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. The department comprises 41 faculty members, including three with a primary appointment in the Department of Civil and Environmental Engineering (CEE); one with a primary appointment in the Institute for Data, Systems, and Society (IDSS); and one with a primary appointment in the Department of Aeronautics and Astronautics (AeroAstro). EAPS also has more than 240 research staff, postdoctoral associates, and visiting scholars.

EAPS is notable for its emphasis on interdisciplinary problems and is involved in numerous laboratories, centers, and programs that address broad questions in the Earth sciences, including those that are among the most pressing societal issues of our time: changes in climate and environment, natural resources and hazards, and the origin and evolution of life on Earth and, perhaps, elsewhere. For example, the Earth Resources Laboratory (under the directorship of Professor Bradford Hager) integrates faculty, staff, and students across disciplinary, department, and school boundaries to investigate geophysical and geological problems in energy and resource development. The Center for Global Change Science (under the directorship of Professor Ronald Prinn) builds cross-Institute activity in meteorology, oceanography, hydrology, chemistry, satellite remote sensing, and policy. The Lorenz Center (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 (MIT-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 respective programs, with the aim of sustaining active and open conversations around educational issues.

Graduate Program

EAPS has vigorous graduate educational programs in the areas of Earth, planets, climate, and life, including geology, geochemistry, geobiology, geophysics, atmospheres, oceans, climate, and planetary science. In fall 2015, EAPS had 159 registered graduate students, including 78 students in the MIT/WHOI Joint Program and one fifth-year master's student. Women constituted 47% of the graduate student population; 5.7% were members of an underrepresented minority group.

The excellence of the EAPS graduate program is built not only on the strength of teaching and supervision by the faculty but also on the involvement of EAPS graduate students in departmental activities. Students develop formal and informal ways of improving their educational experience as well as the student life of the department. For example, the 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 one student presenting his or her research to the student body at the weekly Graduate Student Seminar. Undergraduate majors are encouraged to attend these talks. The departmental Graduate Student Mentoring Program continues to be well received as an 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 2016 academic year, Stephanie Brown, Chawalit Charoenpong, Christine Chen, Michael Eddy, Christopher Kinsley, Marianna Linz, Sharon Newman, and Robert Yi were recognized for their contributions.

EAPS students were also recognized by professional societies and outside organizations. Alex Bogdanoff was awarded a 2016 John A. Knauss Marine Policy Fellowship by the Sea Grant Program of the National Oceanic and Atmospheric Administration (NOAA). Christine Chen received a Geological Society of America Student Research Grant, the Charles A. & June R.P. Ross Research Award, and the Explorers Club Exploration Fund Mamont Scholarship. Michael McClellan and Jaap Nienhuis each received an Outstanding Student Paper Award at the fall 2015 meeting of the American Geophysical Union. Sharon Newman won the Geology Society of America (GSA) Geobiology and Geomicrobiology Division Award for best student oral presentation at GSA 2015 in Baltimore. Mary Knapp received the Best Paper Award at the IEEE Aerospace Conference in March 2016. Details on other AY2016 student awards are available on the EAPS website.

Twenty-two doctoral students and seven master's students graduated from EAPS in AY2016.

Undergraduate Program

EAPS had 23 undergraduate majors in AY2016, 74% of whom were women and 8.7% of whom were members of an underrepresented minority group.

Although the EAPS undergraduate population has always been small, satisfaction is high, and we continue our efforts to increase the number of majors. These activities include events for incoming freshmen, involvement through freshman advising and teaching beyond EAPS, widened use of social media, increased visibility on campus, and an increase in the number of labs tours and talks that take place during Department Explorations in the Independent Activities Period.

The department maintains a strong presence in undergraduate education across MIT so that the general MIT student body has ready access to education in geoscientific aspects of climate and environmental change, natural hazards, and natural energy resources. Professor Susan Solomon co-taught 5.60 Thermodynamics in the spring term, and Professor Mick Follows co-taught an ecology class with Civil and Environmental Engineering. Our faculty members with joint appointments (Kerri Cahoy, Noelle Selin, and Collette Heald) are also active in teaching undergraduates. The 12.340x Global Warming Science subject, taught by Professor Kerry Emanuel, was offered again during the spring 2016 term. 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 a relatively large number of freshman advising seminars. With the combined enrollment of Terrascope and the advising seminars, EAPS connected with 7.5% of the students in the freshman class on a weekly basis. Similarly, EAPS is an active participant in three interdisciplinary minor programs: the broadly based energy minor, the astronomy minor (with the Department of Physics), and the atmospheric chemistry minor (with the Department of Aeronautics and Astronautics, the Department of Chemistry, and the Institute of Data, Systems, and Society).

At the 2016 Student Awards and Recognition Dinner, the Goetze Prize was awarded to Megan Mansfield (advised by Dr. Amanda Bosh) in recognition of her outstanding senior thesis. In addition, she was inducted into Phi Beta Kappa and the physics honor society Sigma Pi Sigma. Madison Douglas received the W.O. Crosby Award for Sustained Excellence in recognition of her academic and intellectual achievements and her general contributions to the department. She also received an Outstanding Student Paper Award at the fall 2015 meeting of the American Geophysical Union. Libby Koolik 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. Brynna Downey was recognized as an outstanding undergraduate teaching assistant for her work in 12.A03 Meteorite Kills Dog, a freshman advising seminar.

Nine students earned bachelor's degrees from EAPS in AY2016.

Faculty

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

Dr. Timothy Cronin, a former EAPS graduate student who recently completed a postdoctoral fellowship at Harvard, joined our faculty as an assistant professor in July 2016.

We also extended an offer to Dr. Matěj Pěc, a geologist currently completing a postdoctoral research project at the University of Minnesota. Pěc will join the department in January 2017.

EAPS will also welcome Dr. Andrew Babbin in January 2017. Babbin, a marine biogeochemist, is currently completing a postdoctoral fellowship in CEE.

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

Promotions

Olivier Jagoutz was promoted to the rank of associate professor with tenure effective July 2016.

Honors and Awards

Kristin Bergmann, Victor P. Starr Career Development Assistant Professor, was voted the Society for Sedimentary Geology's Early Career Councilor. She also received the 2015 Ally of Nature Fund Award.

The New Horizons mission to Pluto, of which Richard Binzel, professor of planetary sciences and Margaret MacVicar Faculty Fellow, is a science team co-investigator, was honored with multiple team awards. Examples include the following:

- *Science* magazine People's Choice Award for #1 Story of 2015
- *Science* magazine Top Ten Breakthroughs of the Year 2015
- *Discovery* magazine 2015 Top Science Story
- *Science News* magazine 2015 Top Science Story
- National Space Club 2016 Goddard Trophy
- American Institute of Aeronautics and Astronautics 2016 Space Ops Award
- Space Foundation 2016 Jack L. Sweigert Exploration Award
- National Space Society 2016 Space Pioneer Award
- Smithsonian Institution 2016 National Air and Space Museum Achievement Award
- *Aviation Week & Space Technology* magazine 2016 Laureate Award
- American Astronautical Society 2016 Neil Armstrong Space Flight Achievement Award

Clark Burchfiel, professor emeritus of geology, received a certificate of appreciation for his contributions to China-US cooperation in science and technology.

Kerry Emanuel, Cecil and Ida Green Professor of Atmospheric Science, was appointed an honorary fellow, the highest award of the United Kingdom's Royal Meteorological Society, "in recognition of a distinguished career and long standing contribution to meteorology."

Raffaele Ferrari, Cecil and Ida Green Professor of Oceanography and chair of the EAPS Program in Atmospheres, Oceans, and Climate, won the Scripps Institution of

Oceanography Robert L. and Bettie P. Cody Award in Ocean Sciences. The Cody Award, presented biennially by Scripps, consists of a gold medal and $10,000.

Timothy Grove, R R Shrock Professor of Geology, was awarded a doctor honoris causa by the University of Liege in Belgium.

John Marshall, Cecil and Ida Green Professor of Oceanography, was awarded the 2016 Bernard Haurwitz Prize by the American Meteorological Society for his "seminal contributions to atmospheric, oceanic, and climate dynamics and the creation of innovative modeling tools and educational resources."

Professor of Geophysics Daniel Rothman was awarded the American Mathematical Society's Levi L. Conant Prize. The Conant Prize recognizes the best expository paper published in either *Notices of the AMS* or the *Bulletin of the AMS* in the preceding five years. Rothman received the prize for "Earth's Carbon Cycle: A Mathematical Perspective," published in 2015 in the *Bulletin of the AMS*.

Noelle Selin, Esther and Harold E. Edgerton Career Development Associate Professor, was named an AAAS (American Association for the Advancement of Science) Leshner Leadership Fellow. Also, she was coauthor of an article that was named the Best Environmental Science & Technology Journal Environmental Policy Paper of 2015.

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

Maria Zuber, E.A. Griswold Professor of Geophysics, was elected chair of the National Science Board.

Community Events

The fifth annual John H. Carlson Lecture at the New England Aquarium, "Watching Water: Nature's Field Guide to Weather and Climate," was given by Bjorn Stevens, director of the Atmosphere in the Earth System Department at the Max-Planck Institute for Meteorology, and a professor at the University of Hamburg. Stevens's engaging and informative lecture explored what may have triggered the shift in climate that kicked off the cycle of ice ages Earth began experiencing three million years ago. In addition to the formal lecture, several groups set up demonstrations and exhibits during the pre-lecture reception, including members of the McGee and Follows groups and students from the EAPS Program in Atmospheres, Oceans, and Climate, who coordinated demonstrations using *iGlobe*, an educational tool developed by Professor Glen Flierl to allow geographic projection of geophysical data onto a sphere.

In January 2016 EAPS hosted a highly successful daylong symposium, "MIT on Climate = Science + Action," aimed at defining the key role of basic science in understanding and reacting to climate change. Speakers, among them several EAPS faculty members, examined what we know, what's left to learn, and the diverse climate-related research happening throughout the institute. The event complemented and reinforced efforts to raise the department's profile as the de facto center for climate science research and education at the Institute.

Communications

News curation, creation, and reporting remain central to EAPS communications. Communications Officer Helen Hill continues to maintain strong ties with the MIT News Office and Media Office and to network with communications staff in other departments, labs, and centers. Although continued cultivation of the EAPS community to share its work proactively remains a daily challenge, increased exposure to current department news through social media, news emails (e.g., *EAPSpeaks*), and electronic signage in common areas helps encourage members to engage in such efforts.

It had long been recognized that the dated styling and limited functionality of our old website were undermining the department's ability to project itself as a world-class entity. Our new site (launched in fall 2015) incorporates a state-of-the-art messaging platform allowing streamlined information delivery to provide visitors with a richer, more engaging experience. In addition, the flexibility of the site's infrastructure allows changes to be made quickly and efficiently in a way not possible with the old one. Current projects include development of pages to display and index *EAPSpeaks* and *EAPS Scope* materials more effectively.

The success of our annual print magazine, *EAPS Scope*, and its usefulness in lieu of a department brochure led us (in fall 2015) to switch *EAPSpeaks*, formerly a weighty biannual electronic newsletter, to a leaner and more manageable monthly news email. Using the commercial email marketing platform MailChimp, we were quickly able to create a stylish new publication, allowing us to share up-to-date news and event information more efficiently.

In 2015 EAPS commissioned a five-minute, professionally produced promotional video intended to educate prospective donors about the EAPS enterprise and to cultivate fellowship support. The video has been well received at multiple donor and community events.

In order to more effectively convey the cross-disciplinary nature of research in the department, EAPS has been actively reframing front-facing materials geared toward external, non-specialist audiences according to four broad interrelated themes: Earth, planets, climate, and life. We look forward to having new printed materials early in AY2017 as well as adapting the way we organize and present materials on our website to reflect this new framework.

Planning is also under way with a new campaign to encourage increased undergraduate awareness of, and engagement with, the department. The communications office is working closely with education officer Vicki McKenna on this effort.

Development

Overview

During FY2016, EAPS development efforts were focused on building fellowship funds, stewardship of existing EAPS donors, and outreach to alumni and new audiences with a particular interest in research into Earth, planets, climate, and life. New gifts and pledges to EAPS in FY2016 totaled approximately $2 million, a decrease from the extraordinary results of FY2015 but nevertheless a valuable boost to EAPS fellowship funds and research support.

At the close of FY2016, attention turned to finding significant partners for the Green Building fundraising campaign. The goal of the effort is to provide modernized laboratory and teaching spaces for EAPS faculty and students, and it is expected that the facility will be a focal point on campus for world-class discovery science as well as a convening center for environmental activities and research.

Fellowships

We are pleased to report that one new endowed fellowship fund was named in FY2016 (the James L. Elliot ’65 Graduate Student Support Fund), and four expendable graduate fellowships were donated by generous members of the EAPS Visiting Committee. In fall 2015, shortly after the groundbreaking New Horizons fly-by of Pluto, the Elliot Fund was launched with a six-figure gift from Cathy Olkin and Terry Olkin in honor of the late Professor Elliot, whose pioneering research led to the discovery of Pluto’s atmosphere. Professor Richard Binzel has been working closely with EAPS senior development officer Angela Ellis on outreach and fundraising efforts, speaking about New Horizons at a number of different venues. Thanks in part to the challenge gift offered by the Olkins, the Elliot Fund has attracted 33 gifts to date.

More than $750,000 has been raised for the Sven Treitel ’53 Graduate Student Support Fund, launched in FY2014, thanks to additional support received during FY2016; in particular, a generous gift was received from Robert C. Cowen ’49, SM ’50, who became the newest member of the EAPS Patrons Circle. In October 2015, during the week of the Society of Exploration Geophysics (SEG) annual meeting in New Orleans, Sven Treitel ’53, SM ’55, PhD ’58, and his wife Renate attended a special dinner hosted by Robert van der Hilst where we celebrated with several EAPS alumni and friends who have supported the fund.

The department is continuing fundraising efforts for each of the named EAPS endowed fellowship funds (Elliot, Klein, Madden, Toksöz, and Treitel) to ensure that their generated endowment income is sufficient to support at least one student per academic year in perpetuity. (As of FY2016, approximately $1.9 million was needed per fellowship to meet this goal.) We will also continue to reach toward our vision of establishing 10 additional fellowship funds for EAPS to ensure that our faculty members have the resources available to recruit the most talented graduate students in all disciplines every year.

Stewardship

The EAPS Patrons Circle, established in 2014 to recognize major fellowship donors, has now reached 27 members. Our second annual EAPS Patrons Circle event was held in April 2016, and we were pleased to welcome among our guests several new patrons who were attending for the first time: Robert C. Cowen ’49, John H. Carlson ’83, Pat Callahan ’75, SM ’77, and David Dee. Patrons met students and faculty members, enjoyed a poster session from current and past fellows, and watched lively presentations by four fellows. Five Norman C. Rasmussen Climate Fellows, the Callahan-Dee Fellow, the Madden and Toksöz Fellows, and the two Whiteman Fellows were among those who met their patrons during this celebratory evening. The event concluded with inspiring remarks from patrons chair Neil C. Rasmussen ’76, SM ’80, who noted that “spaceship Earth” needs careful guidance from people who understand how the planet works and stressed the importance of supporting EAPS graduate students, who can become our “drivers.”

Outreach

In October 2015 (as noted above), the Lorenz Center’s fifth annual John H. Carlson lecture, “Watching Water: Nature’s Field Guide to Weather and Climate,” was delivered by Bjorn Stevens at the New England Aquarium. The lecture attracted an audience of over 250 alumni, students, and members of the public and was followed by a private dinner hosted by Carlson with approximately 80 VIP guests, faculty, and students.

Also during the past year, EAPS and the Earth Resources Laboratory hosted a reception for alumni and friends during the week of the SEG meeting in New Orleans. In addition, EAPS hosted receptions during the American Geophysical Union annual meeting in San Francisco and the GSA meeting in Baltimore. At least 500 guests attended these receptions to network and hear the latest EAPS news.

In December 2015, Visiting Committee member Fred Middleton hosted a lecture and cocktail reception for MIT alumni and friends in Menlo Park, where approximately 100 guests donned 3D glasses to view Professor Richard Binzel’s “Pluto Revealed” images and to hear the latest revelations from the New Horizons mission.

In January 2016, more than 300 faculty members, students, alumni, and members of the public attended the “MIT on Climate: Science + Action” symposium, hosted by EAPS and co-sponsored by the Lorenz Center, the Houghton Fund, and the MIT Alumni Association. Alumni and friends were joined by Chancellor Eric Grimson at a VIP reception following this packed, daylong symposium in the Stata Center that showcased climate research across the Institute.

In May 2016, Professor Ben Weiss spoke about his research (“From Mars to Meteorites”) at the home of MIT alumna Adina Gwartzman ’81, SM ’82, in Cleveland and was introduced to local alumni by Thomas F. Peterson Jr. ’57, who remains a generous supporter of the Weiss group’s research.

Throughout the year, EAPS faculty members were invited to lead tours with the MIT Athletic Association travel program and to speak at MIT club events, thereby helping to raise awareness of EAPS research among a broader cross section of MIT alumni. We continue to partner with the MIT Alumni Association to arrange speaking engagements and travel opportunities, and we collaborate with colleagues in Resource Development to draw attention to EAPS opportunities for engagement, new research, and funding priorities. With the Campaign for a Better World now well under way, we anticipate that the focus of EAPS on discovery science and research that is highly relevant to the health of the planet will encourage more interactions with alumni and prospective donors and further philanthropic support.

Looking Forward: The Campaign for the Green Building

During FY2015 and FY2016, EAPS Visiting Committee chair Neil Pappalardo '64 jumpstarted our efforts to renovate the Green Building by establishing the A. Neil Pappalardo Fund for EAPS capital improvements. The fund has already been invaluable in terms of renovations (and planned renovations) of lab facilities for three new EAPS faculty members. We look forward to gathering further support for capital improvements from MIT alumni and friends who are inspired by the department's interdisciplinary research into the Earth, planets, climate, and life and who share our vision for the iconic Green Building as a center of excellence and a gathering place for students and scientists who are driven by their curiosity about the planet and their desire to make the world a better place.

Faculty Research Highlights

Kristin Bergmann

Professor Bergmann joined the EAPS faculty as an assistant professor in July 2015. Bergmann's research group studies the ancient interactions between the environment and early complex life. In particular, her group focuses on the nature of carbonate sedimentation through time and reconstructing climate change in the Neoproterozoic period (1,000–541 million years ago) and the Cambrian and Ordovician periods (541–443.8 million years ago). The Bergmann lab uses a combination of approaches including fieldwork, micro-analytical methods such as electron microprobe and secondary ion mass spectrometry, and carbonate clumped isotope geochemistry.

The Bergmann lab space on the 10th floor of Building 54 was renovated during the fall of 2015. During spring 2016, the Bergmann group moved into the space and set up the lab for a variety of analyses. Two field seasons in Newfoundland were conducted over the past year, one to sample Cambrian and Ordovician strata on the Port au Port Peninsula and the other to sample Ediacaran (635–541 million years ago) rocks on the Avalon Peninsula. Bergmann also taught a new course on sedimentology in the field that took 11 students to Allamoore, TX, over spring break.

Richard Binzel

After nearly two decades of perseverance to reach the launch pad and more than nine years of flight, Professor Binzel, as a founding member of NASA's New Horizons mission to Pluto, achieved the objective of the first spacecraft reconnaissance of our solar system's most distant planet. As noted above, this historic achievement in space exploration has been honored with multiple team awards from, among others, *Science* magazine, the Smithsonian Institution, and the National Space Society.

Edward Boyle

Professor Boyle's group completed oceanographic sections for lead (Pb) and Pb isotopes in the Southeast Pacific (Ecuador to Tahiti) and the northern North Atlantic (approximately Lisbon to Greenland and Labrador). Among their observations, the group found that Southern Hemisphere Eastern Pacific surface Pb concentrations are lower than those in the Northern Hemisphere but that they are still enriched in anthropogenic Pb relative to deeper waters. In the plume downstream of the East Pacific Rise hydrothermal vents, anthropogenic Pb is stripped from solution onto iron and manganese phases, resulting in the lowest Pb concentrations ever observed in the ocean (less than 0.1 parts per trillion). In the northern North Atlantic, Pb is highest in the eastern mid-depth Labrador Sea Water. A statistical examination of the concentration of Pb in North Atlantic particles shows that 90% of the variance in particulate Pb can be accounted for by solution-surface adsorption onto manganese oxide and lithogenic minerals.

A 150-year-long record of Pb and Pb isotopes from a coral in the South China Sea off Vietnam shows that the main source of Pb is recirculated and upwelled water containing Pb from Chinese emissions into the atmosphere. A study of Pb and Pb isotopes in the coastal waters of Singapore indicates that anthropogenic aerosol Pb with a low $^{206}Pb/^{207}Pb$ ratio deposited into the ocean exchanges with natural crustal Pb with a high $^{206}Pb/^{207}Pb$ ratio on the surfaces of river-borne particles.

Daniel Cziczo

Professor Cziczo's research group seeks to understand the chemical composition, size, and morphology of small atmospheric particles, commonly termed aerosols, and how these properties affect the uptake of water. Research endeavors are organized around answering four questions.

How do particles in the Earth's atmosphere, in particular those produced by human activities, affect the planet's climate? Cziczo seeks to answer this question because the largest uncertainty in understanding the Earth's climate is the formation and persistence of clouds. This uncertainty is due to several poorly understood processes and measurements including (1) the microphysics of how particles nucleate droplets and ice, (2) numbers of droplet- and ice-forming particles as a function of atmospheric properties such as temperature and relative humidity, (3) the atmospheric distribution of droplet- and ice-forming particles, and (4) the role of anthropogenic activities in producing or changing the behavior of droplet- and ice-forming particles. The major focus of the Cziczo group is organized around a set of projects aimed at reducing uncertainty in these four areas. Cziczo uses a combination of laboratory, field, and modeling studies to accomplish this goal. Secondary foci in the field of atmospheric chemistry are better understanding the role of aerosols in visibility, heterogeneous chemistry, and the initiation of precipitation (i.e., the role of aerosols in the Earth's water cycle).

Do we have the right instruments to answer the questions we're interested in? In order to accomplish their goals, the group's members are actively involved in the development of new instruments for laboratory and field use. A major aim has been instrument miniaturization in order to access remote field sites with limited space and power as well as deployment of unmanned aerial vehicles. Development activities include ongoing partnerships with private industry (e.g., Aerodyne Inc. and Droplet Measurement Technologies) and government laboratories (e.g., NOAA's Chemical Sciences Division).

Do clouds around other planets, both within and beyond our solar system, limit our understanding of those planets? EAPS has offered a location where the group's expertise and instrumentation in the areas of terrestrial aerosols and cloud formation can be leveraged to address topics of interest in other fields. In planetary sciences, the group has extended the capabilities of cloud chambers designed and built for terrestrial studies to conditions found on other planets. Studies include determination of the conditions required for cloud formation in the Martian atmosphere and mimicking of exoplanet cloud formation.

Can our instrumentation for atmospheric studies be used to understand pre-industrial aerosols? In the field of paleoclimatology, the Cziczo group has sought to address another of the large uncertainties in understanding climate change: the lack of data characterizing the pre-industrial aerosol loading of the atmosphere. Modern instrumental records of aerosols date back, at most, a few decades. As a means of overcoming this limitation, the group has used a single-particle mass spectrometer to characterize aerosol trapped within ice cores. Using this method, they use a modern technique to characterize aerosols dating back hundreds, possibly thousands, of years. The ultimate goal is to "stitch" pre-industrial to contemporary records via a common instrumental technique.

Kerry Emanuel

During AY2016, Professor Emanuel and his research group continued a number of lines of research and initiated several others. Graduate student Vince Agard and Emanuel continued studying how severe local storms that produce damaging wind, hail, and tornadoes respond to climate change. Diamilet Perez-Betancourt and Emanuel are exploring the dynamics of spiral rainbands in hurricanes. New graduate student Rohini Shivamoggi and Emanuel initiated a line of work on the physics of secondary eyewalls in tropical cyclones.

Emanuel hosted two long-term visitors: Professor Fuqing Zhang from Pennsylvania State University, who was in residence during fall 2015, and Dr. Louise Nuijens from the Max Planck Institute in Hamburg, Germany. Zhang and Emanuel explored the importance of the wind dependence of surface enthalpy fluxes for determining the properties of tropical cyclones, as well as the fundamental predictability of tropical cyclone intensity. Nuijens and Emanuel discovered that the altitude distribution of cumulus convection in a simple two-column model is strongly tri-modal, which has also been observed in natural convection. They are currently trying to understand why this is the case.

Raffaele Ferrari

Professor Ferrari's group had a very productive year. One particularly interesting result was highlighted in *Nature* shortly after being presented at the February 2016 Ocean Sciences meeting. Ocean deep circulation is a crucial element of the climate system as it controls ocean uptake of heat and carbon. Since Walter Munk's seminal 1966 paper, it has been known that deep circulation is fed by waters that become dense enough to sink into the ocean abyss at high latitudes and are brought back toward the surface by the turbulent mixing generated by breaking internal waves. The Ferrari group showed that the textbook picture is not consistent with the observations collected over the last two decades, which indicate that mixing is most vigorous close to the ocean bottom. The waters return at the surface along the ocean boundaries, while mixing drives additional sinking of waters. Ferrari and his group have confirmed their findings with theory, numerical simulations, and observations and are now lobbying for a large observational program to fully test their theory and its implications for Earth's climate.

Beyond this work, other members of the group remained active in studies of air-sea interactions and their impact on ocean biology. They also continued their study of mesoscale turbulence in the atmosphere.

Glenn Flierl

Professor Flierl and his students are investigating physical and biological dynamics in the ocean and other more general problems in geophysical fluid dynamics. Recent publications include a study of the aggregation of zooplankton (the primary food for right whales) to understand why their concentrations can be orders of magnitude larger in the Great South Channel than in the rest of Massachusetts Bay, an analysis of banded flow structures in the ocean, and studies of the fluxes of material associated with turbulent flows. A recent SM thesis from his group examined the structure of vortices in sinusoidal zonal flows with applications to the Red Spot on Jupiter.

Professor Flierl was the lecturer at the 2015 Fluid Dynamics in Earth and Planetary Sciences workshop in Kyoto. In this 15-hour set of lectures, he covered the dynamics of geophysical vortices and jets. Other work from his group was presented at the American Physical Society and Ocean Sciences meetings as well as in seminars.

Professor Flierl has participated in many outreach events using the iGlobe spherical display, including the MIT open house (with Senior Lecturer Lodovica Illari), Earth Day with the Environmental Solutions Initiative, and an Oceans at MIT event at the MIT Museum.

Gregory Fournier

Several research projects within Professor Fournier's lab continued this year, supported by departmental start-up funds and the NASA Astrobiology Institute Foundations of Complex Life team and conducted in collaboration with research groups at MIT and other institutions.

Using computational techniques and genome sequence data, the Fournier group's project to "date the tree of life" attempts to combine genomic, paleontological, physiological, and geological/geochemical evidence to calibrate the evolutionary histories of major groups of microbes. The goal is to estimate when the groups probably evolved and how their metabolisms influenced the planetary system. Up to this point, the project has focused on the history of Archaea and Proteobacteria, the latter in collaboration with the Polz lab in CEE. These analyses have now been expanded to incorporate additional groups of microbes, including cyanobacteria, other phototrophic bacteria, and sulfate-reducing bacteria. Results include the observation that cyanobacteria likely diversified close to the time of the major rise of oxygen approximately 2.3 billion years ago and that sulfate-reducing bacteria probably diversified shortly thereafter, in support of a model according to which oxidized crust weathering delivered large amounts of sulfate to sediments as oxygen levels continued to increase in the early Proterozoic Eon, 2.3 to 1.8 billion years ago.

Danielle Gruen, a new graduate student in the group, started a project dating the expansion of methanogen substrate usage, specifically mapping the genes associated with reducing acetate and methylated compounds. These microbes are important to marine geochemistry and likely co-evolved with certain algae and bacteria. Gruen and Fournier are attempting to construct a biogeochemical narrative across all of these groups.

The Fournier group also made several methodological advances in estimating these dates, including combining multiple gene histories to use horizontally transferred genes in propagating fossil date calibrations across the tree of life and running computer simulations of sets of proposed fossil calibrations at different dates in order to independently evaluate their plausibility. This approach has led them to the conclusion that a two-billion-year-old putative cyanobacterial fossil has likely been misidentified, in agreement with a recent paleontological reassessment of the specimen.

A project focusing on genomes and the rise of oxygen (a collaboration between the Foundations of Complex Life team at MIT and the Alternative Earths team at the University of California, Riverside, together with Roger Summons and postdoctoral associate David Gold) is investigating the history of the emergence and spread of oxygen-related genes across microbial lineages. Mapping the evolutionary histories of these genes using phylogenies based on genome sequence data reveals how and when major groups of microbes likely first encountered oxygen and adapted to changing oxygen levels across 2.5 billion years. This year, the Fournier group performed phylogenetic reconstructions and date calibration estimates of the age of oxygen-dependent sterol biosynthesis enzymes within eukaryotes and certain bacteria, identifying that these genes probably originated within the eukaryal stem ancestor lineage relatively early and were only later acquired by bacterial groups. As part of a funded NASA Director’s Discretionary Fund project, the group also began mapping the acquisition and transfer of other oxygen-dependent genes across different parts of the tree of life to use as an independent proxy for the rise of oxygenated niches following the Great Oxygenation Event.

In addition, members of the group have begun a research project in collaboration with Jack Szostak’s team at Harvard Medical School in which they will investigate the earliest origins of protein synthesis machinery by reconstructing ancestral sequences of families of proteins that load specific tRNA with their cognate amino acids (aaRS proteins). First-year EAPS graduate student Marjorie Cantine has led the effort and is working to integrate both protein sequences and structural data to address this problem. The project’s objective is to test the proposed hypothesis that the ancestor of each major group of aaRS proteins descended from the same gene but arose from opposite strands.

A combinatoric analysis of likely ancestor sequences, guided by their evolutionary history, will allow us to evaluate this controversial hypothesis.

Timothy Grove

Professor Grove and his students and collaborators completed experimental investigations of the melting behavior of two surface lava compositions on Mercury remotely analyzed via the x-ray spectrometer on the MESSENGER spacecraft. These new experiments put constraints on the interior melting processes that occurred within Mercury during its early volcanic history. The two lavas represent the oldest and youngest lava flows on Mercury. The older lava composition records a melting process that began deep in the planet, at 360 kilometers, near the core/mantle boundary at 1,650°C. The younger lava records a melting process that began at a shallower depth, 160 kilometers, and at 1,410°C. The experiments indicate that the planet's interior cooled dramatically, by more than 240°C, between 4.2 and 3.7 billion years ago—a geologically short span of 500 million years. These are the first estimates of the secular cooling of a planet during its early history.

Thomas Herring

Professor Herring is primarily using global positioning system (GPS) data to develop geophysically based models of Earth deformations on the global, regional, and local scales as well as changes in the rotation of the Earth. He is also using interferometric synthetic aperture radar to study small surface deformations and geodetic methods to study Earth's gravity field.

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

Oliver Jagoutz

The members of Professor Jagoutz's group continued their research on the formation and evolution of the continental crust. Jagoutz has been working in northeastern India in the Himalayan mountains for several years to unravel the history of the ocean that once separated India and Eurasia. In a paper published in the *Proceedings of the National Academy of Sciences* in 2016, Jagoutz and his MIT colleague Leigh Royden showed that their pre-collisional scenario could explain the beginning of the ice ages in the Cenozoic. Their numerical simulations indicate that when obduction of ultramafic rocks occurs in the inter-tropical convergence zone, the subsequent weathering of these rocks could sequester significant amounts of CO_2 from the atmosphere.

Third-year PhD student Benjamin Klein and Jagoutz are studying how magmatic processes in the deep crust of arcs form continental crust. First-year graduate student William Shinevar and Jagoutz will work on an algorithm to convert seismic properties to chemical compositions as a means of better constraining compositional variations in the lower continental crust.

John Marshall

Professor Marshall and his research group continued several lines of research. One collaborative project (with research scientist David Ferreira and Professors R. Alan Plumb and Susan Solomon), on the climatic implications of the ozone hole, led to an important publication in the *Journal of Climate*. The response of the Southern Ocean to a repeating seasonal cycle of ozone loss was found to involve rapid cooling followed by slow but persistent warming. This may account for the observed increase in Antarctic sea ice over the past few decades, in contrast to declining sea ice in the Arctic.

David McGee

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

One tool they use in this research is reconstructions of windblown mineral dust deposited in marine sediments, as dust constitutes a unique tracer of past wind patterns and aridity in source areas. Dust also actively influences climate patterns through direct effects on incoming and outgoing radiation and indirect effects on cloud optical properties and precipitation, and it supplies limiting nutrients to the surface ocean and some terrestrial ecosystems.

Group members have mapped past dust emissions and transport from North Africa using an array of marine sediment cores from the North Atlantic Ocean demonstrating that the African dust plume can be reconstructed coherently across thousands of kilometers. Led by graduate students Ross Williams and Christopher Kinsley, this work places quantitative bounds on changes in emissions from the world's largest dust source over the last 20,000 years. The results show factor-of-four changes in long-range dust transport between maximum emissions during high-latitude cooling events at the end of the last ice age and minimum emissions during the early Holocene African Humid Period 5,000 to 11,000 years ago.

The team found no evidence of significant anthropogenic changes in dust emissions from North Africa over the industrial era. Related work has tested and refined the methods used for dust flux reconstructions, and research by postdoctoral fellow Christopher Hayes has constrained modern dust inputs and iron cycling in the ocean. The group has begun to examine the climatic impacts of past changes in Saharan dust emissions, demonstrating that dust-driven cooling of subtropical North Atlantic sea surface temperatures is probably an important amplifier of regional climate variability.

Ongoing collaboration with climate modelers incorporating prognostic dust emissions and transport into models of current and past climates offers a new avenue to test interpretations of dust records, quantify past changes in iron delivery to the oceans, and identify areas for model improvements.

In other research, members of the McGee group have developed records of regional precipitation patterns using lake deposits and stalagmites. Their particular focus is on the use of uranium-thorium disequilibrium dating to offer precise and accurate chronological control, which is essential for comparing independently dated records from around the world. Recent and ongoing research led by graduate students Christine Chen and Gabriela Serrato Marks and research scientist Ben Hardt documents past precipitation changes in Madagascar, Brazil, Vietnam, Mexico, and the central Andes.

J. Taylor Perron

Professor Perron and his group study the processes that shape the surface on Earth and other planets. Their efforts are currently focused on understanding widespread patterns in landscapes, climate effects on erosion, and the landscapes of Mars and Saturn's moon Titan.

A new effort by Perron's group came to fruition in 2015–2016. SM student Mirna Slim and postdoctoral researcher Seulgi Moon led studies of how stresses created by ridges and valleys on Earth's surface affect the breakdown of rock below those landforms. The thin layer near Earth's surface where rocks break down to form soil is so essential to life that it has been dubbed the "critical zone." The extent of fracturing and weathering (physical and chemical breakdown) in this zone controls how erosion sculpts bedrock into mountains, and the chemical reactions that weather rocks help regulate Earth's climate by consuming carbon dioxide. At present, however, it is unknown how deep the weathered zone extends, or how extensively the rock is weathered, in a given location.

One idea is that stresses (forces) imposed by landforms such as valleys and ridges can, depending on their shape, either accelerate the fracturing of rock (mountains breaking their own foundations) or inhibit fracturing, creating different depths and extents of weathering beneath different parts of a landscape. Using computational stress models and field surveys that probed the mechanical integrity of rocks beneath Earth's surface, the group discovered that rocks appear to be damaged in spatially variable patterns identical to those predicted in the "topographic stress" idea.

Possible implications of this work include understanding feedbacks between topography and rock weathering (in which mountainous topography affects how the underlying rock breaks down, which in turn influences how mountainous topography erodes); predicting the characteristics of reservoirs that hold groundwater, fossil fuels, or even injected CO_2; mapping unstable slopes in which fractured rock is more likely to form landslides; and mapping the depth of the life-sustaining "critical zone."

Former MIT postdoctoral researcher Seulgi Moon, now an assistant professor at the University of California, Los Angeles, maps bedrock fractures in Gordon Gulch, CO.

Ronald G. Prinn

Professor Prinn reported that the Center for Global Change Science, its Joint Program on the Science and Policy of Global Change (JPSPGC), and its Advanced Global Atmospheric Gases Experiment (AGAGE), which he directs, produced 66 peer-reviewed scientific papers over the past year; 13 were authored or coauthored by him and members of his group. Through support provided by a combination of federal grants, industry donors, and foundations, research spending continued at about $9 million annually. NASA funding for the AGAGE network was renewed for the period 2016–2021.

The new MIT-led Rwanda Climate Observatory, which is joining AGAGE, has recorded the first simultaneous high-frequency measurements in Africa of carbon dioxide, carbon monoxide, methane, ozone, and black carbon aerosols. In addition, the first high-frequency measurements of the isotopic composition of the greenhouse and ozone-depleting gas nitrous oxide have been obtained at the Ireland AGAGE station. EAPS doctoral students Jimmy Gasore (African station) and Michael McClellan (Irish station) are involved in this AGAGE activity. MIT's climate action plan group announced a new JPSPGC-led study that will define the scientific, economic, and technological pathways needed to restrict global warming to 3.6ºF above pre-industrial levels.

Paola Rizzoli

Professor Rizzoli and her collaborators from the National University of Singapore, Drs. Pavel Tkalich and Bijoy Thompson, have continued to investigate the dynamic and thermodynamic balances of the South China Sea, specifically focusing on the transition in sea surface temperatures from the climatological conditions of the 1980s to those of the late 1990s.

In an effort with collaborator Jun Wei of the University of Beijing, the investigation has been extended to decomposition of the changes in the South China Sea induced by surface fluxes or boundary conditions. A further study has focused on the interactions between the South China Sea and the Indonesian throughflow and the contrasting variabilities induced by the two in the Sulawesi Sea.

The second major objective of the group's research has been further improvement of the coupled ocean/atmosphere climate model developed by Rizzoli in collaboration with Professor Elfatih Eltahir's team in CEE. The model has been used to identify negative feedback mechanisms between the atmosphere and the ocean to correct for negative/positive biases in oceanic/atmospheric variables.

Daniel Rothman

Professor Rothman and his group continue to study the coevolution of life and the environment. These efforts currently seek to provide an understanding of the mechanisms through which the carbon cycle may lose its stability, potentially leading to mass extinction. The group's empirical studies suggest the existence of a threshold beyond which instability can occur; work during the last year has sought to interpret this threshold theoretically in terms of the processes that control the flow of carbon through the atmosphere, oceans, and rocks. To help develop this project into a major Lorenz Center activity, significant philanthropic support is being pursued with the assistance of the Science Philanthropy Alliance.

Rothman's group also continues its work on pattern formation in fluvial systems. Accomplishments in the past year include publication of a paper in the *Proceedings of the National Academy of Sciences* showing that the direction in which a river grows derives from the same mathematical theory that describes path selection in fracture mechanics.

Hilke Schlichting

Professor Schlichting's research focuses on planet formation theory, extrasolar planets, and solar system dynamics. She studies the solar system because it is the only place where planet formation outcomes can be examined in detail, and she uses the diversity and statistical properties of extrasolar planets to test formation theories. Her research over the past year has focused on understanding the formation of a new class of planets discovered in the Kepler space mission, planets that are typically several times more massive than Earth but that orbit their host stars well inside the orbit of Mercury. Understanding the origin of this new and ubiquitous class of planets is crucial for determining the key processes of planet formation and for assessing the suitability of these bodies to harbor life.

Together with graduate student Sivan Ginzburg and Re'em Sari, a professor of astrophysics at the Hebrew University, Schlichting investigated the self-consistently atmospheric accretion and retention of gas envelopes by protoplanetary cores. They showed that close-in exoplanets quickly shed large fractions of their accreted envelopes as the gas disk dissipates and that, in cases in which the thermal energy budget is dominated by their cores (typically planets that have less than 5% of their total mass in their atmospheres), all of the atmospheres can be blown off.

With her graduate student Niraj Inamdar, Schlichting also investigated atmospheric mass loss due to giant impacts and suggested that one or two such impacts might be responsible for the large diversity in bulk densities observed among planets residing in multiple systems.

Susan Solomon

Professor Solomon's research focuses on atmospheric chemistry and its interactions with climate change, as well as on environmental science and policy.

In a paper published in *Science*, Solomon and her group showed that the Antarctic ozone hole is beginning to heal. Industrial chlorofluorocarbons that cause ozone depletion have been phased out under the Montreal Protocol. A chemically driven increase in polar ozone (or "healing") is expected in response to this historic agreement. Observations and model calculations taken together indicate that the onset of healing of Antarctic ozone loss has now emerged. Fingerprints of healing since 2000 have been identified through increases in ozone column amounts, changes in the vertical profile of ozone concentrations, and decreases in the areal extent of the ozone hole. Volcanic eruptions episodically interfere with healing, and this was particularly the case during 2015 (when a record October ozone hole occurred after the Calbuco eruption).

In a paper accepted for publication in *Marine Policy*, Solomon and her colleagues have shown that ocean noise levels produced by commercial shipping can be expected to double by 2030. Ocean noise levels are thought to be increasing as a result of major growth in global shipping activity, but data quantifying those changes are limited in space and time. As an alternative approach, Solomon's group is examining the current and future maximum noise capacity of three segments of the global commercial shipping fleet: container ships, oil tankers, and bulk carriers. Their work shows that continued growth in number of ships, quantity of goods carried, and distances traveled could increase the maximum noise capacity of the global shipping fleet by up to a factor of 1.9 by 2030, with major growth in particular in the container and bulk carrier segments. Thus, in the absence of operational or manufacturing changes to such ships, the contribution of commercial shipping to ambient ocean noise levels can be expected to dramatically increase.

Together with international collaborators, members of the Solomon group contributed to a highly cited study published in *Environmental Research Letters* that addressed whether countries' climate change pledges meet the challenge of being "fair and ambitious" in view of policymakers' calls for a fair and ambitious global climate agreement. Scientific constraints, such as carbon emissions not exceeding a 2°C global warming limit, can help define ambitious approaches to climate targets. The study showed that, combined, the US, European Union, and Chinese pledges left little room for other countries to emit CO_2 if a 2°C limit is the objective, essentially requiring all other countries to move toward per capita emissions 7 to 14 times lower than those of the European Union, the United States, and China by 2030. The study authors argued that a fair and ambitious agreement for a 2°C limit that would be globally inclusive and effective in the long term will require stronger mitigation than the goals currently proposed. Given such necessary and unprecedented mitigation and the current lack of availability of some key technologies, the authors suggested a new diplomatic effort directed at ensuring that the necessary technologies become available in the near future.

Roger Summons

Members of the Summons geobiology laboratory continue their work on geochemical records of early life on Earth and the coevolution of life with its environment. Collaborating with a diverse group of researchers interested in the earliest records of life, they have made significant advances in perfecting chemical and isotopic analyses of fossilized organic matter at micron spatial scales. They have documented multiple sulfur isotope signals of diagenetic pyrite in a continuous sedimentary sequence in three coeval drill cores in the Transvaal Supergroup in South Africa; these data precisely constrain the timing and duration of the Great Oxygenation Event, the name given to geological and geochemical phenomena that record the earliest permanent presence of oxygen in Earth's atmosphere. The findings suggest that this happened 2.33 billion years ago and that it was a rapid process (in geological terms), occurring over a period of 1 million to 10 million years. Oxygen is an absolute requirement for the development of complex life on Earth.

Moving forward in time, to the geological epoch wherein the first fossil evidence of animal life is preserved in rocks approximately 550 to 650 million years old, members of the Summons lab conducted a bioinformatics and molecular clock study of enzymes required for the biosynthesis of unusual steroids attributed to sponges. Their results suggest that sponges had the biochemical capability to make such steroids as many as 600 million years ago, while algae, which make similar steroids, did not acquire that capability until about 100 million years later. The group's findings are consistent with the hypothesis that sponges were the first multicellular animals to appear on Earth.

The Summons group also conducted analog experiments in support of the Mars Science Laboratory mission currently operating the Curiosity rover at Gale Crater on Mars. These studies are placing constraints on the types of organic compounds that might be responsible for the chlorinated hydrocarbons thus far detected by Curiosity.

The research of the Summons group is funded by grants from NASA, the Simons Foundation Collaboration on the Origins of Life, and the National Science Foundation.

Robert D. van der Hilst

Professor van der Hilst has been head of the Department of Earth, Atmospheric and Planetary Sciences since January 2012. His research continues to focus on regional tectonics in Southeast Asia and North America, imaging of Earth's deep interior using dense seismograph arrays (in collaboration with visiting 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). Last year, van der Hilst's team discovered that the heights of mountains and other topographic features in the western United States are determined not only by variations in crustal thickness (that is, through the classical concept of isostasy) but by dynamic processes and variations in mantle composition. They also developed a method for determining contrasts in mass density and seismic wave speed across interfaces deep in Earth's interior (beneath the Central Pacific), which will help determine composition and temperature at depths that are well outside the reach of direct observation and measurement.

Jack Wisdom

Professor Wisdom has been studying the early evolution of the Earth-moon system after the giant impact that is presumed to have formed the moon. Isotopic similarities of the Earth and moon suggest that the moon-forming impact was more severe than previously thought, but this would leave the system with too much angular momentum. It has been suggested that if the system were caught in the evection resonance, the required angular momentum could have been drained from the system.

Last year, Wisdom and graduate student ZhenLiang Tian reported that they had found an alternative mechanism to remove the excess angular momentum: the Earth-moon system can be captured in a limit cycle associated with the evection resonance. The advantage of the limit cycle over the previously suggested evection resonance is that the level of eccentricity is smaller. This is important in that an order of magnitude calculation shows that the proposed evolution in the evection resonance would generate enough heat (from the high orbital eccentricity) to vaporize the moon. Still, it was necessary to model the effects of the heating. In a subsequent investigation of the coupled thermal-orbital evolution of the early Earth-moon system, Wisdom and Tian found that the evection resonance no longer drains angular momentum from the system, because system parameters change too much due to tidal heating. In contrast, the limit cycle extracts about the same amount of angular momentum in the coupled model as in the uncoupled model. The limit cycle thus provides a possible route from the formation of the moon through a giant impact to the present Earth-moon configuration.

Robert D. Van der Hilst
Department Head
Schulmberger Professor of Geosciences