CIRES
COOPERATIVE INSTITUTE FOR RESEARCH IN ENVIRONMENTAL SCIENCES

SPHERES

Edition 12 • 2020

Frozen in the Arctic

In their words // Flying drones at the North Pole // 'Travel' with the team

Where there's smoke, there's science

Learn to live with wildfire // Chasing smoke // More fires, cooler fires

INSIDE

Not thinking clearly in 2100 // Machine learning for solar forecasts
'Promiscuous' enzymes // Moss, mental health and microbes

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SPHERES
A publication of the Cooperative Institute for Research in Environmental Sciences

CIRES, a partnership of the University of Colorado Boulder and NOAA, is dedicated to fundamental and interdisciplinary research targeted at all aspects of the dynamic Earth system and to communicating these findings to the global scientific community, to decision makers and to the public. Our environmental scientists explore many aspects of Earth system science: the atmosphere, cryosphere, hydrosphere, geosphere and biosphere. These spheres of expertise give our magazine its name.

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ON THE COVER:
CIRES videographer Amy Richman, who is producing a planetarium show on the MOSAiC expedition in the Arctic, leans over the edge of a hole cut in the ice at a research station dubbed "Ocean City." Stories begin on page 29.
Photo: Alfred Wegener Institute/Stefan Hendricks (Cc-By 4.0)

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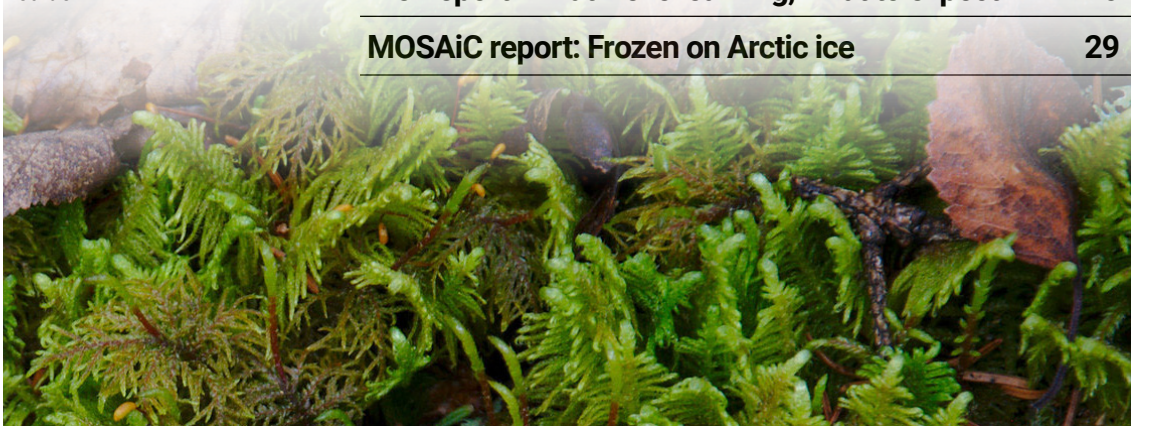
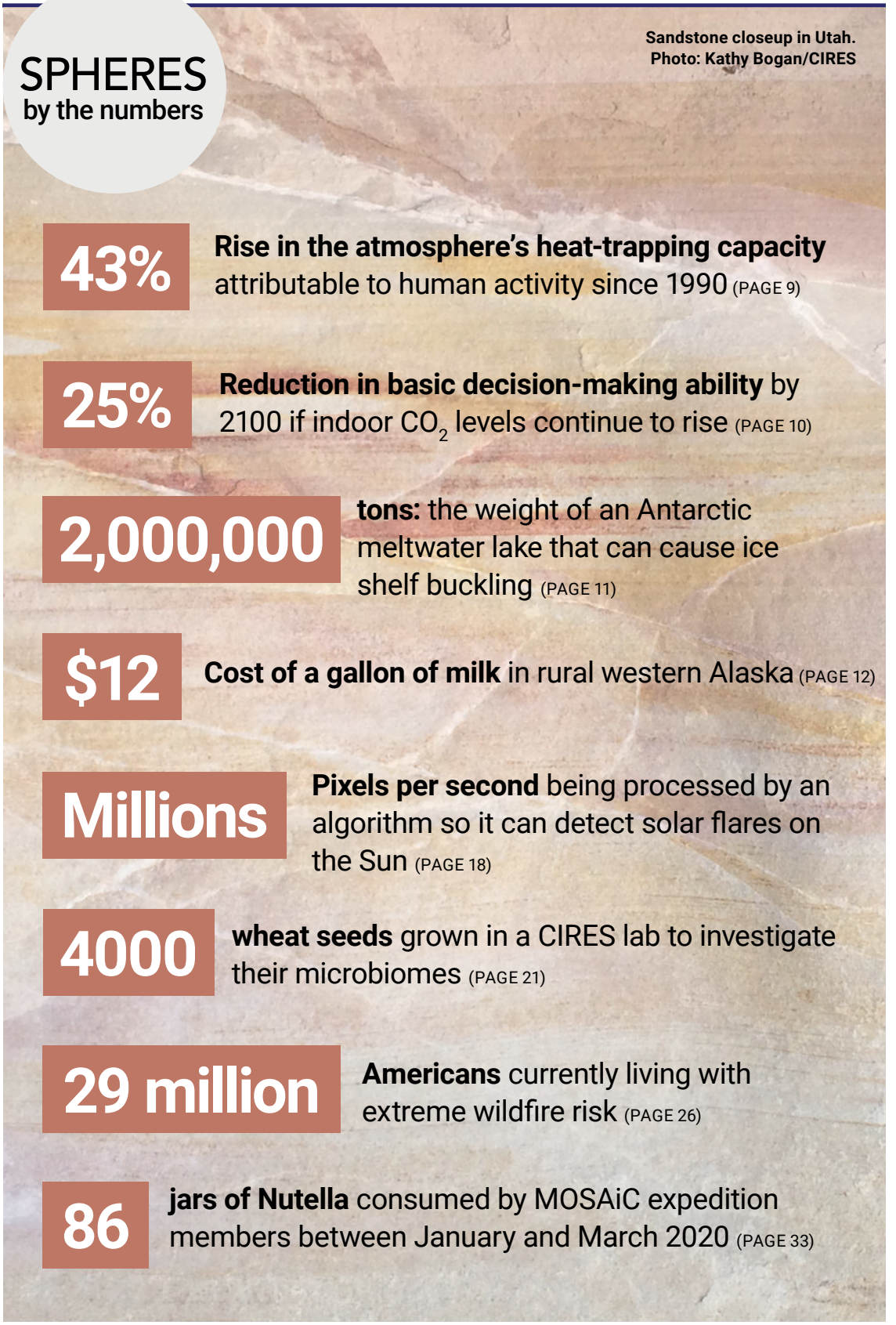
Below: Moss microbiomes may affect surrounding forests (page 21). Photo: Hannah Holland-Moritz/CU Boulder



SPHERES
by the numbers



Sandstone closeup in Utah.
Photo: Kathy Bogan/CIRES

43% **Rise in the atmosphere's heat-trapping capacity** attributable to human activity since 1990 (PAGE 9)

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2,000,000 **tons:** the weight of an Antarctic meltwater lake that can cause ice shelf buckling (PAGE 11)

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4000 **wheat seeds** grown in a CIRES lab to investigate their microbiomes (PAGE 21)

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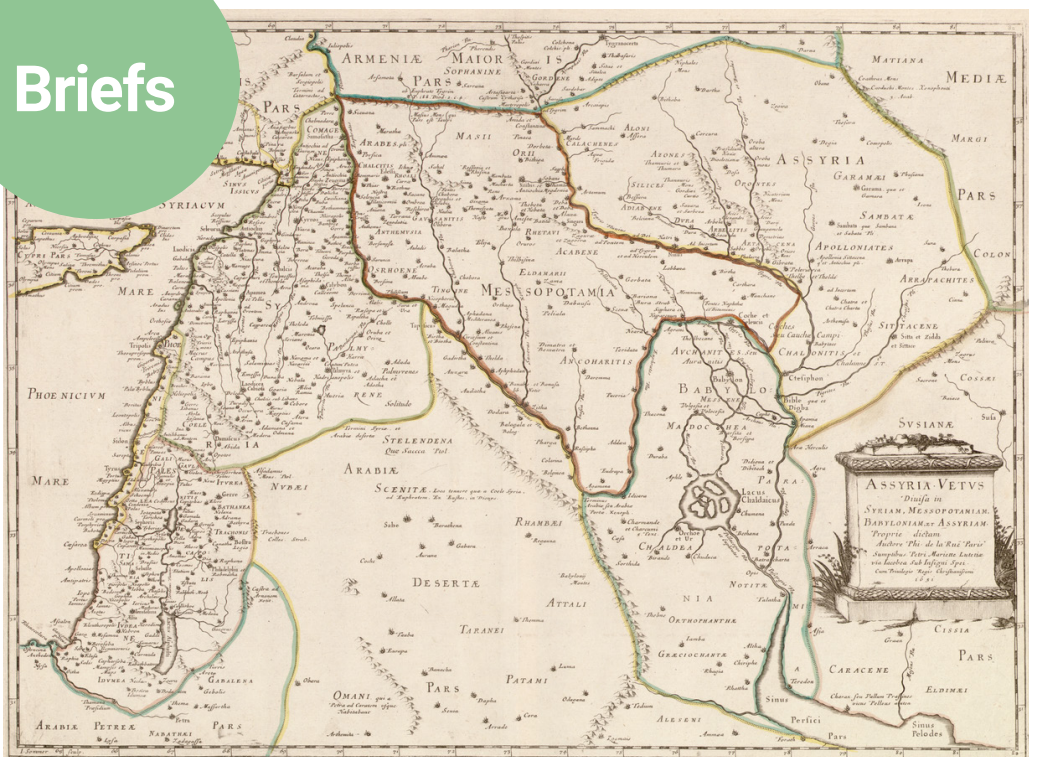
Briefs



This mid-1600s map shows the ancient kingdoms of the Middle East. Assyria borders Mesopotamia on the east. Image: Wikimedia Commons

CLIMATE

Climate change crumbled ancient civilization

Megadroughts likely triggered the fall of the Assyrian Empire in the 7th century B.C., according to research by former CIRES Visiting Fellow **Adam Schneider** and colleagues, who published their work in *Science Advances* in late 2019. The Assyrian Empire, mapped above, whose heartland was in today's northern Iraq, was one of the most powerful civilizations in the world from 912-609 B.C. By analyzing climate records, including layered stalagmites from a northern Iraq cave, Schneider and his colleagues concluded that a series of mega-droughts struck the region decades earlier than previously believed. Those droughts likely weakened agriculture and amplified conflict that was already a part of life in the region.

bit.ly/Assyriacrumbles

Southern Ocean absorbing less CO_2

Climate change is altering the ability of the Southern Ocean off the West Antarctic Peninsula to absorb carbon dioxide, according to a *Nature Climate Change* study—an important finding because the

CONTINUED ON PAGE 5

Smith Island rises out of the Southern Ocean, which is experiencing some of the most rapid climate change on the planet. Photo: Michael Rhodes/CIRES

CONTINUED FROM PAGE 4

Southern Ocean absorbs nearly half of the CO_2 taken up by all the world's oceans.

From 1993 to 2017, the Southern Ocean was stable, letting algae grow and draw down more CO_2 from the atmosphere, the paper reported. But the region is experiencing some of the most rapid climate change on Earth, including dramatic temperature increases and sea-ice decline. And the Rutgers University-led research team found that as sea ice continues to decline, the Southern Ocean may become less stable and absorb less CO_2.

The August 2019 study tapped 25 years of measurements in the Southern Ocean by CIRES and NOAA scientists.

bit.ly/southernoceanlessCO2

Warm ocean attacks ice shelves

Upside-down "rivers" of warm ocean water are eroding the fractured edges of thick, floating Antarctic ice shelves from below, helping to create conditions that lead to ice-shelf breakup and sea-level rise, according to a new study by CIRES alum **Karen Alley,** CIRES senior scientist **Ted Scambos** and two colleagues.

Their work, published in October 2019 in *Science Advances,* described a new process important to the future of Antarctica's ice and the continent's contribution to rising seas. Models and forecasts do not yet account for the newly understood and troubling scenario, which is already underway.

bit.ly/warmoceanattacks

ATMOSPHERIC CHEMISTRY

Surprising carbon drawdown

North American ecosystems pull unexpectedly large amounts of carbon dioxide out of the atmosphere and into the biosphere during El Niño years. That's one result from a detailed analysis of 20 years of NOAA air sampling data, published in June 2019 in *Science Advances*. The NOAA and CIRES authors, led by CIRES' **Lei Hu,** noted that during El Niños, there's more CO_2 in the atmosphere, and they found that North American ecosystems draw down a great deal of it: 2.24 billion tons more annually than during La Niñas. That's about one-third of North American CO_2 emissions. The effect appears to

A CIRES and NOAA study found that the North American biosphere absorbs a startling amount of CO_2 in response to El Niño's warming of the Pacific Ocean. Photo: Theo Stein/NOAA

be primarily due to North American precipitation patterns during El Niños, which favor plant growth.

"This is a new insight into the biosphere and it offers a way for models to refine their treatment of carbon flux to help improve future predictions," said Hu.

bit.ly/carbondrawdown

Tiny particles lead to brighter clouds in the Tropics

When clouds loft tropical air masses higher in the atmosphere, that air can carry up gases that form into tiny particles, starting a process that may brighten lower-level clouds. Clouds alter Earth's radiative balance, and ultimately climate, depending on how bright they are. Because this particle-forming/cloud-brightening process might occur over 40 percent of Earth's surface, climate models may underestimate the cooling impact of some clouds.

"Understanding how these particles contribute to cloud properties in the tropics will help us better represent clouds in climate models," said **Christina Williamson**, a CIRES scientist at

CONTINUED ON PAGE 6

Briefs

A natural gas flare in McKenzie County, North Dakota. Photo: Tim Evanson/Creative Commons

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NOAA and lead author of the October 2019 *Nature* paper. Her team's work relied on global atmospheric measurements from ATom, a NASA study that spanned the Arctic to the Antarctic.

bit.ly/tinyparticlesbrighterclouds

Satellites capture oil, gas production

Oil and gas production doubled in some parts of the United States between 2017 and 2019, and scientists can use satellites to see impacts of that trend: a significant increase in the release of the lung-irritating air pollutant nitrogen dioxide, for example, and a more-than-doubling of the amount of natural gas flared into the atmosphere.

"We see the industry's growing impact from space," said CIRES scientist **Barbara Dix**, lead author of the assessment published in the AGU journal *Geophysical Research Letters* in early 2020. "We really are at the point where we can use satellite data to give feedback to companies and regulators."

bit.ly/satellitescapture

HAZARDS

Space weather advisories protect airline crew, passengers

A new international advisory system is working to keep aircraft crew and passengers safe from space weather, thanks in part to a team of CIRES and NOAA developers, forecasters and scientists in Boulder.

"Thunderstorms or snow can disrupt flights. What we call 'space weather' can be disruptive, too," said **Rob Steenburgh** of NOAA's Space Weather Prediction Center. Space weather—such as solar flares or massive ejections of material from the Sun's corona— can temporarily interfere with navigation or even increase atmospheric radiation levels. And—much as with a blizzard or looming thunderstorm—airlines can take action, changing an aircraft's flight path to avoid or lessen those impacts, said CIRES solar physicist **Hazel Bain**. She, Steenburgh and more than a dozen colleagues built a space weather advisory system for the International Civil Aviation Organization in one year; it went live in late 2019.

bit.ly/spaceweatheradvisories

Hot droughts get hotter

Climate change threatens to make "hot droughts" significantly hotter—and longer—than they used to be, according to a CIRES-led study published in the *Journal of Climate* in July 2019. In the southern Great Plains and Southwest especially, soil moisture vanishes during severe droughts, and cooling by evaporation from the soil and transpiration from plants cannot provide the relief they might have in the 1800s, before appreciable global warming. The result is supercharging of drought-related heat waves, researchers concluded.

bit.ly/hotdroughts

Invasive grasses promote wildfire

Invasive cheatgrass, reviled by ranchers and conservationists in the western United States, has long since earned a reputation as a firestarter, making wildfires worse and more common. Same with climate warming: it's making western wildfires worse as well. But it's not just cheatgrass or a hotter West. A recent

Emily Fusco (University of Massachusetts Amherst) works on a project in Arizona assessing the combined impacts of invasive buffelgrass and fire on Sonoran Desert ecosystems. Photo: Chelsea Nagy/CIRES

analysis found at least seven other non-native grasses increasing wildfire risk in places across the country, some doubling or even tripling the likelihood of fires in grass-invaded areas. The team, including CIRES' **Chelsea Nagy** (Earth Lab), published its "pyrogeographic" assessment in November 2019 in *Proceedings of the National Academy of Sciences*.

bit.ly/invasivegrasses

Game on: Students tackle hazards

Middle and high school students across Colorado navigated a series of natural hazards last year: wildfire, drought and flood. They safeguarded their communities by making critical choices about such issues as how much to invest in fire suppression equipment, whether to build new water storage reservoirs and planning evacuation routes. Luckily, they weren't in any real danger—it was an educational simulation.

CIRES Education & Outreach partnered with NOAA's Regional Integrated Sciences and Assessments program to create hazard lessons and scenario-based role-playing games focused on community resilience. The Hazard Education, Awareness, and Resilience Task Force (HEART Force) engages rural communities to take proactive steps to prepare for natural hazards.

"Kids got the game," said one middle school teacher who played the game with her class. "They were very engaged!"

EDUCATION

Professionals hone big data skills

Last year, 19 students in CU Boulder's Earth Data Analytics program analyzed huge volumes of data on air pollution, glaciers, flood detection and more. The 10-month professional graduate certificate program, now in its second year, is offered either fully online or in person. It's one of just a few in the nation to focus specifically on applying data science techniques to the Earth and environmental sciences.

"There is a deluge of freely available data available now," said **Leah Wasser,** director of Earth Analytics Education at Earth Lab. "And there's a real demand for people with the skills needed to work with this flood of data to help unlock answers to pressing environmental challenges."

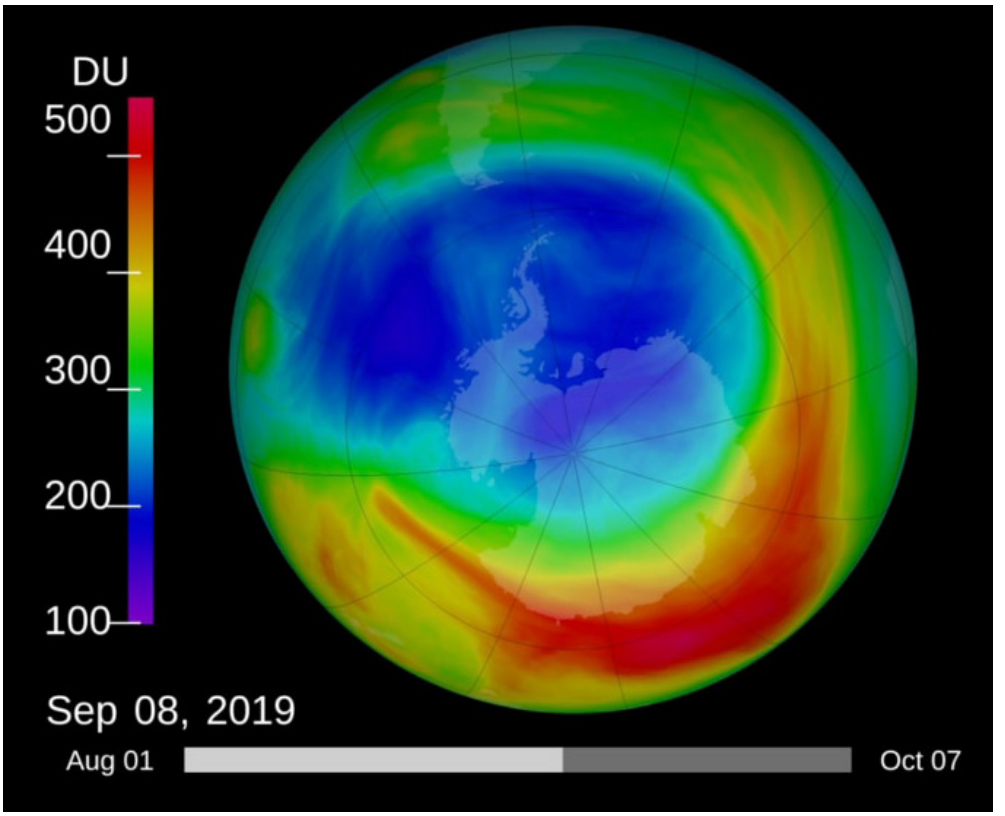
bit.ly/earthlabcert

Sick of cat videos? Check out Earth and space animations instead

Download NOAA's SOS Explorer™ (SOSx) Mobile app to watch visually stunning movies on a virtual globe! These aren't your typical movies—they're animations of earth science data: satellite observations of the ocean, atmosphere, space and land, and output from numerical models scientists use to monitor Earth and space.

The app has been available since August 2019, when a team of NOAA, CIRES and CIRA scientists in NOAA's Global Systems Laboratory released SOSx Mobile, the most portable of a suite of visualization tools that includes Science On a Sphere® (SOS), a room-sized animated globe featured in more than 160 museums worldwide.

bit.ly/SOSxMobile



A NASA depiction of the 2019 ozone hole, which reached a peak extent of just 6.3 million square miles on September 8, 2019, the smallest maximum extent observed in decades. Image: Katy Mersmann/NASA Goddard

Warm stratosphere kept 2019 ozone hole small

OZONE HOLE

Unusual weather patterns in the atmosphere high over Antarctica dramatically limited ozone depletion in September and October 2019, resulting in the smallest ozone hole observed since 1982, NASA and NOAA scientists reported in October. Several CIRES scientists working in NOAA's Global Monitoring Laboratory contributed measurements and analysis to the annual update, and CIRES' **Amy Butler**, who works in NOAA's Chemical Sciences Laboratory, anticipated the low-loss ozone season.

"A large polar stratospheric warming is under way in the Southern Hemisphere," Butler and colleagues from around the world wrote in a *Nature* Correspondence piece published September 23, 2019. A similar event in 2002 was associated with a reduction in the size of the Antarctic ozone hole. "The 2019 event is predicted to be no less remarkable," they wrote.

On September 8, 2019, the annual ozone hole reached a peak extent of 6.3 million square miles (16. 4 million square kilometers); it's been about 8 million square miles in more typical, recent years. NOAA and NASA confirmed the maximum size of the ozone hole in mid October, after waiting to see if ozone depletion would increase again or not.

Last season's smaller ozone hole was due to warmer stratospheric temperatures and should not be interpreted as a sign that the ozone layer was suddenly on a fast track to recovery, the team of NOAA, NASA and other experts concluded. Those warmer temperatures meant fewer polar stratospheric clouds; and it's on cloud particles that ozone-destroying reactions take place. Stratospheric warming in September 2019 was unprecedented and substantially limited ozone depletion, Butler and her colleagues reported in *Nature*.

bit.ly/smallestozonehole

Rising emissions drive greenhouse gas index higher

CLIMATE

Record levels of greenhouse gas pollution continued to increase humanity's impact on the atmosphere's heat-trapping capacity during 2018, according to a yearly analysis released by NOAA in May 2019.

NOAA's Annual Greenhouse Gas Index (AGGI) tracks the influence of carbon dioxide, methane and other greenhouse gases on climate since the start of the Industrial Revolution. In 2018, the index rose to a value of 1.43, meaning that the increase in the atmosphere's heat-trapping capacity attributable to human activity has risen 43 percent since 1990 (1990 is the baseline year for the international Kyoto Protocol, which established targets for reducing greenhouse gas pollution).

The index is based on hundreds of air samples collected worldwide and then carefully analyzed by a team of CIRES and federal researchers working at NOAA's Earth System Research Laboratories in Boulder, Colorado.

"Greenhouse gas pollution traps heat in the atmosphere, which has consequences," said **James Butler**, director of NOAA's Global Monitoring Laboratory. "There's no getting around it—burning fossil fuels is changing the course of our planet's future. How society deals with that will be a major challenge in coming decades."

esrl.noaa.gov/gmd/aggi

CIRES researchers Sonja Wolter and Jack Higgs prepare the components of an AirCore payload string for air sampling. Photo: Tim Newberger/CIRES

Ozone treaty stops trends in So. Hemisphere winds

OZONE HOLE

Chemicals that deplete Earth's protective ozone layer have also triggered changes in Southern Hemisphere winds. A 2020 study shows that those changes have paused and might be reversing because of the Montreal Protocol, an international treaty that phased out use of ozone-depleting chemicals.

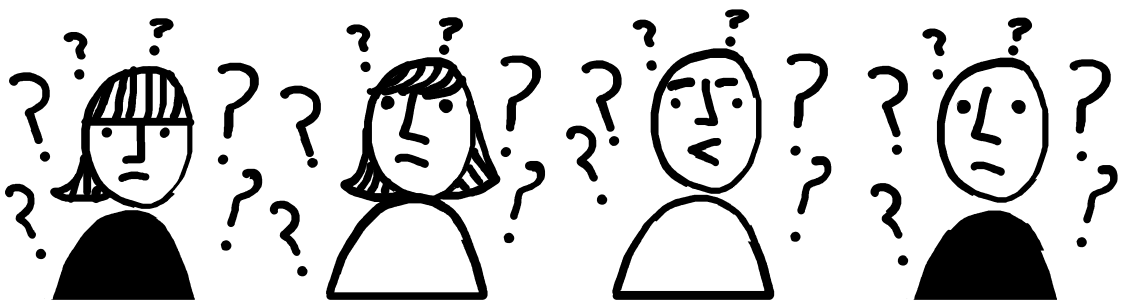
"This study adds to growing evidence showing the profound effectiveness of the Montreal Protocol. Not only has it spurred healing of the ozone layer, it's also driving recent changes in Southern Hemisphere air circulation patterns," said **Antara Banerjee,** a CIRES Visiting Fellow working in NOAA and lead author of a March 2020 *Nature* paper.

The ozone hole, discovered in 1985, forms every spring high over Antarctica. Ozone depletion cools the air, strengthening the winds of the polar vortex and affecting winds down to Earth's surface. Ultimately, ozone depletion has pushed the mid-latitude jet stream and dry regions at the edge of the tropics toward the South Pole. Other studies have linked these circulation trends to weather changes in the Southern Hemisphere, including rainfall, and to ocean currents and salinity.

The 1987 Montreal Protocol phased out production of many ozone-destroying substances. Since about 2000, concentrations of those chemicals in the stratosphere started to decline and the ozone hole began to recover. The researchers showed that at about the same time, the Southern Hemisphere circulation stopped expanding polewards—a pause or slight reversal of the earlier trends.

What happens in the future depends on whether ozone continues to recover—and how fast CO_2 levels continue to climb, since rising CO_2 emissions push the Southern Hemisphere circulation polewards, opposing the effect of ozone recovery.

bit.ly/sohemispherewinds



Feeling fuzzy? You might try opening a window

AIR QUALITY

By the year 2100, we may not be thinking too clearly.

Rising atmospheric carbon dioxide concentrations (CO_2) might mean that people will be breathing indoor air with CO_2 levels up to 1400 parts per million (ppm) by the end of this century, according to a CU Boulder-led study. That's more than three times today's outdoor CO_2 levels and is well beyond what humans have ever experienced. Air with such high CO_2 concentrations can significantly impair our strategic thinking and decision making abilities.

"It's amazing how high CO_2 gets in enclosed spaces," said **Kris Karnauskas**, CIRES Fellow, associate professor at CU Boulder and lead on the April 2020 *GeoHealth* study. "It affects everybody—from kids packed into classrooms to scientists to regular folks in their homes and workplaces."

In general, CO_2 levels are higher indoors—imagine a crowded, stuffy lecture hall. The CO_2 concentrations in buildings are a result of both the gas entering from the outdoors and the CO_2 generated by building occupants exhaling.

Karnauskas and his colleagues developed an end-to-end model that considers future outdoor CO_2 concentrations, the relationship between indoor and outdoor CO_2 and the impact on human cognition. They found that if outdoor CO_2 concentrations rise to 930 ppm by 2100 (the Intergovernmental Panel on Climate Change's unmitigated emissions scenario) that would nudge indoor concentrations to 1400ppm, well within the harmful-to-cognition zone.

"This is a hidden impact of climate change, one that could, ironically, impact our very ability to think about and solve the problem itself," Karnauskas said. The team hopes their findings spark further research on the indirect, overlooked impacts of climate change.

bit.ly/CO2cognition

World Magnetic Model gets out-of-cycle update

WMM 2020

In December 2019, NOAA's NCEI released the World Magnetic Model, which forecasts that the northern magnetic pole will keep drifting toward Russia, although at a slowly decreasing speed—down to about 40 km per year compared to the average annual speed of 55 km over the past 20 years.

EARTH SCIENCE

CIRES and federal scientists in NOAA's National Centers for Environmental Information (NCEI) track changes in Earth's magnetic field to update the World Magnetic Model (WMM), which is essential to safe navigation by the U.S. military and NATO, commercial airlines, search and rescue operations and other activities around the North Pole.

Usually, NCEI releases an updated WMM every five years. But after the 2015 release, scientists discovered that Earth's northern magnetic pole was moving away from the Canadian Arctic toward Siberia more quickly than expected. That led to larger-than-expected errors in the WMM 2015's forecast of magnetic field variation, the NCEI team found.

The National Geospatial Intelligence Agency, the team's key client,

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Ice shelves buckle under weight of meltwater lakes

CRYOSPHERE

A team of CIRES, University of Cambridge and University of Chicago scientists was the first to directly observe an Antarctic ice shelf bending under the weight of meltwater ponding on top. The phenomenon may have triggered the epic 2002 collapse of the Larsen B ice shelf.

A meltwater lake can weigh up to two million tons: That pushes downward on the ice, creating an indent. When the lake drains, the indent pops back up. This repeated flexure could weaken—and even break—ice shelves, said the researchers in their 2019 *Nature Communications* paper.

The team, led by CIRES Visiting Fellow **Alison Banwell**, (now a research scientist) tracked the flexure on the McMurdo Ice Shelf by deploying a series of GPS sensors on poles drilled into the ice and measuring their elevation during the full melt season. They could clearly see the ice shelf bending at the center of each lake bed they studied.

"These observations help us better understand the triggers of ice shelf break up, which ultimately leads to sea level rise, as ice shelves act to buttress the inland ice from flowing into the ocean," Banwell said. "Our results can be used to better predict which ice shelves are most susceptible to collapse."

bit.ly/bucklingiceshelves

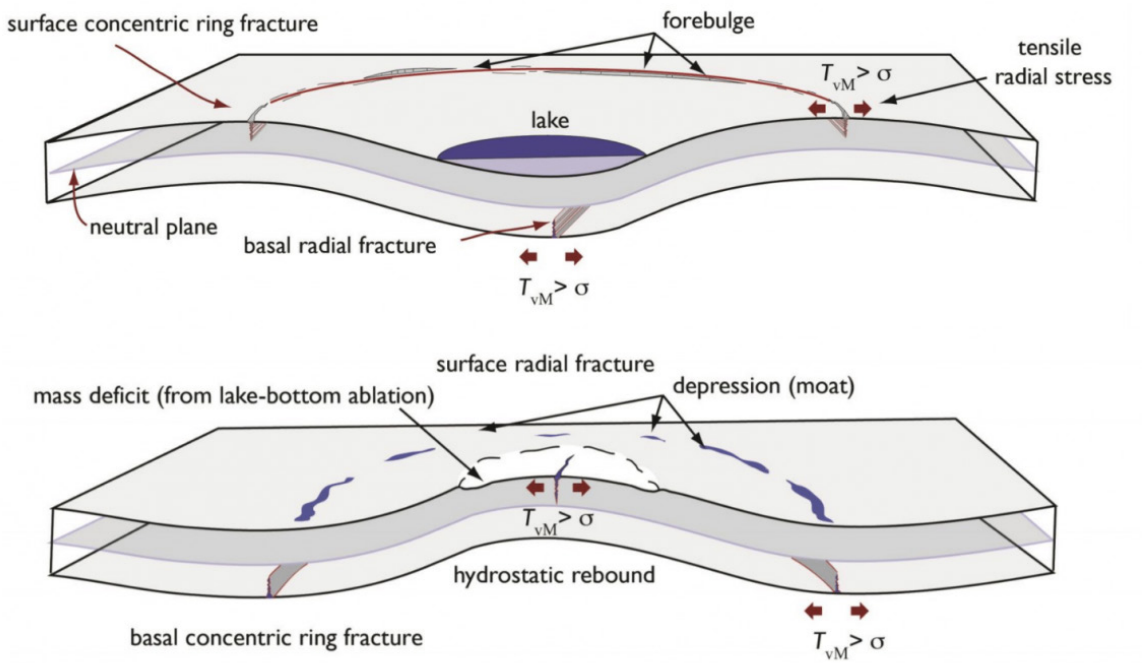


Image: Alison Banwell/CIRES, et al.

CONTINUED FROM PAGE 10

decided that an update couldn't wait until 2020. So the scientists worked to develop and quality check a new model in February 2019, to represent changes in the magnetic field between 2015 and early 2019. The out-of-cycle update ensured ongoing safe navigation and earned the team a 2019 CIRES Outstanding Performance Award.

In 2020, CIRES and NCEI scientists also updated the High-Definition Geomagnetic Model, which maps Earth's main magnetic field and the field below the surface, providing magnetic field values (including total field, dip and declination) at any point near Earth's crust. The high-definition model is for scientists and specialized users such directional drillers in the oil and gas industry.

bit.ly/WMMupdate

Fishing boats line the shore in Unalakleet, Alaska. Photo: Mwita Chacha

Alaskan Elders emphasize precarious food security after two winters of an ice-free Bering Sea

BY AGNIESZKA GAUTIER //
NATIONAL SNOW AND ICE DATA CENTER

CLIMATE

During 2019, thousands of migratory birds washed up dead on beaches across the Bering Sea region, capturing attention and concern well beyond. For the first time, such observations by Alaskan Indigenous Elders became part of the NOAA Arctic Report Card, an annual update on environmental changes in the Arctic. Since 2006, the report's main focus has been on the physical sciences and ecology.

"Given recent dramatic changes in the Bering Sea, we needed to include Indigenous voices in the 2019 report," said **Matt Druckenmiller,** one of the report's three editors and a research scientist for the Exchange for Local Observation and Knowledge of the Arctic (ELOKA) project at the National Snow and Ice Data Center (NSIDC), part of CIRES.

The Bering Sea has been nearly ice-free for the last two winters, affecting daily life and shifting subsistence calendars. One tribal member in Unalakleet, Alaska near the Bering Sea reported having to travel farther than previous years to hunt ugruk (bearded seal). Elders also observed higher air and water temperatures, a dramatic shrinking of sea ice cover, changing snow patterns, more frequent rain-on-snow events, marine mammals washing up on shores—either starved or infected and inedible—and storm surges eroding community shorelines, runways, homes and even fish camps along river mouths.

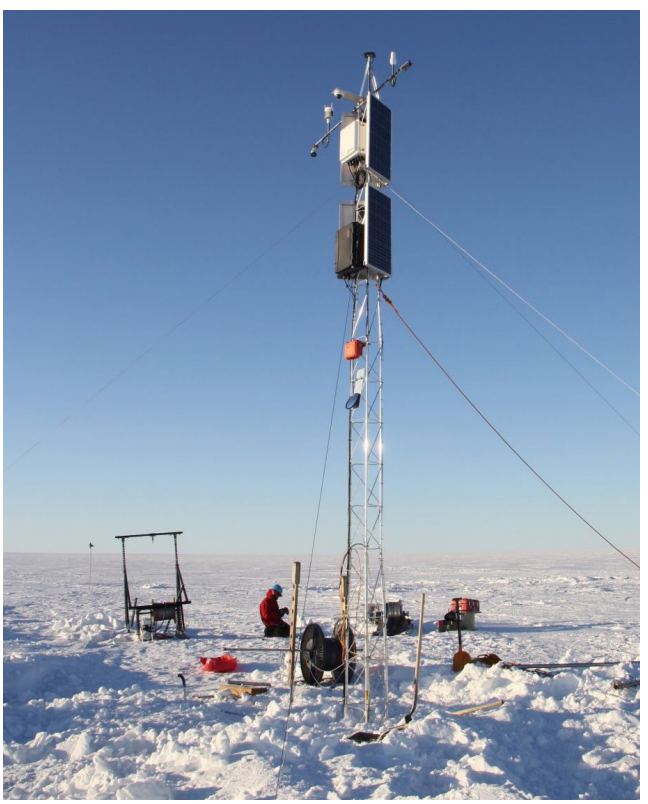
The elders' conversation, however, kept circling back to food security, Druckenmiller said: "If you include the high cost of living here, it becomes pretty apparent that food security is a very sensitive issue." The cost of fuel in rural, western Alaska is three times what it is in the contiguous United States. Electricity is five times more expensive. A gallon of milk can run $12. "Elders just want to make sure their children have a safe future and the same food to eat," Druckenmiller added.

The 2019 NOAA Arctic Report Card, released in December at the American Geophysical Union fall meeting in San Francisco, included Indigenous observations for the first time, but not the last. Druckenmiller expects to co-edit the 2020 report and again include Indigenous voices.

bit.ly/alaskan-elders

Towering work by CU students fuels Antarctic science

Team JANE assembling the AMIGOS tower with mounts to test for the solar panel attachment. From left to right: Jack Soltys, Ryan Weatherbee, Skylar Edwards and Emma Tomlinson. Photo: Team JANE



The AMIGOS-III A tower was installed on the Thwaites Ice Shelf. The tower stands roughly seven meters (23 feet) above the snow surface to allow it to operate through two-to-three years of snow accumulation. Photo: Ted Scambos/CIRES

BY AUDREY PAYNE //
NATIONAL SNOW AND ICE DATA CENTER

GLACIOLOGY

Seven engineering undergrads walked into a bagel shop. Rather than discuss lab assignments or upcoming exams, the students turned to more dire topics: they brainstormed ways to study a massive glacier's response to climate change, including how its contribution to sea level rise will impact their generation.

Raymie Fotherby, Ryan Weatherbee, Emma Tomlinson, Sid Arora, Coovi Meha, Skylar Edwards and **Jack Soltys** from the University of Colorado Boulder spent a year working as part of the Thwaites-Amundsen Regional Survey and Network (TARSAN) project team for the International Thwaites Glacier Collaboration (ITGC). ITGC is a joint United States and United Kingdom mission to address two critical questions about Antarctica's Thwaites Glacier: how much could it contribute to sea level rise, and how soon? The TARSAN project team is looking at some of the differences between Thwaites Glacier and the nearby Dotson Ice Shelf, which appears to be more stable than Thwaites.

To answer these questions, the engineering students built three Automated Meteorology-Ice Geophysics-Ocean Systems (AMIGOS) instruments, each equipped to measure a variety of factors both on the ice and in the ocean: temperature, snow height, wind, pressure, ocean currents, ocean salinity and more. CIRES scientist Ted Scambos installed the towers in Antarctica in late 2019.

"This project has opened so many doors," said Arora. "The more I worked on this project, the more I'm thinking of doing oceanic or atmospheric research. It's really opened my mind to possibilities beyond my major."

bit.ly/CUstudents-ice-station


Caroline Alden


Eric James


Jeff Lukas


Stephen Montzka

CIRES, NOAA, CU Boulder researchers earn 2019 Governor's Awards for High-Impact Research

CIRES researchers contributed to all three projects recognized by the Colorado Governor's Awards for High-Impact Research in November 2019. This annual award competition is run by CO-LABS, a consortium of federally funded scientific laboratories, universities, businesses, local governments and community leaders.

2019 award winners:

Finding methane leaks: A multi-institution team of engineers, atmospheric scientists and others developed an instrument that can pinpoint small methane leaks from more than one mile away. CIRES' **Caroline Alden** was part of the team, led by colleagues from the National Institute of Standards and Technology and LongPath Technologies.

Calculating flood risk: In a public-private partnership, a diverse group of experts worked to estimate probable maximum precipitation and frequency of extreme events above dams in Colorado and New Mexico. The project, led by NOAA and the Colorado Division of Water Resources, helped inform safety and community resilience efforts and state engineers' priorities. CIRES' **Eric James** and **Jeff Lukas** were team members.

Tracking down emissions: A team led by NOAA's **Stephen Montzka**, also a CIRES Fellow, uncovered violations of the Montreal Protocol, an international agreement to protect the planet's ozone layer. The researchers discovered an unexpected global increase in emissions of CFC-11, one of the main chemicals responsible for the Antarctic ozone hole. The work implied outlaw production of the chemical and led to international efforts to deal with rogue emissions. CIRES scientists were nine of the 14 team members.

bit.ly/2019COLABS-Gov-Awards

OTHER AWARDS AND HONORS

CIRES Director **Waleed Abdalati** was elected a Fellow of the American Association for the Advancement of Science in November 2019.

CIRES Fellow **Veronica Vaida** was elected to the National Academy of Sciences in April 2020.

Four CIRES scientists were *Web of Science* highly cited researchers in 2019: **Jose Jimenez, Noah Fierer, Julienne Stroeve** and former Ph.D. student **Jonathan Leff.**

Four CIRES scientists in NOAA's National Centers for Environmental Information were part of a team that won a U.S. Department of Commerce Silver Medal in 2019, for work on digital elevation models informing coastal inundation, tsunami and hurricane hazards: **Kelly Carignan, Matt Love, Chris Amante** and **Nic Arcos.**

Early-career scientists receive presidential honors for 2019 work on atmospheric science, drought

The White House named two CIRES atmospheric scientists and a NOAA colleague in Boulder among 309 recipients of the 2019 Presidential Early Career Awards for Scientists and Engineers (PECASE), the highest honor bestowed by the U.S. government on science and engineering professionals in the early stages of their research careers.

Brian McDonald and **Andrew Rollins** were working with CIRES when nominated; both are now federal scientists at NOAA. Their NOAA colleague **Andrew Hoell** in Boulder was also honored.

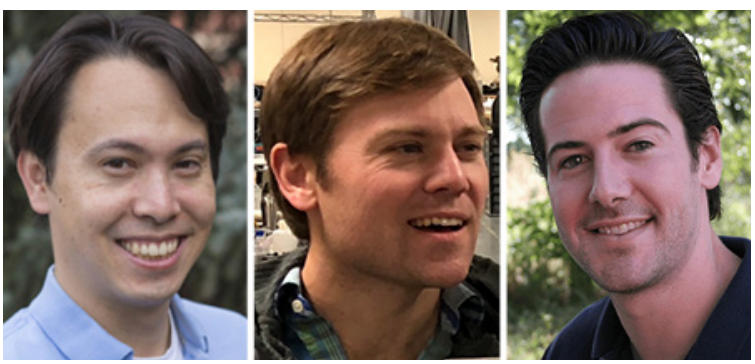
A researcher who works in NOAA's Chemical Sciences Laboratory, McDonald has earned attention in recent years for elegant work to understand the sources of atmospheric pollutants that contribute to poor air quality and impact climate. Andrew Rollins also works in CSL; he develops instruments that can detect very small quantities of water vapor, an important greenhouse gas, and sulfur dioxide from anthropogenic and natural sources including volcanic eruptions, which also influences Earth's climate.

"Brian McDonald and Andrew Rollins are innovative and accomplished early career scientists, credited with major advances in atmospheric modeling and observational systems," said **David Fahey**, Director of NOAA's Chemical Sciences Laboratory.

Andrew Hoell is a research meteorologist in NOAA's Physical Sciences Laboratory whose work focuses on drought, including predictability of food and water insecurity and impacts on communities around the world.

McDonald and Rollins join several other CIRES researchers who have won the PECASE in recent years: **Anne Perring** (2017); **Gijs de Boer** (2016); and **David Noone** and **Rebecca Washenfelder** (2012).

bit.ly/PECASEfor2019



2019 PECASE Award winners, left to right: Brian McDonald, Andrew Rollins, Andrew Hoell

NSIDC Director Mark Serreze named Distinguished Professor

CIRES Fellow **Mark Serreze,** director of the National Snow and Ice Data Center and a Professor of Geography at CU Boulder, achieved distinguished professorship in 2019. To earn this highest honor awarded to faculty in the CU system, candidates must demonstrate exemplary performance in research or creative work, have a record of excellence in classroom teaching and supervision of individual learning and exhibit outstanding leadership and service. Serreze joins CIRES Fellows Margaret Tolbert and Peter Molnar as a Distinguished Professor.

"If I have achieved anything in my career that merits this recognition, it is because of the support that I have received from my family, colleagues and the University of Colorado," Serreze said.

bit.ly/serrezedistinguished

‘Rescued’ records from the past lay groundwork for understanding today’s climate

Researchers use old weather data to study past climate, discover previously unknown hurricanes

BY THEO STEIN // NOAA COMMUNICATIONS

DATASETS

It’s the stuff of science fiction: a time machine that allows researchers to reach back into yesteryear and ask new questions about long-ago events.

In 2019, a CIRES-led research team updated a weather “time machine” under development since 2011. This third version of the 20th Century Reanalysis Project (20CRv3) is a complex, high-resolution reconstruction of global climate that estimates the weather for every day back to 1806. It’s the scientific fruit of an international effort by CIRES and federal researchers in NOAA’s Physical Sciences Laboratory and supported by the U.S. Department of Energy.

The research opportunities this work makes available are almost boundless, said **Gil Compo**, a CIRES scientist working at NOAA who leads the reanalysis project. “We’re throwing open the door to lost history, and inviting scientists to pore through,” Compo said.

Using NOAA’s Global Forecast System, researchers reconstructed the global atmosphere using surface pressure readings, sea temperature and sea ice observations from archival records, some transcribed by citizen volunteers. From these data, the system estimates temperature, pressure, winds, moisture, solar radiation and clouds, among other variables.

Scientists have used previous 20th Century Reanalysis datasets to study large-scale climate trends as well as the impacts of historical extreme weather events. The datasets allow researchers to explore how climate change is influencing temperature, precipitation and atmospheric circulation.

“This tool lets us quantitatively compare today’s storms, floods, blizzards, heat waves and droughts to those of the past and figure out whether or not climate change is having an effect,” Compo said.

A captain taking sightings with a sextant in the early 1900s. Photo: New Bedford Whaling Museum archive

Scientists have also used previous versions of the “old weather” data to discover unknown hurricanes, study the climate impact of past volcanic eruptions, investigate the timing of bird migrations and even explore the economic impact of diseases spread by the tsetse fly in sub-Saharan Africa.

Others have used the data to enrich the

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RECCS interns collect magnetic data from smartphones on the CU Boulder campus during summer 2018. The aim is to test whether researchers can obtain meaningful magnetic data from a large number of noisy measurements, thereby filling some gaps in global magnetic data coverage. Photo: Richard Saltus/CIRES

A summer of mentorship, a lifetime of science

Community college students team with CIRES researchers to explore and experience hands-on STEM opportunities

BY KATIE WEEMAN // CIRES SCIENCE WRITER

EDUCATION & OUTREACH

On a sunny day in June 2018, Prudence Crawmer stepped carefully along a CU Boulder footpath, measuring Earth's magnetic pull with her smartphone, using an app called CrowdMag. Along with eight other student researchers, she collected geomagnetic data, later using it to identify magnetic field disturbances that could affect navigation. These disturbances can be caused by human-made objects such as bridges or underground pipes.

In December 2019, Crawmer navigated the foggy streets of downtown San Francisco with her smartphone's maps app—an app that could one day be made more accurate using the work she did on Crowdmag. It was that work that brought her to the Bay Area: She won a science poster contest and a trip to attend the American Geophysical Union (AGU) Fall Meeting, the largest Earth and space science conference in the world.

Crawmer credits these opportunities to CIRES' Research Experiences for Community College Students (RECCS) program—a nine-week summer research internship funded by the National Science Foundation.

"My resume grew so much from RECCS," said Crawmer. "I was exposed to research career paths I never knew existed."

Since childhood, Crawmer has loved the outdoors, and all things Earth science. She had an established career as a massage therapist, but

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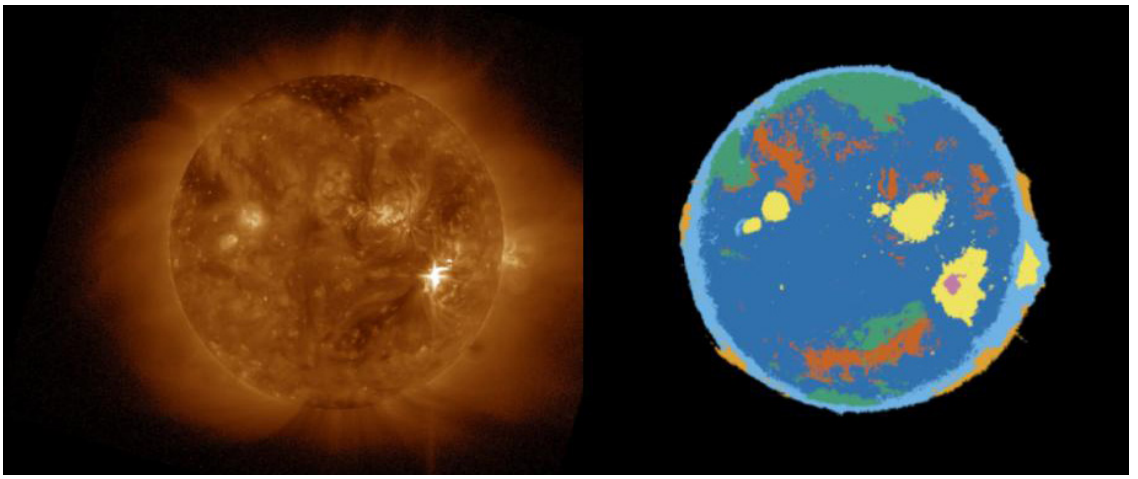

A new machine-learning technique transforms solar observations into quickly understandable, multi-colored maps, with colors identifying solar features. Yellows are active regions; dark blues are quiet. Image: Dan Seaton and J. Marcus Hughes/CU Boulder, CIRES and NCEI

Algorithm can detect solar flares

Machine-learning tool may improve space weather forecasts

BY KARIN VERGOTH // CIRES SCIENCE WRITER

SPACE WEATHER

Computers can learn to find solar flares and other events in vast streams of solar images—and that discovery helps NOAA forecasters issue timely alerts.

Changing conditions on the Sun and in space—broadly called "space weather"—can affect various technologies on Earth, blocking radio communications, damaging power grids and diminishing navigation system accuracy. So CIRES scientists at NOAA's National Centers for Environmental Information and CU Boulder developed a machine-learning technique to search massive amounts of satellite data and pick out features significant for space weather.

"Being able to process solar data in real time is important because flares erupting on the Sun impact Earth over the course of minutes," said **Rob Steenburgh**, a forecaster in the NOAA Space Weather Prediction Center in Boulder, Colorado.

To predict incoming space weather, forecasters summarize current conditions on the Sun twice daily. They use hand-drawn maps labeled with various solar features, including active regions, filaments and coronal hole boundaries. But solar imagers produce a new set of observations every few minutes: the Solar Ultraviolet Imager (SUVI) on NOAA's GOES-R Series satellites runs on a 4-minute cycle, collecting data in six different wavelengths every cycle. Keeping up with all that data would take up a lot of a forecaster's time.

"We need tools to process solar data into digestible chunks," said **Dan Seaton**, a CIRES and NCEI scientist and one of the paper's co-authors. The research was published in October 2019 in the *Journal of Space Weather and Space Climate*.

J. Marcus Hughes, a CIRES and NCEI scientist and CU Boulder graduate student, created a computer algorithm that can look at all SUVI images simultaneously and spot patterns. With his colleagues, Hughes created a database of expert-labeled maps of the Sun and used those images to teach a computer to identify solar features important for forecasting. "We didn't tell it how to identify those features, but what to look for—things like flares, coronal holes, bright regions, filaments and prominences. The computer learns the 'how' through the algorithm," said Hughes, the study's lead author.

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Hidden gems in bacterial genomes aid evolution

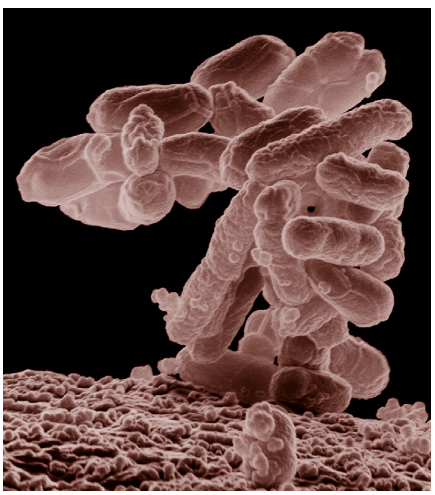
How bacteria use 'promiscuous' enzymes to adapt to change

BY JULIA MEDEIROS AND KATY HUMAN //
CIRES COMMUNICATIONS TEAM

MICROBIOLOGY

Imagine some bacteria living in an environment that changes suddenly. Maybe a new chemical appears, offering a possible source of nutrition. Or maybe an essential chemical previously present in the environment becomes unavailable, and the cells must come up with a way to make it or perish.

Bacteria are remarkably adaptable, and often respond to environmental challenges or opportunities by evolving new enzymes and sometimes entirely new metabolic pathways that allow them to break down different nutrients or synthesize useful new chemicals.



An electron micrograph of a cluster of *E. coli* bacteria, magnified 10,000 times. Photo: Wikimedia Commons

So how do bacteria come up with entirely new ways of coping, metabolically, with changing environments? And by searching for answers, can we learn something about the evolution and diversity of life, itself?

These are the kinds of questions that preoccupy CIRES Fellow and evolutionary biologist **Shelley Copley,** who co-authored a seminal 2019 paper on the evolution of metabolic pathways.

"The problem is that we're standing at the end of 3.8 billion years, trying to figure out what happened," Copley said. "The processes by which new pathways have emerged are lost in time," she and her co-authors wrote in the *Proceedings of the National Academies of Science.*

To try to shed some light on billions of years of evolution, Copley and her colleagues took advantage of two key things: 1) the short generation time of *E. coli* bacteria, which makes it possible to grow cells for hundreds or thousands of generations within a brief period of time; and 2) many years of laboratory experience creating conditions that force bacteria to adapt, and then taking "snapshots" of what's happening inside cells along the way.

"The beauty of our system is that we know exactly what we're starting with... and we can isolate populations at various times and sequence their genomes to follow the appearance of mutations," Copley said.

For the *PNAS* paper, Copley's team knocked out a gene in *E. coli* that was expected to be essential for survival: it helps the bacteria produce a co-enzyme called pyridoxal 5'-phosphate or PLP—better known as vitamin B6. That co-enzyme helps catalyze many kinds of critical reactions inside cells.

Within just 150 generations, the bacteria had evolved a different pathway to make PLP. It started as a happy accident, the result of random mutations that unexpectedly helped the bacteria survive and thrive.

"We dug into one of these lineages in gory detail," Copley said. The researchers found that the new PLP production pathway required four steps, each catalyzed by a "promiscuous" secondary activity of an enzyme that normally serves another function. Promiscuous reactions are often very inefficient, but they are certainly better than nothing, particularly when a reaction becomes important for survival.

Promiscuous reactions arise because "enzyme active sites are very reactive places,"

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Big problems, little solutions

Center for Microbial Exploration looks under the microscope to bolster the health of our planet and our minds

BY JULIA MEDEIROS //
CIRES SCIENCE WRITING INTERN

MICROBIOLOGY

Every step we take, whether across a grassy park or down a city sidewalk, below our feet is an ecosystem teeming with life. Thousands of microbes, invisible to the naked eye, make life function as we know it. These tiny organisms play a role in everything from the sprouting of a single flower out of the dirt to regulation of the global carbon cycle. With climate change threatening to tip these processes out of balance, better understanding microbial activity could be key to humans adapting to looming crises such as drought and disease.

The Center for Microbial Exploration (CME) at the University of Colorado Boulder, founded in 2019, highlights the growing recognition that microbiology is a crucial component of many scientific fields. Center members' research follows microbes at play in agriculture, the Arctic and even our own bodies. Despite looking at vastly different ecosystems, these scientists all want to know the same thing: what microbes are there and what are they doing? It has taken decades to arrive at even partial answers.

"The mysteries of the microbial world never cease to amaze. Even basic questions often remain unanswered," said **Noah Fierer,** CIRES Fellow and professor of Ecology and Evolutionary Biology at CU Boulder.

It was this knowledge gap that drew Fierer to the field of microbiology. In his 20 years of studying microbes, he's seen a lot of advances in methods, including DNA technologies that allow scientists to more easily identify organisms in a sample. Still, there are potentially thousands of undiscovered microbes with unknown capabilities to explore.

As CME director, Fierer wants to help close that gap by providing a space for collaboration across disciplines.

bit.ly/big-problems-little-solutions

Could microbiology improve sustainable agriculture?

When **Corinne Walsh** was deciding on a research focus for her Ph.D. in Fierer's lab, she knew she wanted to do something that could help tackle big, real world problems beyond the lab. So she turned to one of the most important cereal crops across the globe: wheat.

Humans have studied wheat for centuries, creating a large body of work on the reactions of wheat to chemicals like fertilizers and pesticides. But there is less research into the microbiomes of these plants.

"The microbiome angle is thinking about sustainable agriculture in terms of less chemical inputs," said Walsh. "It's thinking about if you can understand the biology of the system a little more and optimize it from a microbiological perspective."

Walsh is investigating how the microbiome of

a wheat plant is assembled. Does the wheat plant itself determine the kinds of microbes that are present, or is it more dependent on the soil? That question is critical to understanding and possibly even manipulating the relationships between

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Corinne Walsh, a graduate student in Ecology and Evolutionary Biology at CU Boulder, demonstrates how she prepared growth plates for wheat seeds to grow in laboratory conditions with different soil samples applied. She was exploring the relationship between microbes and wheat productivity. Photos: Julia Medeiros/CIRES

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microbes and plants.

To dig into the question, Walsh collected soil samples from 200 locations across the United States. She used those samples to grow around 4,000 wheat seeds in laboratory conditions and will next analyze their DNA to find out if the different soil microbes influenced the wheat microbiomes. Defining to what extent the microbiome can be influenced will help experts understand just how much different soil microbes can potentially help strengthen the plant in times of drought and blight—something on the minds of farmers around the world as temperatures rise.

At a loss without moss: Boreal forests need microbial pals

Deep in the boreal forests of the Northern Hemisphere, microbes are hard at work. Nitrogen-fixing bacteria are responsible for the growth of the mosses stretching across the forest floor. As these forests are threatened by more frequent and intense fires, scientists are investigating how moss-dwelling microbes are important not only for the health of the forest but also for the entire planet.

"These mosses are massive," said **Hannah Holland-Moritz**, a Ph.D. candidate in the Ecology and Evolutionary Biology department at CU Boulder. "You can sometimes sink up to your knee in them."

Working with a team from the University of Florida and Northern Arizona University, Holland-Moritz analyzed samples of eight boreal moss species in Fairbanks, Alaska and found that all eight had bacterial communities capable of nitrogen fixation, despite each having diverse bacterial lineages. The team further investigated the genetic material of some lesser-known lineages to try and identify those characteristics

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that make them suited to living on moss, such as the processes they use to obtain nutrients.

Finding out which bacteria are driving the nitrogen fixation process can tell scientists more about how and where carbon is stored in boreal forests. Nitrogen input helps moss grow larger and continue to sequester carbon, but eventually it stops and dies. In a peat bog, the dead moss and the carbon within it become trapped in the wet, spongy quagmire instead of decomposing and releasing carbon dioxide into the atmosphere.

As rising temperatures threaten to wipe out the moss and microbes of boreal forest and bogs, thousands of years of stored carbon could be released, turning the Northern Hemisphere from a carbon sink to a powerful carbon source.

Ph.D. candidate Hannah Holland-Moritz studies the microbiome of moss such as *Polytrichum*, found in the boreal forests of Alaska. She describes the plants as "massive,"saying, "You can sometimes sink up to your knee in them." Photo: Hannah Holland-Moritz/CU Boulder

Stress-busting soil microbes may boost mental health

The study of soil microbes is not only useful for the natural world outside, but also for the one within us. Research has shown that a soil microbe called *Mycobacterium vaccae*, a bacterium with anti-inflammatory properties, reduces stress and fear in mice.

For over two decades, **Christopher Lowry**, a professor in integrative physiology at CU Boulder and CME member, has been studying the beneficial role that bacteria like *M. vaccae* play in the stress resilience of animals. The concept of resilience is not only about alleviating stress after the fact, but preparing for the impact before it hits.

"When we think about psychiatric disorders, we often think that it's about the discovery of novel treatments," said Lowry. "But we should also be thinking about how we can prevent these conditions from occuring in the first place."

This involves exploring the microbiome-gut-brain axis—the two-way communication line between microbes in the gut and the brain. Scientists know this communication is important, but the challenge arises in determining the exact mechanisms used to facilitate it.

Lowry has spent the majority of his career investigating how *M. vaccae* works within this axis. But this is only one species of thousands of bacteria that can live within the human body, interacting in many ways that may have an impact on mental health. Lowry's work, in demonstrating that *M. vaccae* can have positive effects, means that it is likely other bacteria could as well, suggesting further research into the use of bacteria for treatment of depression, anxiety and posttraumatic stress disorder (PTSD).

Evolving bacteria

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Copley explained. "And nothing in biology is perfect. So if a non-canonical molecule wanders into the active site of an enzyme, sometimes chemistry can happen." She and her colleagues were surprised by the fact that none of the new mutations actually changed enzymes involved in the new pathway. Instead, the mutations created "quick-and-dirty" ways to overcome the cells' PLP synthesis problem. One trick: maximize an enzyme's promiscuous activity by making its primary activity harder to perform, perhaps by decreasing the levels of its normal substrates. That might not be great for the bacteria in some ways, but could help it survive awhile if it had no other way to make vitamin B6.

"So one lesson is how easy it is to patch together metabolic pathways given the enormous number of promiscuous activities available in the cell," Copley concluded. "There are probably 1,500 enzymes in *E. coli*. If each has 10 promiscuous activities, that would make 15,000 possible enzyme activities available. You can combine those in lots of different ways."

Lifetime of science

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still dreamed of being a scientist, so she started taking Earth science classes at Pikes Peak Community College in Colorado Springs. One day, an ad for RECCS popped up in her inbox.

A few months later she was bonding with other eager student research interns, exploring a list of possible research topics, including "geomagnetism," a word she didn't recognize. RECCS educators paired Crawmer with CIRES' **Rick Saltus** and **Manoj Nair,** scientists who are part of the NOAA National Centers for Environmental Information (NCEI) geomagnetism team.

The team worked on improving a citizen-science app called CrowdMag, which senses the invisible force originating from currents in the molten iron of Earth's outer core; local geology and human infrastructure can affect that invisible magnetic field, as can solar wind. Most smartphones have a digital magnetometer that measures Earth's magnetic pull—it's how your phone's compass works. The CrowdMag app harnesses a phone's WiFi connection, magnetic data and location, and automatically sends that data to NOAA, where the CIRES/NCEI geomagnetic team uses the information to create aggregate maps that improve mobile navigation.

"CrowdMag's enthusiastic users have contributed millions of data points," said Saltus. "Pru's work has taken use of the app in a whole new direction and her radiant exuberance continues to build support for the project."

At the end of her RECCS experience, Crawmer summarized her work in a poster and submitted it to AGU's Student Virtual Poster Session competition. And she won! She presented her winning poster virtually in 2018—and earned the bonus prize of a trip to the 2019 AGU Fall Meeting at San Francisco's Moscone Center.

During the conference, Crawmer wandered the 87-acre convention center, soaking up as much as she could by attending lectures, poster sessions, networking events and booth exhibits.

"RECCS opened so many doors for me during this entire experience," said Crawmer, now a full-time undergraduate at the University of Colorado Colorado Springs. "I'm not sure exactly what I want my future career to be yet, but I now know I feel a pull toward field research."

Research Experiences for Community College Students

RECCS is a summer research internship program for Colorado community college students. The program gives students an authentic research experience that allows them to explore environmental or geosciences and gain the confidence to transition to a four-year program in the STEM disciplines and pursue careers in research.
More: cires.colorado.edu/outreach/reccs

Rescued records

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scientific understanding of specific weather events lodged in cultural memory, including the sinking of the *Titanic* or the extraordinary winter of 1880-1881, which was chronicled by Laura Ingalls Wilder in her book *The Long Winter*.

20CRv3 uses millions more observations than previous versions, especially for earlier periods. The new reanalysis includes up to 25 percent more available observations for years before 1930.

Running the model and crunching all the data required astronomical computing resources. To accomplish this third upgrade, the Department of Energy donated 600 million cpu hours to process 21 million gigabytes of data.

The result? A much better indication of where the weather estimates are more reliable and where more observations are needed.

"The atmospheric estimates from 20CRv3, as well as their uncertainties, are much more reliable than those from the previous reanalysis, particularly in the 19th century," said **Laura Slivinski**, a CIRES scientist in NOAA and lead author of a 2019 paper describing the 20CRv3. "We're more certain about how much we know and where we need to know more."

Professional scientists and ordinary citizens alike contributed to the reanalysis, through groups including Atmospheric Circulation Reconstructions over the Earth (ACRE). ACRE marshaled help from experts and novices to extract meteorological observations from historical documents including ship logs to help refine "old weather" reconstructions.

Targeted data rescue can be extraordinarily valuable—for example, logs of 19th Century wooden sailing vessels attempting to penetrate the Arctic and Antarctic: "These data have been invaluable to us because they come from the otherwise data-sparse polar regions," Slivinski said. "20CRv3 also provides a literal map to further advances in precision by identifying regions and time periods where additional weather observations will improve model estimates."

The 19th and early 20th centuries, especially in the Southern Hemisphere, still have high uncertainty, but data rescue can help fix that. "This dataset can keep getting better as we unlock more observations from historical archives," Compo said.

bit.ly/oldweathertimemachine

Detecting solar flares

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The algorithm identifies solar features using a decision-tree approach that follows a set of simple rules to distinguish between different traits. It examines an image one pixel at a time and decides, for example, whether the pixel is brighter or dimmer than a certain threshold before sending it down a branch of the tree. This repeats until, at the very bottom of the tree, each pixel fits only one category or feature—a flare, for example.

The algorithm learns hundreds of decision trees—and makes hundreds of decisions along each tree—to distinguish between different solar features and determine the "majority vote" for each pixel. Once the system is trained, it can classify millions of pixels in seconds, supporting forecasts that could be routine or require an alert or warning.

"Because the algorithm can look at 20 years' worth of images and find patterns in the data, we'll be able to answer questions and solve problems that have been intractable."

Dan Seaton, CIRES/NCEI

"Because the algorithm learns so rapidly it can help forecasters understand what's happening on the Sun far more quickly than they currently do," Hughes said.

The algorithm's skill at finding patterns assists short-term forecasting and also scientists evaluating long-term solar data. "Because the algorithm can look at 20 years' worth of images and find patterns in the data, we'll be able to answer questions and solve problems that have been intractable," Seaton said.

NCEI and SWPC are testing the new tool for tracking changing solar conditions so forecasters can issue more accurate watches, warnings and alerts.

bit.ly/realtimesolarflares

Fire 'season' now year-round

Humans spark smaller, cooler fires—but more of them

BY KATIE WEEMAN // CIRES SCIENCE WRITER

Fires started by people have steadily increased in recent decades—sparking a major shift in U.S. wildfire norms, according to a CIRES-led study. Fires are broadly becoming larger and more frequent with extended fire season lengths. At the same time, human-sparked wildfires are more frequent, smaller, less hot and occur over longer seasons than fires started by lightning.

The shift towards longer fire seasons with more frequent fires presents new challenges to U.S. wildfire managers and firefighters, said **Megan Cattau**, a former CIRES and CU Boulder Earth Lab scientist and lead on the 2019 *Global Ecology and Biogeography* study.

"We can't even call it a fire season anymore—it's nearly all year round," added Cattau, now at Boise State University.

Many studies have examined the impacts of fuel and climate on U.S. wildfire patterns, but few have examined the impacts of ignition source. So Cattau and her colleagues pulled data from multiple sources and looked at ignition trends in roughly 3300, 50-km grid cells covering the United States, between 1984 and 2016.

The team analyzed a suite of satellite data and 1.8 million government records to identify wildfire ignition patterns across the country. Satellite records cannot distinguish between prescribed fires, human-ignited fires or lightning-ignited fires. So Cattau and her team also turned to U.S. Forest Service databases that include ignition type.

They found that anthropogenic ignitions and lightning ignitions are fundamentally different. Wildfires kindled by lightning tend to be larger and more intense, but occur only during certain times of the year. Anthropogenic fires occur more frequently and over a much longer season—but are less "hot" and smaller on average, since people may spark wildfires in low-fire seasons like early spring and more frequent fires mean less time for fuel to build up. Human-started fires can also burn closer to cities where firefighters can respond faster.

"More human-caused fires results in decreased fire intensity and size, but that's not necessarily good," said Cattau. "Any deviation from historical fire patterns, from what that land evolved with, can cause problems. Fire is part of the ecosystem. And now its role is changing."

bit.ly/yearroundfire

The sun rises over Lake Oroville through the smokey haze from the Ponderosa Fire in Butte County, California in 2017. Photo: Ken James/California Department of Water Resources

Learning to live with fire

A conversation with wildfire expert Jennifer Balch

Jennifer Balch is a CIRES Fellow, director of CIRES' Earth Lab, university director of the North Central Climate Adaptation Science Center and Associate Professor of Geography at the University of Colorado Boulder. Her research addresses fire's role in the Earth system, and fire's relationship to global trends of climate warming and human activity (e.g., land cover change, fire ignitions).

Spheres: How is wildfire changing?

Balch: A little bit of warming is leading to a lot more burning. In the U.S. West, regional temperatures have increased by almost 2 degrees F since the late 1800s, snowmelt is occurring a month earlier in some places and fire season length has increased by almost three months.

Human-caused warming has effectively made fuels much drier and doubled the amount of western forests that have burned since 1984.

In California, we know there is a direct link between warmer temperatures and more fires, particularly in forests. Since the 1970s, the amount of burned area in California has increased five-fold.

What are the implications?

One is that wildfires are costing us, dearly. In the United States, we spend over $2 billion per year fighting wildfires. About 1.8 million homes in the western U.S. are at high risk of wildfire damage: $309 billion in total property value. About 29 million people live with extreme wildfire risk; 13 million of these people are socially vulnerable Americans.

People provide the ignitions for 84 percent of our nation's wildfires. And it's not just downed power lines that cause sparks. Campfires, burning debris, driving off the side of the road, electrical equipment and fireworks are just some of the many ways that we start fires. Climate change is making wildfires worse, and we're providing the spark.

A crew chief from the California Army National Guard releases water over the 2013's destructive Rim Fire near Yosemite National Park. Photo: U.S. California Air National Guard

What's the future of wildfire?

Wildfires are here to stay. We expect wildfires will be more common in the future, so we need to learn to better live with them. Risks associated with wildfire are shifting—but policies to deal with fire have not kept pace. We need policy efforts to build better and burn better in the United States so we can adapt to increasing wildfire in a changing climate. We need to figure out how to live with fire.

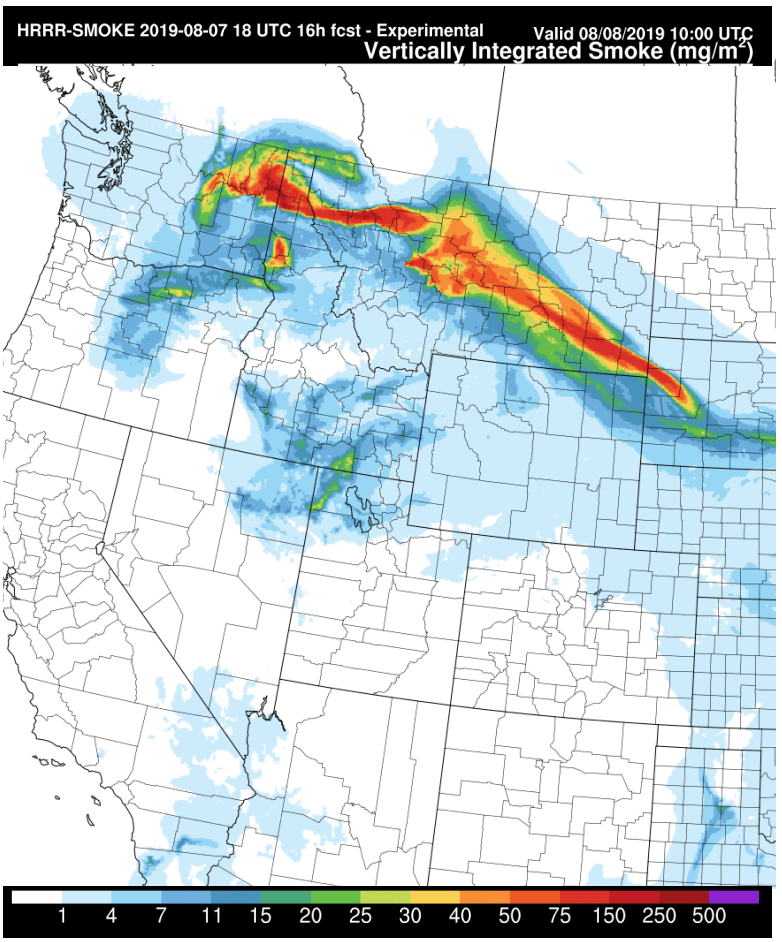
Where there's smoke, there's info for the future

Thunderstorms generated by giant wildfires in the summer of 2017 injected a small volcano's worth of aerosol into the stratosphere, creating a smoke plume that lasted for many months. CIRES and NOAA researchers studying the plume found that black carbon or soot in the smoke was key to the plume's rapid rise: the soot absorbed solar radiation, heating the surrounding air and allowing the plume to rise quickly.

The billowing smoke cloud allowed researchers to test climate models estimating how long the particulate cloud would persist—in this case, the cloud reached a maximum height of 23 km (14 mi) and remained in the stratosphere for almost nine months. "We compared observations with model calculations of the smoke plume to understand why the smoke plume rose so high and persisted so long, which can be applied to other stratospheric aerosol injections including volcanoes or nuclear explosions," said NOAA scientist Karen Rosenlof, a member of the research team that also included scientists from CU Boulder, Naval Research Laboratory, Rutgers University and other institutions.

Their findings were published in *Science* in August 2019.

bit.ly/persistant-plume



This image shows the forecasted smoke plume on August 7, 2019, from the Williams Flats Fire in Washington, which was sampled during the FIREX-AQ campaign. Figure: CIRES/NOAA

HRRR-Smoke models relationships among weather, smoke, visibility

The experimental High-Resolution Rapid Refresh-Smoke (HRRR-Smoke) is the first numerical weather prediction model in the United States that simulates smoke impact on surface visibility. Developed by CIRES and NOAA scientists in NOAA's Global Systems Laboratory, the model predicts how weather could impact smoke movement and how smoke could reduce visibility and air temperatures. HRRR-Smoke is scheduled to be implemented into NOAA National Weather Service operations in 2020.

The Castle Fire in Arizona during a FIREX-AQ flight on August 13, 2019. Smoke was visible from the north and south rims of the Grand Canyon. Photo: Rebecca Hornbrook/National Center for Atmospheric Research

Chasing smoke and its secrets

FIREX-AQ marshalls multiple resources to improve wildfire air quality forecasts

BY KARIN VERGOTH // CIRES SCIENCE WRITER

Extreme wildfire seasons are no longer an outlier in the U.S. West, where climate change is drying out plants and people are moving deeper into forests. All that fire produces a lot of smoke—and a serious air pollution problem.

In the summer of 2019, NOAA and NASA teamed up on a massive research campaign called FIREX-AQ (Fire Influence on Regional to Global Environments and Air Quality) that used satellites, aircraft, mobile and ground stations to study smoke from western wildfires as well as agricultural crop fires and prescribed burns across the southern United States.

Hundreds of scientists, including many from CIRES, participated in the field campaign with the goals of exploring the chemistry of trace gases and aerosols in smoke, improving weather and air quality models and providing better forecasts to first responders, public health and land management officials.

FIREX-AQ launched July 22, 2019, when the NASA DC-8 aircraft—packed with highly sophisticated chemistry instruments—flew from Palmdale, California, to its temporary base in Boise, Idaho. For the next month, it chased wildfire smoke across the West, along with two NOAA Twin Otters flying at lower altitudes and at night, when fires smolder and smoke drains into the valleys.

From its base in Palmdale, the NASA ER-2 aircraft collected measurements from much higher altitudes with remote-sensing instruments. Ground stations and mobile vans observed smoke at the surface, where it matters most for public health. Scientists plan to compare these measurements with data from NOAA and NASA satellites to learn how to extract more information from what satellites see.

After its stint in Boise, the NASA DC-8 headed to Salina, Kansas, home base for a series of flights sampling smoke from agricultural fires and prescribed burns in the southeastern United States. The NOAA Twin Otters stayed in the Pacific Northwest to sample fires there.

The field campaign wrapped up in early September 2019, after 21 DC-8 flights and 40 Twin Otter flights. Now, the researchers are analyzing data from the summer mission, with data being made public in March 2020.

bit.ly/secrets-of-smoke

my Sphere

Days of the Polar Night

MOSAiC, Multidisciplinary Drifting Observatory for the Study of Arctic Climate, is an international research expedition to study the Arctic climate system, including the atmosphere, sea ice, ocean, ecosystem and connections among them all. Beginning in fall 2019, the *RV Polarstern* icebreaker froze into Arctic sea ice to drift with it for a full year, allowing scientists to collect data in every season. CIRES' Matthew Shupe is co-coordinating the mission.

SEPTEMBER 20, 2019

"MOSAiC's drift across the Arctic Ocean is one of the most ambitious single Arctic research expeditions that NSF has ever supported. There is no doubt that MOSAiC will open a new chapter in our ability to understand the changes underway in the Arctic and to predict future trends."

Kelly K. Falkner, head of the National Science Foundation's Office of Polar Programs

"We did it: all 64 researchers and well over 1,000 pieces of cargo are now securely on board *Polarstern*."

Marcel Nicolaus, sea ice physicist at the Alfred Wegener Institute

"There are many more uncertainties than usual, many aspects are new and unique, and even the exact date of our return is unknown."

RV Polarstern Captain Stefan Schwarze, during his first address on board

LATE SEPTEMBER 2019

"Climate change is changing Arctic ice... sea ice has gotten thinner, making it move faster. That means we can no longer use data from the long term, 30-year record to accurately predict ice pathways—we can only use the last decade or so."

Thomas Krumpen, Alfred Wegener Institute scientist

SEPTEMBER - OCTOBER 2019

"For the organisms at the very base of the food web, it most likely means a longer growing season due to less ice cover in the summer months, so more light can reach them. 'This has huge implications,' says Allison Fong, AWI ecologist."

From "What will an ice-free Arctic look like?" by Martha Henriques in *BBC Future*

The *RV Polarstern* on its way to freezing into the sea ice for the winter. Photo: Sam Cornish/University of Oxford

OCTOBER 15, 2019

"One of the floes that *Polarstern* surveyed, despite some thin ice, proved to also contain a substantially thicker and more stable area.... After comparing notes with our colleagues on the *Akademik Fedorov,* we decided on this floe, which will be home to the *Polarstern* and countless researchers for the year to come... From very early on, the floe's most stable area was dubbed 'the fortress'."

Stefan Hendricks,
Alfred Wegener Institute

OCTOBER 22, 2019

"We were a bit nervous about the southerly drift for our first couple weeks... felt strange to be headed in the wrong direction, towards Siberia.... But now it finally feels like we've made our way into the Transpolar Drift, starting to move towards our final destination on the other side of the Arctic."

Matthew Shupe,
CIRES scientist and co-coordinator of the MOSAiC expedition

MID-OCTOBER 2019

"That was wild, dynamic, and terrifying."

Ian Raphael, Dartmouth College graduate student, after a crack started to spread tens of meters away from where the group was standing on the ice, from "The Voyage to the End of Ice" by Shannon Hall, *Quanta Magazine*

OCTOBER 29, 2019

"... the days themselves blur together. Same schedule: Wake as late as possible to still get breakfast, short planning meeting, head out to the ice for work, back for lunch, then head out for round two on the ice, returning in time for dinner. Group meeting, planning meeting, leadership meeting. Look at the day's data and deal with other details for the next day's work. Possibly a bit of social time or exercise. Then hit the bed. Rinse, repeat."

Matthew Shupe

NOVEMBER 2019

A powerful winter storm swept over the German *RV Polarstern* in early November, tearing

new cracks in the ice floe next to the ship and sending ice-based instruments adrift. No people were hurt during the storm.

"This storm was a fantastic opportunity to study the important role of such events in Arctic climate. We already see the effects in our measurements before, during and after."

Markus Rex, Alfred Wegener Institute, lead of MOSAiC expedition

NOVEMBER 24, 2019

"We have great gear to deal with the conditions: good boots, body suits that float and keep most water out. We carry throw bags and ice picks to help get out of the water if it gets to that point. And importantly, we travel together in groups."

Matthew Shupe

DECEMBER 4, 2019

"In terms of traveling on the ice, we have established a 'walking culture.' We can't entirely avoid using snowmobiles, especially when it comes to setting up large and heavy structures on the ice. Nevertheless, now most trips are made on foot or using skis. Skis have become quite popular, and lend our work a very rustic character when we 'hike' across the (in some places, heavily deformed) ice, towing a Nansen sledge behind us."

Marcel Nicolaus

DECEMBER 9, 2019

"I feel my feet getting colder on the steel tower rungs. My fingers get slightly warmer inside my gloves, but never really warm… and with each successive activity, they slip deeper into cold. Starting to lose the dexterity a bit, so that gets challenging. I completed the job and started dressing the cables on the way down the tower, but then had to get down and warm up…. This was one of the deepest colds I've experienced thus far at MOSAiC…. But a little heat inside the Met Hut (and a bit of jumping around as the thawing ache really hurt!) and things were back and regulated."

Matthew Shupe

DECEMBER 14, 2019

"Today, again, the ice was moving underfoot. As we walked on a bridge over a crack, the crack was widening. At another area, we hopped from ice chunk to ice chunk to get across."

Matthew Shupe

MOSAiC researchers begin setting up their equipment on the ice. Photo: Sam Cornish/University of Oxford

DECEMBER 23, 2019

"We are still in polar night. The horizon is not visible and we only have limited view from what the ship's light can illuminate. In the fog and mist you can see the beams....We are on a ship in the ice, so when you look out, you just see the different ice and snow shapes moving by, not the ocean waves."

David Costa,
CIRES/NOAA scientist returning from Leg 1 of MOSAiC

JANUARY 2020

"The magnitude of the ice deformation was much more than we were expecting... all the time there were new cracks opening. So that's more like an indication of a new Arctic."

Jari Haapala,
sea ice expert at the Finnish Meteorological Institute,
from the *E&E News* blog, "IceBound"
by Chelsea Harvey

FEBRUARY 7, 2020

"You're on the sea ice, and after a while you forget about it. But then you remind yourself that, no no no, this is one meter of sea ice and you have 4,200 meters of ocean underneath. And you realize this especially when the ice starts to move and there are openings."

Esther Horvath,
AWI documentary photographer, from
"Endless Night at -50 Degrees: A Look at Life on an Icebreaker" by Henry Fountain
in *The New York Times*

FEBRUARY 24, 2020

"The breakfast menu offers everything the heart desires: from pancakes to scrambled eggs, to freshly baked rolls. And when you have a day on the ice ahead of you, you need every calorie. For me, an ROV* day means having my lunch out on the ice. So I quickly pack my lunchbox and fill my thermos, then head for the winch room. Once there, it takes me about 10 minutes to put on all my polar gear: thermal underwear, thick socks, a fleece jumper, balaclava and parka, snow pants and snow boots."

*"... ROV stands for Remotely Operated Vehicle, a small underwater robot packed to the gills with cameras and scientific instruments."

Daniela Krampe,
Ph.D. student at the Alfred Wegener Institute

MARCH 6, 2020

"Leg 2 of #MOSAiCexpedition in numbers: The expedition members & crew consumed 8,100 eggs, 1,360 kg of potatoes, and 86 jars of #Nutella. Needless to say, that's not all they ate."

@MOSAiCArctic on Twitter

MARCH 6, 2020

"Even more than the cold, the darkness was amazing. Everything looked monochromatic, like pictures taken on the moon."

Steve Archer,
Bigelow Laboratory for Ocean Sciences

MARCH 12, 2020

"The sun is back!"

RV Polarstern captain Stefan Schwarze,
@MOSAiCArctic on Twitter

MARCH 28, 2020

"Over the last 2 weeks we have observed the ice rending into smaller & smaller pieces such that our 9 stress sensors that were once on the same piece of ice are now on 6 separate pieces. Although these ice dynamics make logistics more challenging by accessing the stress sensors by #helicopter, understanding how and why sea ice breaks apart is important both for predicting future #climatechange and navigation."
#MOSAiCexpedition #Arctic #icedrift

David Clemens-Sewall,
Ph.D. student at Dartmouth College on Twitter

APRIL 2020

"During long hours in the ice-coring tent, [Jessie] Creamean would occasionally step outside and gaze at the moon or the stars and try to take in the vastness of the Arctic night. 'Sometimes the blowing snow would sparkle, and you'd just be struck by the beauty of it all,' she says. 'To know that you were one of the very few people who had ever seen that, who had ever stepped foot up there—it was awe-inspiring.'"

From "Why The Mosaic Expedition's Research Is So Vital To Climate Change Research"
by Michelle Nijhuis, *Smithsonian Magazine*

APRIL 2020

"I volunteered to go to Met City with some folks to do some routine checks. This was the first time I had been to Met City since... the beginning of March. Not only has the ice changed so much that it now takes a series of crack hopping and many twists and turns to get there ... the lighting is also so different, with the sun hiding behind the clouds or shining bright, instead of sitting just below the horizon. It is truly a new world, and I'm sure it will become yet a different world throughout the next months."

Gina Jozef, Ph.D. student at CIRES/CU Boulder

Michael Gallagher (CIRES & NOAA) and Taneil Uttal (NOAA) stand near an atmospheric surface flux station on sea ice. Photo: Michael Gallagher/CIRES

Radiance Calmer (left) and Jonathan Hamilton place a DataHawk drone on its launcher for its first test flight in Boulder, Colorado. It is being used by Gijs de Boer's team on the MOSAiC expedition, and can gather atmospheric data on temperature, pressure and humidity. Photo: Julia Medeiros/CIRES

Drone research soars higher

Unmanned aircraft let scientists measure Arctic atmosphere

BY JULIA MEDEIROS //
CIRES SCIENCE WRITING INTERN

Radiance Calmer holds the wide wings of a drone in place on its launcher, scanning the blue Boulder sky for potential obstacles. Behind her, **Jonathan Hamilton** stands with a controller in hand. Calmer counts down, "Three...two... one...zero!" and releases. The drone flies off the launcher, hovers just a few feet above the ground for a precarious moment, and then zooms into the clouds at 35 mph.

That February 2020 practice run was just one of two years' worth of flight tests preparing for an Arctic mission that is pushing the limits in atmospheric research.

Calmer, a postdoctoral researcher with CIRES, and Hamilton, an aerospace engineering graduate student at the University of Colorado Boulder, leave in May for the MOSAiC expedition where they will pilot drones to collect atmospheric data over the frozen Arctic Ocean. The project, spanning several months, involves 20 drones outfitted for atmospheric science and marks the first time drones have been used to gather near-surface atmospheric readings so far north.

Gina Jozef, a Ph.D. candidate in CIRES and CU Boulder's Atmospheric and Oceanic Sciences department, has been blogging her experience aboard the *RV Polarstern*. "Throughout the week, we did seven successful flights (and two unsuccessful flights) which is a record!" Jozef wrote in early April.

The drone project is largely the brainchild of **Gijs De Boer**, a CIRES scientist affiliated with NOAA's Physical Sciences Laboratory. De Boer's journey to MOSAiC began in 2012, when he wrote a review paper on the importance of Arctic clouds in atmospheric processes. "I realized that we [didn't] necessarily have the right observational tools to fully measure all the things that come together to support the lifecycle of these

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clouds," de Boer said.

He began experimenting with unmanned aircraft as a way to collect missing pieces of atmospheric data not only in the Arctic but across the globe. Drones could help close some knowledge gaps: for example, the lower atmosphere in remote Arctic regions where low-altitude flights on manned research aircraft are dangerous. Drones also allow for flexibility; a pilot can quickly direct an unmanned aircraft system (UAS) to interesting features in the landscape like cracks in the ice.

The drones on the *RV Polarstern* carry instruments to measure things like temperature, wind, humidity and solar intensity. Together, these measurements provide a profile de Boer hopes will help scientists better understand how much energy is transported between ocean and atmosphere in the Arctic.

Calmer and Hamilton will be on MOSAiC's "new leg 4," with an adjusted timeline caused by the COVID-19 pandemic. From May to late August, the team will watch part of the Arctic atmosphere transition from spring to summer, as sea ice melts. Shifts in the Arctic melt season are a major climate change indicator, with temperatures rapidly rising over the north polar region and implications for warming around the rest of the planet.

Hamilton estimates that he's spent at least 41 hours flying UAS, in Boulder and in Svalbard, Norway, where he and de Boer traveled in spring 2019 to put their systems through the paces in an environment that's more similar to what they will face on MOSAiC.

Despite meticulous planning and testing, uncertainties remain. A lack of satellite imagery makes mapping launching points difficult, and ice ridges can complicate equipment placement. Jozef already found that batteries drain faster than expected, leading to some premature landings in risky locations on the ice.

Those uncertainties are part of pressing the boundaries on atmospheric research. "If we come back with all 20 drones I'm going to be a bit disappointed," de Boer said. "It likely means we weren't pushing our limits far enough or that outside factors prevented us from [more flights]."

All aboard: Explore the Arctic at home with CIRES Education & Outreach

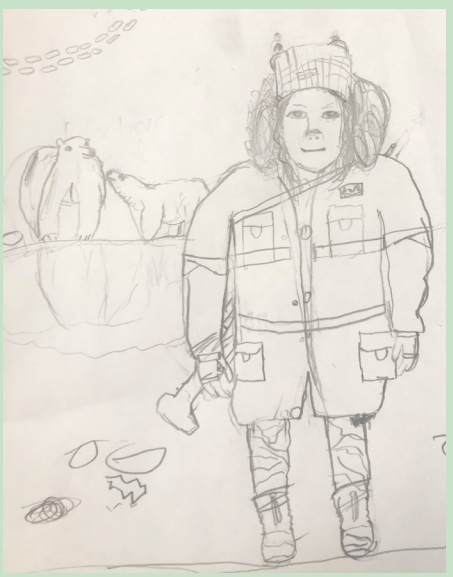
Learners everywhere can drift along (virtually) for an icy ride aboard the *RV Polarstern* icebreaker, frozen in Arctic sea ice. Funded by the National Science Foundation, the CIRES Education & Outreach program is delivering Arctic curricula and expedition updates straight to your inbox, mobile phone or computer.

The team's weekly MOSAiC Monday newsletter directs K-12 teachers to educational activities and other engaging materials. Take a 360-degree tour of the *Polarstern*, plot the ship's route and more.

"It has been fascinating seeing the *Polarstern* move around the Arctic," said one middle school student from Colorado. "Graphing the changes in the environment visually has also been really cool because I get to see everything that is changing, like the hours of daylight, the sea ice extent and the temperature."

For anyone interested in the Arctic mission, the monthly "Postcards from the Arctic Ice" newsletter provides regular updates from the ship.

If video learning is your thing, check out the MOSAiC MOOC (Massive Open Online Course): dozens of interviews with Arctic experts. Watch through Coursera (coursera.org/learn/frozen-in-the-ice) or YouTube (bit.ly/FrozenArcticMOOC).



Eben, age 11, of Truro, Norway, contributed this drawing of a polar bear guard to the Museum of MOSAiC Art, open to all at mosaic.colorado.edu/museum-mosaic-art-momoa

MOSAIC EXPEDITION

In their own words

Scientists from around the world have been telling the story of MOSAiC, the research expedition that has frozen a ship into the Arctic ice for a year. We've collected some of their words on pages 29-33 of this edition of *Spheres*, to share tales of the team's first seven months on the ice, through the polar night.

You can read more at:

follow.mosaic-expedition.org

mosaic.colorado.edu/blogs

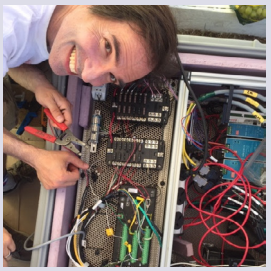
mosaicexpeditiongina.wordpress.com/blog-feed/

blogs.helmholtz.de/polarstern/en/

uaf-iarc.org/engagement/expeditions/mosaic/

polartrec.com/expeditions/mosaic/journals

arm.gov/news-events/field-notes



David Costa, CIRES and NOAA

Jessie Creamean, Colorado State University

Kelly K. Falkner, National Science Foundation

Allison Fong, Alfred Wegener Institute

Jaari Hapala, Finnish Meteorological Institute

Stefan Hendricks, Alfred Wegener Institute

Esther Horvath, Alfred Wegener Institute

Gina Jozef, CIRES and CU Boulder

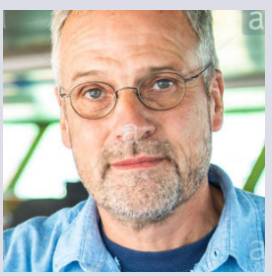
Daniela Krampe, Alfred Wegener Institute

Thomas Krumpen, Alfred Wegener Institute

Marcel Nicolaus, Alfred Wegener Institute

Ian Raphael, Dartmouth College

Markus Rex, Alfred Wegener Institute



Stefan Schwarze, captain, *RV Polarstern*

Matthew Shupe, CIRES and NOAA

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