Department of Earth, Atmospheric and Planetary Sciences

The Department of Earth, Atmospheric and Planetary Sciences (EAPS) studies 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 to inform policy and solutions, for example, concerning climate change and natural resources management. The department comprises 42 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 another with a primary appointment in the Department of Mathematics, and more than 310 students, research staff, postdoctoral researchers, 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 of natural hazards; understanding the origin and evolution of life on Earth; and, perhaps, discovering signs of life elsewhere. For example, the Earth Resources Laboratory—under directorship of Laurent Demanet, professors of Mathematics and EAPS—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 directorship of Ronald G. Prinn, TEPCO Professor and professor of Atmospheric Chemistry—builds cross-institute activity in meteorology, oceanography, hydrology, chemistry, satellite remote sensing, and policy. The Lorenz Center—under co-directorship of Kerry Andrew Emanuel, Cecil and Ida Green Professor of Atmospheric Science, and Daniel H. Rothman, professor of Geophysics—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 are committed to the development and maintenance of vibrant education programs at both the graduate and undergraduate level, even if the latter is small. 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.

Throughout AY2021, EAPS conducted classes via an online format using Zoom and the Canvas platforms.

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 2020, EAPS had 173 graduate students—170 PhD, three SM—registered in the department, including 83 students in the MIT-WHOI Joint Program. Women constituted 51% of the graduate student population, and 9% 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. While this past year meant limited in person access, graduate students still continued academic seminars in the department via the Zoom platform. This provided students with opportunities to not only present their own research, but to also invite external speakers who normally would not have been able to travel to campus to provide an in person seminar.

EAPS awards an annual prize for excellence in teaching to highlight the superior work of its teaching assistants. During AY2021, Noah Anderson, Katie Halloran, Jing He, and Joshua Murray were recognized for their contributions, particularly their ability to innovate online teaching strategies to best serve students in a remote format.

Highlights of our students recognized by MIT and their respective professional societies and outside organizations:

- Ekaterina Bolotskaya: the MathWorks Science Fellowship
- Zahra Essack: the Schlumberger Foundation Faculty for the Future Fellowship.
- Fatima Hussain: the Women in Innovation and STEM Database (WISDM) Fellowship from the MIT Innovation Initiative
- Rohini Shivamoggi: the MIT Recognizing Individuals Supporting Equity (RISE) Mens et Manus Award,
- Julia Wilcots: the MIT Larry G. Benedict Leadership Award
- Eli Mansbach: Future Investigators in NASA EARTH and Space Science and Technology (FINESST) grant to conduct research in paleomagnetism

Visit the EAPS website for other AY2021 student awards.

EAPS graduated a total of 20 doctoral students and five master's students in AY2021. Visit the EAPS website for the full list of degree recipients.

Undergraduate Program

EAPS had 17 undergraduate majors in AY2021, of whom 16 were women and one a member of an underrepresented minority group. We note that the EAPS undergraduate population has always been small but the students are very active in the department and are interested in promoting the department to help increase undergraduate enrollment.

In the spring of 2020 when the pandemic hit, the academic program administrator in EAPS met with all of the undergraduates about the importance of finding ways to keep their community thriving. In AY202,1 this group of undergraduates took that seriously with regular Zoom get-togethers, game nights, academic seminars, and recruitment events for first-year undergraduates. The students had monthly meetings with the Education Office to check in on academic progress, impacts of online and hybrid learning formats, living situations, and mental health and well-being.

Despite the remote nature of the academic year, EAPS provided 140 Undergraduate Research Opportunity Program (UROP) opportunities to undergraduate students. In fall 2020 there were 52 UROPS, 23 during Independent Activities Period, 36 in spring term, and 28 for summer term. The majority of UROPS were conducted remotely but there were in laboratory opportunities for students who were housed on campus with CovidPass.

The number of EAPS majors is small, but 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. Michael J. (Mick) Follows, professor of Oceanography, co-taught an ecology class with CEE. Our faculty members with joint appointments—Kerri Cahoy, associate professors of AeroAstro and EAPS; Noelle Eckley Selin, associate professors of EAPS, and Data, Systems, and Society, and associate director of IDSS; Collette L. Heald, professors of CEE and EAPS; Ruben Juanes, professor of CEE; Dara Entekhabi, Bacardi and Stockhold Water Foundation Professor, and professors of CEE and EAPS; and Laurent Demanet—are also active in teaching undergraduates. The department supports and provides leadership of two major undergraduate programs at MIT: Terrascope, under directorship of David McGee, associate professor of Paleoclimate, and the Experimental Studies Group, under directorship of Leigh H. Royden, professor of Geology and Geophysics. EAPS also offers First-year Advising Seminars. Due to the Covid-19 pandemic in fall 2020, EAPS was unable to offer First-Year Pre-Orientation Programs as our historical offerings involved travel with groups to Yellowstone National Park and Mount Washington. EAPS undergraduates did an excellent job of developing orientation sessions for first-year students that introduced students to the scientific opportunities within EAPS. EAPS is also an active participant in four interdisciplinary minor programs: the broadly-based Energy minor; the Astronomy minor, with Physics; the Atmospheric Chemistry minor, with Chemistry, AeroAstro, CEE, and IDSS; and the Environment and Sustainability minor, which is a collaboration of courses from 17 departments.

The 2021 Student Awards were again moved to an online ceremony due to the Covid-19 pandemic. The *Goetze Prize* was awarded to Megan Guenther (advised by Timothy L. Grove, Cecil and Ida Green Professor of Geology) in recognition of her outstanding senior thesis. Julia Clarke received the *W.O. Crosby Award for Sustained Excellence*, recognizing her achievement, both academic and intellectual, as well as general contributions to the department. Juliana Drozd 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 high grade point average, focused course work, and leadership within EAPS. Sarah Weidman received an *Undergraduate Teaching Assistant Award* for her work as a teaching assistant.

In addition to departmental awards, EAPS undergraduates have been recognized by both MIT and external groups. Lily Zhang was named a recipient of the Barry Goldwater Scholarship. Aviva Intveld received the National Oceanic and Atmospheric Administration (NOAA) Hollings Undergraduate Scholarship. Finally, both Sheila Baber and Azzo Seguin were inducted into Xi Chapter of Phi Beta Kappa.

Faculty

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

We are in the tenth year of the junior faculty mentorship program, originally 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 of 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 alike are satisfied with the new system, and feedback solicited from junior faculty will be used to make further improvements.

New Hires

Searches in the past three years resulted in six faculty offers at the junior level—two men and four women, of which two are women of color—and one faculty offer to a woman at the senior level, all of which were accepted. The 5:2 gender ratio, both in offers and acceptances, helps diversify our faculty.

Effective July 2021, Arlene M. Fiore, professor of Atmospheric Chemistry, has joined the department as a full professor. Fiore is the first person to be appointed as the Peter H. Stone and Paolo Malanotte Stone Professor, a full professorship that was generously endowed to EAPS by EAPS Professor Emeritus Peter H. Stone and Professor of Physical Oceanography Paola Malanotte-Rizzoli.

Promotions Effective July 2021

Oliver E. Jagoutz, associate professor of Geology, and Shuhei Ono, associate professor of Geochemistry, have both been promoted to the rank of full professor.

Diversity, Equity, and Inclusion Summary

EAPS took important steps this year toward increasing the diversity of its faculty, staff, and students, fostering inclusive environments, and advancing equitable practices. In September 2020, a new associate department head for Diversity, Equity and Inclusion (DEI) position was created, and David McGee was appointed to the position. At the same time, the departmental DEI committee was formed, bringing together staff, faculty, graduate students, postdoctoral researchers, research scientists, and undergraduate students to coordinate and advance DEI efforts in the department.

In fall 2020, the committee developed a DEI Roadmap that established priorities and timelines for DEI actions for the next 18 months. Later in the year, the committee created an internal website that shares climate survey results, meeting minutes, and demographic data with the rest of the department. The committee also established practices for recognizing and celebrating department members' service contributions, including creating a departmental service award that was received by Towards Inclusion and Diversity in EAPS (TIDE)—a student-led group in the department—and coordinating a nomination process for MIT-wide awards. This effort resulted in Kristin Bergmann, Weedon Career Development Professor and assistant professor of Geology and Geochemistry, being awarded the Paul Gray Faculty Award for Public Service and more as mentioned in the award highlights section.

In spring 2021, EAPS organized a group of approximately 40 department members to take part in an National Science Foundation (NSF)-funded program called "Unlearning Racism in Geoscience (URGE)". In addition to reading and discussing articles and viewing interviews with leading experts in DEI in Earth science, the group examined departmental practices and structures and made recommendations to the department that will be considered over the coming months. Outside of URGE, the department also provided its members with learning opportunities through departmental seminars by leading Earth science experts on DEI Kuheli Dutt, assistant dean for DEI in the School of Science, Melissa Burt, and Erika Marin-Spiotta, as well as informational sessions about reporting structures from Institute Discrimination and Harassment Response.

Building on efforts by the 2017–2019 Diversity Council, EAPS faculty have also established clear, equity-focused faculty search processes, and this year these processes were formally revised and adopted by the faculty. The practices include bias awareness training for the search committee, regular interaction with the associate department head for DEI, inclusion of a DEI statement in candidates' applications, and a formal graduate student group organizing feedback on finalists. Though these practices have only been used in the last three years, the data are encouraging: in searches from 2014–2017, seven out of eight offers went to white men; in searches from 2018–2021, five out of seven offers went to women, of which three were women of color. As a result of these searches and the recent appointment of Arlene Fiore to the Stone professorship, five new women faculty members have either recently started in EAPS or will start in the next 18 months, marking important progress toward shifting the demographics of our faculty toward the gender-balanced composition of our graduate students.

This year, EAPS also established a DEI Officer position jointly with the Department of Chemistry. A spring 2021 search led by David McGee,Timothy M. Swager, John D. MacArthur Professor and professor of Chemistry, and a search committee consisting of students, staff, and faculty from both departments resulted in the hiring of EmmaLee Pallai, who started in July 2021 and brings substantial expertise advancing understanding and equity in academia and other complex organizations. The investment by both departments in this high-level staff position promises to substantially expand our capacity for further DEI progress.

Finally, while this report focuses on departmentally-coordinated actions, key DEI actions have also been taken by students, postdoctoral researchers, and other members of EAPS. TIDE has played an important role in advancing DEI actions, organizing an application mentorship program for graduate students from diverse backgrounds, running a seminar on the legacy of racism, colonialism, and extraction in Earth science, and organizing an affinity group for students of color. In addition, the new group Let's Invest in K–12 (LINK-12) organized K–12 outreach opportunities for department members, both by pairing individual EAPS members with classroom teachers and by partnering with 826 Boston, a nonprofit working with Boston Public Schools.

Communications

The evolving pandemic and remote operations posed a number of ongoing logistical challenges, and opportunities to adapt, for the Communications Office. In response, the team continued to experiment with tools to help streamline internal department communications and build community (e.g. Slack, GatherTown, weekly events digest emails). To aid productivity amongst headquarter staff, the communications team also built detailed project management templates using Asana—a project management tool that helped eliminate confusion during event planning by clearly communicating deadlines, assignments, and feedback, organize shared materials, and took pressure off of collaborators' email inboxes.

For news and online media, EAPS experienced success growing our audiences and reach. In addition to continuing a high yield of successful news pitches to MIT News—earning coverage of scientific papers at a rate often surpassing School of Science peers—our website traffic experienced impressive growth, including a 13% uptick in unique pageviews and a 28% increase in total site visitors which contribute to an average of 14,500 visitors per month. EAPS Twitter and Instagram accounts have maintained robust growth trends thanks to an ongoing strategic approach to promoting news, events, and people profiles, as well as continued coordination with communications peers across School of Science and the Institute. Conversely, Facebook growth has maintained a downward trend, in line with overall social media trends as the core Facebook audience continues to skew older while younger audiences drift to other platforms. Facebook has also continued to make changes to its algorithms which makes comparing apples-to-apples historical data difficult. This decline in analytics is being experienced across MIT-owned Facebook accounts, with peer communicators beginning to entertain sunsetting their Facebook presence or at least decreasing the amount of time devoted to content posted on the platform.

Twitter:

- 21% increase in average monthly impressions to 87,300
- 30% increase in impressions per post to 5,200
- 16% increase in followers to 6,900

Instagram:

- 34% increase in followers to 2,500
- 20% increase in reach to 844 average per post
- 20% increase in likes or reactions to 81 average per post

Facebook:

- 38% decrease in reach and in average impressions per post
- 1% decrease in followers to approximately 9,500

Despite remote operations, EAPS had a successful year of outreach, including hosting the annual Kendall Lecture and a number of special Faculty Forum events with MIT Alumni Association and Resource Development. Broadly, EAPS remote lectures and seminars experienced higher attendance than in years past when events were in person—something that will be taken into consideration as we promote and design events into the future. EAPS Communications also helped a group of postdoctoral researchers and student organizers get connected with the Office of Government and Community Relations in order to launch a pilot for LINK-12.

EAPS also had another successful year hosting an MIT Graduate Program in Science Writing half-time research assistant who contributed several stories and performed critical background research for others, while also updating the EAPS section of the MIT Climate Portal website with dozens of climate-related news stories from our library. We look forward to continuing with this program for AY2022.

Resource Development

In FY2021, new gifts and pledges to the EAPS totaled $10.23 million, which included a total of $6.75 million in new commitments for the Earth and Environment Pavilion (Building 55). In November 2020, EAPS passed the landmark requirement to raise $30 million towards the construction of this new building adjoining the Green Building (Building 54), and the MIT Corporation approved the project to move forward to the design and construction phase. We are indebted to those major donors who stepped forward to ensure the success of our campaign. Building 55 will be a stunning addition to MIT's campus, serving as a new central hub for climate, earth, and space science programs and education, and an inviting new portal to the Green Building. We are now raising funds for some exciting enhancements to the new space.

Other notable development achievements in FY2021 included almost $800,000 raised for graduate fellowships and $111,000 raised for EAPS Discretionary support. New funds created by EAPS major donors in FY2021 included the iGlobe Educational Fund and the Babcock Fund that will also support the new EAPS Endowed Fund.

In addition to the above totals, EAPS Development also worked in partnership with faculty and MIT Radio Society students to raise $1.9 million to rescue and renew infrastructure on the roof of the Green Building, including the historic Big Dish and to replace the iconic radar dome that had marked MIT's skyline for decades and had been destined for demolition.

Despite the restrictions imposed by the pandemic during FY2021, EAPS managed to keep in touch with our donors and networks through e-newsletters, virtual meetings, and events throughout the year. We are indebted to our loyal alumni, the EAPS Visiting Committee, and many other friends—such as the Simons Foundation, Amateur Radio

Digital Communications, Heising-Simons Foundation, the Breakthrough Foundation, and VoLo Foundation—for supporting EAPS ground-breaking fundamental research into the Earth, Planets, Climate, and Origins of Life. We are grateful to those whose investments in Buildings 54, 55 and 4 will enable EAPS to both pursue our research with the latest amenities and attract the next generation of talented Earth and space scientists to MIT to work on some of the most challenging issues facing our planet.

Faculty Research Highlights

Andrew Babbin

The group of Andrew Babbin, assistant professor of EAPS, comprises oceanographers, biogeochemists, engineers, and microbial ecologists seeking to understand the environment and climate from the perspective of the interactions microbes have with their chemical environment and with each other. Their approach is multi-faceted, combining field sampling, analysis of large datasets, precision microfluidics, genetic engineering, bioinformatics, cell culture, and numerical modeling. They focus primarily on the cycling of the element nitrogen, and its relationship with carbon and oxygen. Progress has been made on multiple fronts despite the effects of the pandemic. One study, incorporating the work of multiple MIT graduate students—Tyler Tamasi MS ’19, Diana Dumit, Laura Weber PhD ’20, and Sarah Schwartz), discovered prevalent anaerobic microbial metabolisms among tropical corals and quantified rates of nitrous oxide production. Another important study in which Steven Smriga, research scientist, and Davide Ciccarese, postdoctoral associate, participated, investigated the drawdown of dissolved oxygen across particles as bacteria colonize them and the associated activation of denitrification genes. As for the rest of the world, the pandemic presented a unique challenge for the group given its primary focus on field data collection and experimental analysis. Specific experiments were delayed until access to campus was permitted, research cruises were postponed indefinitely, and deployment of a new instrument to the Galapagos to measure nitrous oxide was infeasible.

Publications

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Edward Boyle

Professor of Ocean Geochemistry Edward Boyle’s group has completed their exploration of the marine geochemistry of chromium—Cr, in both the +III and +IV oxidation states—and chromium isotopes in oceanic oxygen depleted zones (ODZs). Cr isotopes are being used by geologists to infer aspects of oxygen in ancient environments, but there has been little process documentation from the modern environment. They have studied samples from the three major ocean ODZ's: Eastern Tropical North Pacific (ETNP), Eastern Tropical South Pacific (ETSP), and the Arabian Sea. They find that the upper zone of the ODZs has the strongest reduction of Cr(VI) to Cr(III) (with an isotope fractionation of -1.3‰) and that the isotope fractionation during reduction is the same in both the ETNP and ETSP ODZs. The Arabian Sea shows Cr isotopic values consistent with a similar redox process. This work is documented in a *Proceedings of the National Academy of Sciences (PNAS)* publication and in Tianyi Huang's just-defended PhD thesis.

The group has developed a new low-blank method for the analysis of picomolar concentrations of lead (Pb) concentrations and Pb isotope ratios using Pb-205 spike. They have also completed three quarters of the analyses of Pb and Pb isotopes from a long ocean transect from the Bering Sea to Tahiti (US GEOTRACES GP15 section). We find a strong plume of Australian-type Pb (with $^{206}Pb/^{207}Pb$ as low as 1.15) moving northward at 300–700m depth at stations at 20°S and 10.5°S in the Sub-Antarctic Mode Water. This signal may be created either by atmospheric transport directly from Australia—as clearly seen from the recent wildfire smoke plumes—or from the southern Indian Ocean which shows this signal as far south as 40°S and transported into the Pacific by the eastward-flowing Circumpolar Current. In the deep waters at those stations, $^{206}Pb/^{207}Pb$ is high (>1.185) reflecting either South American anthropogenic lead (Peru, Chile) transported to depth by sinking particles or from 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. They also published a manuscript on Pb and Pb isotopes for the Peru to Tahiti Eastern Pacific Zonal Transect at approximately 15°S (US GEOTRACES GP16 section) that also sees Chinese Pb in the upper waters north of 10°S. As part of our MIT-Portugal project with Lélia Matos, researcher with the Instituto Português do Mar e da Atmosfera (Portugues Institute for the Ocean and Atmosphere) in Lisbon, they analyzed Pb and Pb isotopes from a 200-year-old cold-water coral collected from 1400m depth off of the Iberian Peninsula and several others from the western North Atlantic and Gulf of Mexico. They find 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, and the presence of US-derived Pb in the western regions.

Camilla Cattania

Camilla Cattania joined the EAPS faculty as an assistant professor in July 2020. Cattania and her group study fault mechanics and earthquake physics, primarily using numerical simulations and frictional theory. Their focus in the last year has been on understanding the role of complex fault geometry on seismic sequences and slow slip, using numerical simulations and frictional theory. In a paper published earlier this year, Cattania demonstrated that fault roughness provides a physical explanation for foreshocks occurring prior to large earthquakes, and can explain the spatio-temporal characteristics observed in nature. First year student Yudong Sun has studied the effect of roughness on slow slip events in subduction zones, while postdoctoral fellow Enrico Milanese is working on the temporal evolution of fault geometry caused by wear along a rough surface.

Julien de Wit

The scope of Assistant Professor of EAPS Julien de Wit's research is to build a platform to maximize our odds of identifying signs of habitability and/or Life with the upcoming generation of observatory, notably the James Webb Space Telescope. Doing so requires (1) finding terrestrial temperate exoplanets whose atmospheres can be studied in details with upcoming telescopes and (2) developing the data analysis framework to support the reliable study of such planets.

Regarding finding terrestrial temperate exoplanets, after the success of TRAPPIST-1's discovery their Consortium installed six more telescopes around the globe. Despite this substantial increase in observational capabilities, no other planetary system has been found. Over the period covered by this report, de Wit has allocated a substantial portion of his own research time developing a new processing pipeline leveraging new data science techniques and inputs or metrics to help his group correct for effects otherwise inadequately accounted for thereby masking or mimicking transit signals. The result is a whole new perspective on the five years of data gathered until now and candidates to follow up on, and hopefully to be confirmed as the new "TRAPPIST-1" by the end of 2021.

Regarding developing the data analysis framework, building on the foundational analytic work on transmission spectroscopy presented in de Wit & Seager, *Science*, 2013, he explored with Prajwal Niraula, graduate student, the effect that assumptions and uncertainties underlying opacity databases will have on our capability to remotely characterize exoplanetary atmospheres. They found that while the field of astronomy is expecting to have lifted an accuracy wall via a new generation of telescopes, another wall lays right behind owing to these assumptions and uncertainties. This work will be complemented by their work with Benjamin Rackham, postdoctoral fellow, highlighting the fact that another accuracy wall (less limiting though) is stemming from our limited understanding of stellar inhomogeneous photospheres. The bottom line of this multi-disciplinary initiative is that in order to maximize the return on investment of a billion-dollar observational facility, a thorough investigation of the error budgeting is advised to consistently lift accuracy walls to the same accuracy level (here approximately 1–5 part per million) across all related disciplines. The medium-term goal for their team is to develop such a rigorous multi-disciplinary framework, pivotal to reliably mine upcoming exoplanetary and astronomy data.

Regarding outreach and public activities, our first edition of "12.400 Our Space Odyssey" opened to students and alumni was a terrific success. The wide range of topics discussed and speakers hosted lead to excellent and deep exchanges amongst participants and remarkable final essays. They are eager to investigate converting some of this material to an MITx course.

Kerry Emanuel

During this pandemic year, Kerry Emanuel worked primarily on helping his four graduate students finish their PhD theses, in securing two postdoctoral fellowships funded by private firms, and on his graduate-level textbook on tropical meteorology. His graduate student Raphael Rousseau-Rizzi completed his PhD in May 2021, showing that the Atlantic hurricane drought of the 1970s and 1980s was very likely caused by sulfate aerosol pollution originating in northern Europe. His graduate student Jonathan Lin worked on a comprehensive theoretical framework for examining how low-frequency variability of the tropical troposphere is affected by upward wave propagation into the stratosphere and how the quasi-biennial oscillation of the equatorial stratosphere can thereby modify tropical weather. With Rohini Shivamoggi, he continued to investigate how secondary eyewalls develop in tropical cyclones, focusing on the physical mechanisms at work. With Sydney Sroka—a Mechical Engineering PhD student under his supervision—he continued highly advanced two-phase flow computation of the formation and effects of sea spray under very high wind conditions.

Emanuel also worked remotely with a postdoctoral researcher, Ali Sarhadi, on using an advanced tropical cyclone synthesizer to quantify tropical cyclone flood risk for the area around New Bedford, Massachusetts. We generated a very large set of synthetic hurricanes affecting New Bedford, crucially including the rainfall from such storms and their storm surges. Sarhadi is a hydrologist who was able to use this information to drive an advanced hydrological flood model to simulate both fluvial and pluvial floods affecting New Bedford. Being a foreign national, Sarhadi was unable to assume a postdoctoral position at MIT owing to the Covid-19 pandemic. Therefore, he worked for free during all of this period but will take up the postdoctoral fellowship this fall.

Awards

Emanuel was elected a Foreign Member of the Royal Society in 2020.

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See the complete list of references.

Raffaele Ferrari

While the Ferrari group—lead by Raffaele Ferrari, Breen M. Kerr (1951) Professor and professor of Dynamical Oceanography—has exciting research to report, they acknowledge the difficulties that everybody had to face this past year due to the Covid-19 pandemic.

The Boundary Layer Turbulence field campaign off the coast of Ireland has finally started in earnest with the first of three oceanographic cruises, after a delay of a year due to the Covid-19 pandemic. The goal of this field campaign is to test the hypothesis we put forward a lustrum ago that strong upslope currents develop along abyssal seamounts and ridges in response to strong turbulence there. Graduate student Henri Drake used a combination of theory and numerical simulations to study the dynamics of these currents and assess their role in returning to the ocean surface the heat and carbon that sinks to the ocean bottom at the poles. His PhD thesis defense was attended by 122 people, confirming the excitement generated by this research, but also the advantage of virtual presentations. Also exciting is the recent report from our colleagues on the first cruise that they have detected for the first time the predicted strong upslope current by releasing and tracking a fluorescent dye at the ocean bottom.

The Schmidt Futures sponsored Climate Modelling Alliance (CliMA) has also made great progress. The group at MIT has developed a new numerical model of the ocean, Ocenanigans, written in the Julia language which makes it possible to run very efficiently on GPUs and CPUs. They are now ready to couple Oceananigans with the atmospheric model developed at the California Institute of Technology and move toward a full climate model. They have also made progress in developing algorithms to represent the physics occurring at scales below the climate model resolution. Major accomplishments include an algorithm for upper ocean turbulence trained with a neural network and a new algorithm to represent the heat transport by large scale ocean vortices—this latter problem defied climate scientists for decades.

Raffaele Ferrari has advised two Super UROP students—Adeline Hillier and Ulyana Piterbarg—who led the application of machine learning techniques to the development of the CliMA model. Henri Drake was awarded a NOAA Climate and Global Change Postdoctoral Fellowship and Grace O'Neil a MathWorks Science Fellowships. The group spent the fall drafting a document on rules we agreed to respect for making the group inclusive and supportive. Drake and Ferrari participated in URGE, an NSF-funded and geoscientist-led initiative.

Glenn Flierl

Glenn Richard Flierl, professor of Oceanography, and his students are investigating physical and biological dynamics in the ocean and other more general problems in geophysical fluid dynamics. Recent publications include studies of the large eddies, which draw phytoplankton and nutrients off the shelf, near the coast of Northern Brazil. The article in the *PNAS*, in collaboration with Wanying Kang, offered an explanation of why geysers occur only near the southern pole of Enceladus. They argued that there is a symmetry breaking instability associated with the tidal heating of the ice shell and positive feedback between thinning enhancing melting, with the ice flow unable to stop it at global scales. They continue examining turbulence in partially or fully ionized fluids with applications to gas giants and exoplanet atmospheres. The simulations of the flow in the presence of a strong magnetic field and rotation, which is not aligned with the field, are showing that the idea that magneto-hydrodynamic effects are more complicated than the common parameterization as a drag might indicate. Collaboration with former student, Madeleine Youngs, is continuing, both in the study of why deep water forms in the North Atlantic but not the North Pacific, and on the influence of topography on the transport of heat and the uptake of carbon in the Southern Ocean.

Flierl has participated in several outreach events, using the newly-developed Environmental Science Globe—these have included the Cambridge Science Festival and the 826 Boston session, helping middle school students gain some understanding of the circulation patterns in the atmosphere. This web-based application has also been used by Professor Tamara Ledley at Bentley University, and more extensive outreach to K–12 is planned.

Gregory Fournier

Gregory P. Fournier, associate professor of Geobiology, leads the Fournier lab.

Goals, Objectives, and Priorities

1. publishing research completed during 2019 and 2020, including
    a. a new molecular clock age estimate for the origin of cyanobacteria and oxygenic photosynthesis during the Mesoarchean, long before the great oxygenation event (GOE), using integrated dating techniques including fossil calibration and horizontal gene transfer constraints;
    b. the reconstructed evolutionary history of enzymes within cyanobacteria used to synthesize UV-protecting scytonemin molecules, which they show originated in the Paleoproterozoic shortly after the GOE
    c. 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, phylogenetic signals needed to accurately resolve the deepest branches in the Tree of Life;
    d. an evolutionary reconstruction of collagen-degrading enzymes encoded by genes horizontally transferred from within early animal lineages to several microbial and plants groups, that constrains the age of these microbial lineages within the Neoproterozoic; and
    e. an evolutionary analysis of the genes encoding proteins within green sulfur bacteria (GSB) responsible for carbon fixation, showing that this metabolic pathway is relatively young within GSB, and was likely preceded by carbon fixation using the Calvin Cycle.
2. Completion of the primary objective for their research supported by the NSF Integrated Earth Sciences award and Simons Foundation Collaboration on the Origins of Life award. This involves implementing our completed pipeline for detecting "index" horizontal gene transfers across the Tree of Life that are informative for establishing the relative ages of groups on the Tree of Life. Using these detected transfers, they have already revised age estimates for Cyanobacteria, in a publication that is currently in revision at *Proceedings of the Royal Society B: Biological Sciences*. Since last year they have improved a next-generation version of this pipeline, and have greatly expanded their scope and approach to include constraining the ages of every major group of bacteria within the Tree of Life.
3. Continuation of current research efforts to be completed within the year.

William Frank

Assistant Professor of EAPS William B. Frank joined MIT from the University of Southern California in July 2020. Arriving with a postdoctoral researcher and a graduate student, Frank focused on building up his research group during the Covid-19 pandemic; as of July 2021, there are three postdoctoral researchers and two students in the group, with two new students starting fall 2021. Building up the research group also included connecting with Assistant Professor Camilla Cattania, who also arrived in July 2020, to form a joint earthquake science research community within EAPS Geophysics that has been virtually meeting weekly. This regular meeting has been providing a regular forum for students and postdoctoral researchers to interact across research groups when they haven't yet had the chance to meet each other in person or even discover MIT's campus. Frank's research program has expanded into new fields, such as interrogating transient changes beneath volcanoes with teleseismic earthquakes—graduate student Jared Bryan received a Student Presentation award on this topic at the Annual Meeting of the Seismological Society of America in April—and satellite imaging of slow crustal deformation—supported by Frank's first NASA sponsored research project. Frank's group plans to return to campus in fall 2021 to tackle new research targets.

Timothy Grove

Professor Grove and recent postdoctoral colleague Stephanie Krein completed two modeling studies that recover the conditions and processes of mantle melting beneath mid-ocean ridges.

The first model, *Petrogen*, predicts the major and trace element compositions of basaltic melts of plagioclase lherzolite, spinel lherzolite, and garnet lherzolite. The model tests melting processes that occur to produce mid-ocean ridge basalts (MORBs) using the full spectrum of geochemical evidence which includes major elements, trace elements, and isotopes. The motivation for developing this model is that geochemists commonly use evidence from only one of these three geochemical data sets, and the conclusions drawn from one type of geochemical data are often at odds with processes that are inferred from the other geochemical data. They apply *Petrogen* to the question of whether MORB melting occurs in the garnet lherzolite stability field (i.e. deep, >75 km)—a long standing and complicated controversy in MORB geochemistry. They find that when evidence from all three geochemical data sets is combined, melting in the spinel lherzolite and plagioclase lherzolite facies (i.e. shallow < 45–30 km) of mantle peridotite with variable major and trace element compositions at different mantle potential temperatures can explain the evidence from all three data sets, and garnet lherzolite melting is not required.

The second model, *Reverse Petrogen (RevPet)*, uses the compositions of evolved erupted MORBs and returns them to the original melt that was produced by mantle melting. MORBs have experienced multiphase fractional crystallization and *RevPet* corrects for this and returns the composition to the melt composition that was produced in the mantle. They use *RevPet* to predict the melting conditions of a global MORB data set of 13,589 MORB glasses. They find that the mantle melting conditions for most MORB is between 1,350 and 1,400°C except near hot spots where it increases to 1,600°C. A subset of MORBS record very low temperatures of mantle melting (<1,250°C) at low pressures (< 1 GPa) which reflects mantle cooling during melting at the base of the lithosphere in very slow spreading ocean ridge environments. Read more at the MIT News article on *Reverse Petrogen*.

It is very satisfying to see these well documented and clearly explained models out there and available to the broad geochemical community. This approach can be used in other tectonic settings where mantle melting processes are "dry," including plumes, continental basaltic volcanism, and more.

Publications

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- Krein, S. B., Molitor, Z. J., Grove, T. L., *Reverse Petrogen*: A Multiphase Dry Reverse Fractional Crystallization-Mantle Melting Thermobarometer Applied to 13,589 Mid-Ocean Ridge Basalt Glasses, *Journal of Geophysical Research* 126 (2021), https://doi.org/10.1029/2020JB021292

Teaching Activities and Institute Service

In the fall, Grove taught a Freshman Advising Seminar, 12.A03 Meteorite from Mars Kills Dog.

In the spring, he taught a graduate class, 12.486 Advanced Igneous Petrology.

In September, Grove joined the ReseArch Scientist CAreer LadderS (RASCALS) committee. Their charge was to undertake a review of the advancement opportunities for Research Scientists in MIT's School of Science. They delivered a report on our findings to Dean Nergis Mavalvala in June.

Grove is the chair of Matej Pec's mentoring committee.

Other Service and Community Outreach

In early October 2021, Grove was asked to chair the Panel on the Moon and Mercury for the National Academy of Sciences Planetary Sciences and Astrobiology Decadal Survey, a report that will be delivered to the Academy in March 2022 and that will recommend future NASA planetary missions for the upcoming decade. This turns out to be a huge amount of work, because they have to meet virtually and they were tasked by NASA to follow a new structure for the report.

Grove continues to serve on American Geophysical Union's Development Board.

He also continues as executive editor for *Contributions to Mineralogy and Petrology*, and serve as an editor for the *PNAS*.

Thomas Herring

Thomas A. Herring, professor of Geophysics, and his group are using primarily global navigation satellite system (GNSS) data to develop geophysics based models of Earth deformations on global, regional, and local scales, and changes in the rotation of the Earth. They have completed the reprocessing of GNSS data collected for the past 20 years. The reprocessing included data from the European GALILEO system (2017–2020) as well as the US GPS system from 2000–2020. Ongoing processing, will continue the analyses of GPS and GALIELO results. The Chinese Bediou and Russian GLONASS systems will also be added. The results from this reprocessing will be used internationally for studying geophysical processes. This effort is being coordinated by the International GNSS service (IGS). Herring along with Salim Masoumi from Geosciences Australia are the analysis center coordinators for the IGS. The Herring 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, postseismic 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 few millimeters precision and the group also works actively in developing stochastic models to explain the noise characteristics in the data while being cautious about maintaining novel signals in the data.

Publications

- Martens, H. R., Argus, D. F., Norberg, C., G. Blewitt, T. A. Herring, A. W. Moore, W.C. Hammond, and C. Kreemer, Atmospheric pressure loading in GPS positions: dependency on GPS processing methods and effect on assessment of seasonal deformation in the contiguous USA and Alaska, *Journal of Geodesy* 94 (2020): 115, https://doi.org/10.1007/s00190-020-01445-w

John Marshall

During AY2021, John C. Marshall, Cecil and Ida Green Professor of Oceanography, 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 their studies of icy moons with postdoctoral researchers Suyash Bire and Wanying Kang.

Graduate student Faye Elgart completed her general examinations. Ali Ramadhan continues his work on machine learning applied to ocean processes. New to the group are graduate student PJ Tucker and postdoctoral researcher Qian Li, who is working on climate modeling in collaboration with the Goddard Institute for Space Science.

Marshall was pleased with student comments on remote classes. In November 2021, he was awarded the A.G. Huntsman Award of the Royal Society of Canada for contributions to Oceanography and Climate Science.

Shuhei Ono

Associate Professor Shuhei Ono's group studied geochemical cycles of sulfur and methane at the interface between biosphere and geosphere. The group measures samples collected from geothermal fluids and deep sediments as well as carries out laboratory experiments with a goal to develop a novel tool to trace the sources and sinks of sulfur and methane.

The complete shutdown of the laboratory during the summer of 2020 delayed their research program. Planned trips were postponed or cancelled, and all experiments were halted abruptly. This also provided a time to reorganize, discuss big picture questions, and finishing pending manuscripts.

Graduate student Patrick Beaudry reported the methane isotopolgue data for methane in geothermal fluids in Iceland. Their data suggests a hot and deep source of methane generated in supercritical water independent of circulating subcritical shallow groundwater (Beaudry et al., 2021). In the summer 2020, Jeemin Rhim successfully defended her PhD dissertation, titled "Experimental investigation of isotopologue fractionation during microbial methanogenesis". Her manuscripts are under preparation. Graduate student Ellen Lalk studied origins of methane in methane hydrates. They discovered that methane in hydrate deposits was generated at depth (typically 0.8±0.4 km) and migrated upwards. Postdoctoral researcher Eric Ryberg joined the laboratory in September 2020, and has worked on culturing methanogens on electrode.

Teaching Activity and Institute Services

- Freshman advisor
- Member of the EAPS Diversity Committee
- Member of the faculty search committee, Climate Science 2019, Geochemistry 2021

Member of the Joint Committee on Chemical Oceanography, MIT-WHOIPublications

- Beaudry P., Stefánsson A., Fiebig J., Rhim J. H., and Ono S., High temperature generation and equilibration of methane in terrestrial geothermal systems: Evidence from clumped isotopologues, *Geochimica et Cosmochimica Acta* 309 (2021): 209–234, https://doi.org/10.1016/j.gca.2021.06.034.
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- Liu J., Antler G., Pellerin A., Izon G., Dohrmann I., Findlay A. J., Røy H., Ono S., Turchyn A. V, Kasten S. and Jørgensen B. B., Isotopically "heavy" pyrite in marine sediments due to high sedimentation rates and non-steady-state deposition, *Geology* 49 (2021): 816–821, https://doi.org/10.1130/G48415.1.
- Ono S., Rhim J. H., Gruen D. S., Taubner H., Kölling M., and Wegener G., Clumped isotopologue fractionation by microbial cultures performing the anaerobic oxidation of methane, *Geochimica et Cosmochimica Acta* 293 (2021): 70–85, https://doi.org/10.1016/j.gca.2020.10.015.

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- McDermott J. M., Sylva S. P., Ono S., German C. R., and Seewald J. S., Abiotic redox reactions in hydrothermal mixing zones: Decreased energy availability for the subsurface biosphere, *PNAS* 117 (2020): 20453–20461, https://doi.org/10.1073/pnas.2003108117.

Paola Rizzoli

Paola M. Rizzoli, professor of Physical Oceanography, was personally invited by Professor Hashim Sarkis—dean of the MIT School of Architecture and Urban Planning and curator of the 17th Biennale of Architecture in Venice from May 22 to November 21, 2021—to be responsible of the stand "Resilience of Venice" in the Venice room Arsenale.

In 2017 Rizzoli started a new initiative in Venice, Italy, based on the collaboration between MIT, the Venice University of Architecture (IUAV), the Venice Water Authority, and the Consorzio Venezia Nuova (CVN). The latter one is the conglomerate of companies in charge of the planning and construction of the Modulo Spermimentale Elettromeccanico (MOSE) barriers for the protection of Venice and its lagoon from the 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 history of the MOSE barriers. Rizzoli has a deep knowledge of both the scientific aspects of the oceanographic problem as well as of the engineering alternatives which have culminate in the choice of the MOSE as protecting solution.

Three Summer Schools have been held in the island of Pellestrina, in the Venice lagoon. The first school was held on May 29 to June 11, 2017, with the object: Venice/MOSE. "A study on a temporary site between the lagoon and the sea". The second school was held on June 11 to 22, 2018 with the object: "Border but not marginalized territories: the case of the Pellestrina island". The third school was held on June 28 to July 18, 2019, with the object: "Resilience of Venice and its lagoon." Thirteen MIT students, supported by the MISTI-Italy Program attended. They were joined by an equal number of Italian IUAV students.

Daniel Rothman

Recent work by Daniel Rothman's group has focused on mechanisms of positive feedback and instability in the long-term climate-carbon cycle system. Research led by Rothman's graduate student Constantin Arnscheidt suggests that such self-amplification is evident in fluctuations of Earth's climate during the last 66 million years. Arnscheidt and Rothman reveal a warming bias, in which warmer events tend to be more extreme, with greater shifts in temperature, than cooling events. They attribute these results to a natural multiplicative effect in which a modest increase in temperature leads to faster biogeochemical processes within the carbon cycle, leading, on average, to greater warming. Theoretical predictions based on stochastic differential equations with multiplicative noise support these conclusions.

References and Publications

A news release announcing these findings is on MIT News.

- Arnscheidt C. W. and Rothman D. H., Asymmetry of extreme Cenozoic climate-carbon cycle events, *Science Advances* 7 Issue 33 (2021), https://doi.org/10.1126/sciadv.abg6864.

Roger Summons

Members of Professor of Geobiology Roger Everett Summons's laboratory continue to query geochemical records to learn more about Earth's early life and its co-evolution with the environment. Collaborating with other researchers interested in these topics, we endeavor to advance knowledge about the production of diagnostic lipids by contemporary microorganisms, how these are preserved in ancient sediments and how this record informs us about environmental conditions in deep time. Our funding largely originates from the Simons Foundation Collaboration on the Origins of Life.

For 2021, they continued their efforts to establish the timing, pace, and biogeochemical consequences of the oxygenation of Earth's ocean atmosphere system. They approach the problem from two directions with one being detailed examination of the geological record for evidence of the presence of O_2 in the atmosphere. The second direction looks at the evolutionary consequences of ocean and atmosphere oxygenation where they made the enigmatic observation that the presence modern phototrophic sulfur bacteria, which are strict anaerobes, actually increased as the oceans became more oxygenated. They postulate that was a consequence of the increased oxidative weathering of continental sedimentary sulfides that resulted in a massive increase in the marine sulfate inventory. Under conditions of restricted ocean circulation and ocean warming (Fox et al., 2021), this sulfate is respired by sulfate reducing bacteria to provide the hydrogen sulfide required by the phototrophic sulfur bacteria (Cui et al., 2020; Roussel et al., 2020).

They also contributed to interpretation of results coming from the Sample Analysis at Mars (SAM) instrument suite of the Mars Science Laboratory Mission to Mars (Franz et al., 2020; Millan et al., 2020) and to the identification of possible sources of the organic matter that is currently preserved in Mars sediments (Newman et al., 2020).

Work also continued on the environments and drivers of early hominin evolution including a new hypothesis concerning the first use of cooking, not by fire but by hydrothermal heat, that would have improved food digestibility and nutrition (Sistiaga et al., 2021). They also continue to collaborate with other MIT researchers on the Human Microbiome Conservancy Project (Groussin et al., 2021).

Publications

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Robert D. van der Hilst

Robert Van der Hilst, Schlumberger Professor of Geosciences, has been head of EAPS since January 2012. His research program, which has become smaller since becoming department head, continues to focus on:

1. regional tectonics in South East Asia and North America,
2. imaging of Earth's deep interior using dense seismograph arrays, in collaboration with visiting professors Maarten De Hoop of Rice University and Michel Campillo of the Grenoble Alpes University, France and colleagues at Imperial College London, and
3. development of algorithms for better inference of Earth's internal structure. In a new development, they have begun to use seismic data to monitor temporal changes in medium properties during tidal, seismic and hydrological cycles. In recent years, Van der Hilst (with De Hoop) finalized a multi-year study of the inverse problem for seismic surface waves, presented a novel approach to characterizing elastic properties and composition in the lithosphere of North America, and developed new methods for estimating 3D structure and its uncertainties and measuring minute changes in the propagation speed of seismic waves due to deformation or changes in composition (e.g., water content) of the medium. Applications of the latter are currently focusing on the development of rigorous and relatively inexpensive ways of monitoring hydrological systems in California.

Publications Supporting Priority Three

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