used to explore connections among climate, erosion, and plate tectonics. First, recent PhD graduate Kimberly Huppert continued the group's focus on volcanic islands. Sea cliffs border more than half of the world's ocean coasts, but there was previously no way to predict how fast these rocky coasts will erode under different conditions. Huppert, Perron, and Woods Hole's Andrew Ashton used variations in coastal erosion rates around the Hawaiian Islands to show how the erosion of rocky coasts depends on wave climate. In addition, Huppert, Perron, and Leigh Royden showed that the lifetime of volcanic islands (the length of time they spend above sea level) depends on how fast tectonic plates carry them away from sources of uplift in the Earth's mantle. This result explains global variations in island life spans, which influence island topography, biodiversity, and climate.

In the second research direction, two investigations led by recent PhD graduate Paul Richardson showed how sunlight indirectly controls erosion rates in water-limited landscapes, causing slopes that face the Earth's poles to be steeper than slopes that face the equator.

Perron took on the role of EAPS associate department head in July 2018. He has led or facilitated several efforts to enhance undergraduate and graduate education in the department, including the creation of course offerings and modules that encourage more undergraduates to explore EAPS; a new PhD degree in computational earth, atmospheric, and planetary sciences through the Computational Science and Engineering program; a more uniform format for the PhD general exam; and a new course designed to build camaraderie among first-year graduate students. He also helped lead the EAPS Task Force 2023 process in 2019–2020 and coordinated the response of the EAPS academic program to the COVID-19 pandemic.

Paola Rizzoli

In 2017, Professor Rizzoli started a new initiative in Venice, Italy, based on the collaboration among MIT, the Venice University of Architecture (IUAV), the Venice Water Authority, and the Consorzio Venezia Nuova (CVN). CVN is the conglomerate of companies in charge of the planning and construction of the MOSE (MOdulo Sperimentale Elettromeccanico) barriers for the protection of Venice and its lagoon from Adriatic Sea storm surges. The initiative is focused on transmitting to an audience of students, American and Italian, the know-how in science and technology accumulated in more than 25 years of the history of the MOSE barriers. Rizzoli has deep knowledge of both the scientific aspects of the oceanographic problem and the engineering alternatives that culminated in the choice of MOSE as the protective solution.

Three summer schools have been held on the island of Pellestrina in the Venice lagoon. The first was held in 2017 and the second in 2018. The third summer school, focusing on the resilience of Venice and its lagoon, was held in June and July 2019. Thirteen MIT students, supported by the MIT-Italy Program, attended, along with 13 IUAV students. About 15 faculty members from MIT, IUAV, and the Universities of Padua and Venice Ca'Foscari constituted the teaching body and jointly supervised the students.

Daniel Rothman

Recent work by Professor Rothman and his group has focused on the mechanisms that lead to instability in the Earth's carbon cycle. One of their publications highlights the role of a threshold for excitation, suggesting that, after suitable rescaling, a common threshold has existed for the past several hundred million years. A second paper emphasizes the role of a critical rate of change and applies it to the instigation of global glaciation ("Snowball Earth") conditions. Current efforts within the group seek to understand the many abrupt, intermittent warming events of the last 65 million years.

Sara Seager

Professor Seager worked as deputy science director of the MIT-led Transiting Exoplanet Survey Satellite (TESS) NASA mission. She was responsible for the TESS project's delivery of planet candidates from the TESS mission to the community. With the TESS prime mission coming to an end, she stepped down from the position in June 2020. TESS will move into an extended mission phase, and Professor Seager will continue to supervise students and postdocs at MIT working on TESS data.

Seager's Arcsecond Space Telescope Enabling Research in Astrophysics (ASTERIA) space satellite (CubeSat) that was incubated at MIT during a 2010–2011 16.83x Space Systems Engineering series of classes successfully completed its mission in 2019, went silent in December of that year, and deorbited from atmospheric drag in April 2020.

Seager's research team spent a good part of the year working on the Venus atmosphere. They played a part in a tremendous new discovery that will be announced in September 2020. The work involved interpreting new data on the Venus atmosphere obtained by a team in the United Kingdom using the Atacama Large Millimeter/submillimeter Array (ALMA) radio telescope array located in Chile.

Professor Seager's team continued to push the envelope in exoplanet characterization efforts, including work on hot lava worlds using experiments at MIT and the search for life by way of biosignatures.

Susan Solomon

Professor Solomon's group continues to focus on understanding ozone depletion and recovery and on climate change processes and responses to forcing. They have been successful in making significant contributions to both again in the past year. They published one paper showing that springtime Arctic total ozone column information provides improved predictability for surface temperatures in some regions of the Northern Hemisphere, with several months of lead time. In related work, they expanded their scope to include the value of total ozone data for predictions of seasonal sea ice.

They also published two papers on changes in atmospheric circulation related to ozone recovery and have another about to be submitted. It is exciting to document such changes in response to human actions to limit chlorofluorocarbon (CFC) emissions.

In addition, they have completed another paper, very favorably reviewed for *Nature Communications* and likely to be accepted soon, that covers in greater detail than previous work the emissions of CFC-11 and CFC-12 due to "banks" left in refrigeration, foams, air conditioners, and so forth. CFCs deplete stratospheric ozone and are controlled by the Montreal Protocol, and they are also strong greenhouse gases that contribute to climate change. This work is especially important given recent studies showing unexpected emissions of CFC-11 that appear to be related to illegal production in China. Clearly, quantifying other sources of this gas is essential to fully understand the scale and seriousness of the purported Chinese source. Their paper also shows that there is unexpected emission of CFC-113 that is nearly as large as the unexpected CFC-11, raising important new questions about the sources of this gas.

Roger Summons

Members of the Summons geobiology laboratory continue their work on geochemical records regarding early life and the evolution of planet Earth. Collaborating with other researchers interested in these topics, they endeavor to advance knowledge about the environmental controls on the production of diagnostic lipids in modern organisms and diverse environmental settings and their meaning with respect to interpreting ancient fossilized counterparts. Their funding largely originates from the Simons Collaboration on the Origins of Life.

A signature achievement in 2019 resulted from a collaboration with colleagues at Stanford and the University of Oklahoma. The Summons group reported the identification of proteins in a specific clade of ocean plankton residing at the heart of a proxy widely used for sea surface temperature reconstructions. This new knowledge confirms that the proxy originates from temperature sensitivity encoded into lipid membranes of Thaumarchaeota, solidifying confidence in the proxy itself.

The Summons group collaborated on a number of studies relevant to the interpretation of data from the Curiosity rover of the Mars Science Laboratory Mission. In addition, they collaborated on biogeochemical studies of the immediate aftermath of the Chicxulub impactor that initiated the end-Cretaceous mass extinction.

Professor Summons was elected to the US National Academy of Sciences in April 2020.

Robert D. van der Hilst

Professor van der Hilst has been head of 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 professor Maarten De Hoop of Rice University, visiting professor Michel Campillo of the University of Grenoble in France, and colleagues at Imperial College London), and development of algorithms for high-resolution seismic imaging of earthquakes (in collaboration with De Hoop). Over the past several years, van der Hilst's team has developed a method for determining contrasts in mass density and seismic wave speed across interfaces deep in the Earth's interior, and from such measurements they have estimated composition and temperature beneath the Hawaiian Central Pacific at depths well outside the reach of direct observation and measurement. Furthermore, they have developed novel approaches to imaging the structure of Earth's crust and the upper mantle beneath North America and Asia and assessing seismicity in active orogenic belts such as the European Alps and subduction zones. In addition, last year van der Hilst and De Hoop finished theoretical treatises on seismic surface waves and established a novel method for tomographic inversion of seismic data. They also demonstrated that one can use seismic waves to detect and quantify deformation of a volcano due to tides and changes in precipitation and atmospheric temperature and refined the technique for making such measurements.

Benjamin Weiss

The Weiss lab 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. They analyze planetary samples and conduct in situ spacecraft exploration of solar system bodies to understand the history of these geophysical and geochemical processes.

With postdoc James Bryson, Weiss showed that two unusual meteorites formed beyond 20 AU from the Sun, far beyond the formation locations of other meteorites. This is the first robust evidence of known planetary samples that formed in the outer solar system. The subsequent arrival of these meteorites on Earth supports the inward migration of asteroid-sized bodies into the asteroid belt. Such small-body migration has been proposed to result from the growth and/or migration of the gas giants, suggesting that these planets played a key role in the architectural evolution of the solar system. Furthermore, the group now has planetary samples of Kuiper belt objects that will provide records of the geophysical and geochemical evolution of these largely poorly understood bodies.

Jack Wisdom

Professor Wisdom and his former PhD student Zhen Liang Tian published an important new work on the early evolution of the Earth-moon system in the *Proceedings of the National Academy of Sciences* ("Vertical Angular Momentum Constraint on Lunar Formation and Orbital History"). This work shows that recently advocated scenarios for the formation of the moon with an initial high-obliquity Earth are not consistent with the current configuration of the Earth-moon system and places constraints on all other scenarios for the formation of the moon.

Professor Wisdom was named a Legacy Fellow of the American Astronomical Society ("legacy" refers to the fact that this is the first time fellows have been named by the society). Only 200 fellows were selected; the society has approximately 8,000 members.

Robert D. van der Hilst
Department Head
Schlumberger Professor of Geosciences