Eos

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SCIENCE NEWS BY AGU

Europe's Biodiversity Strategy

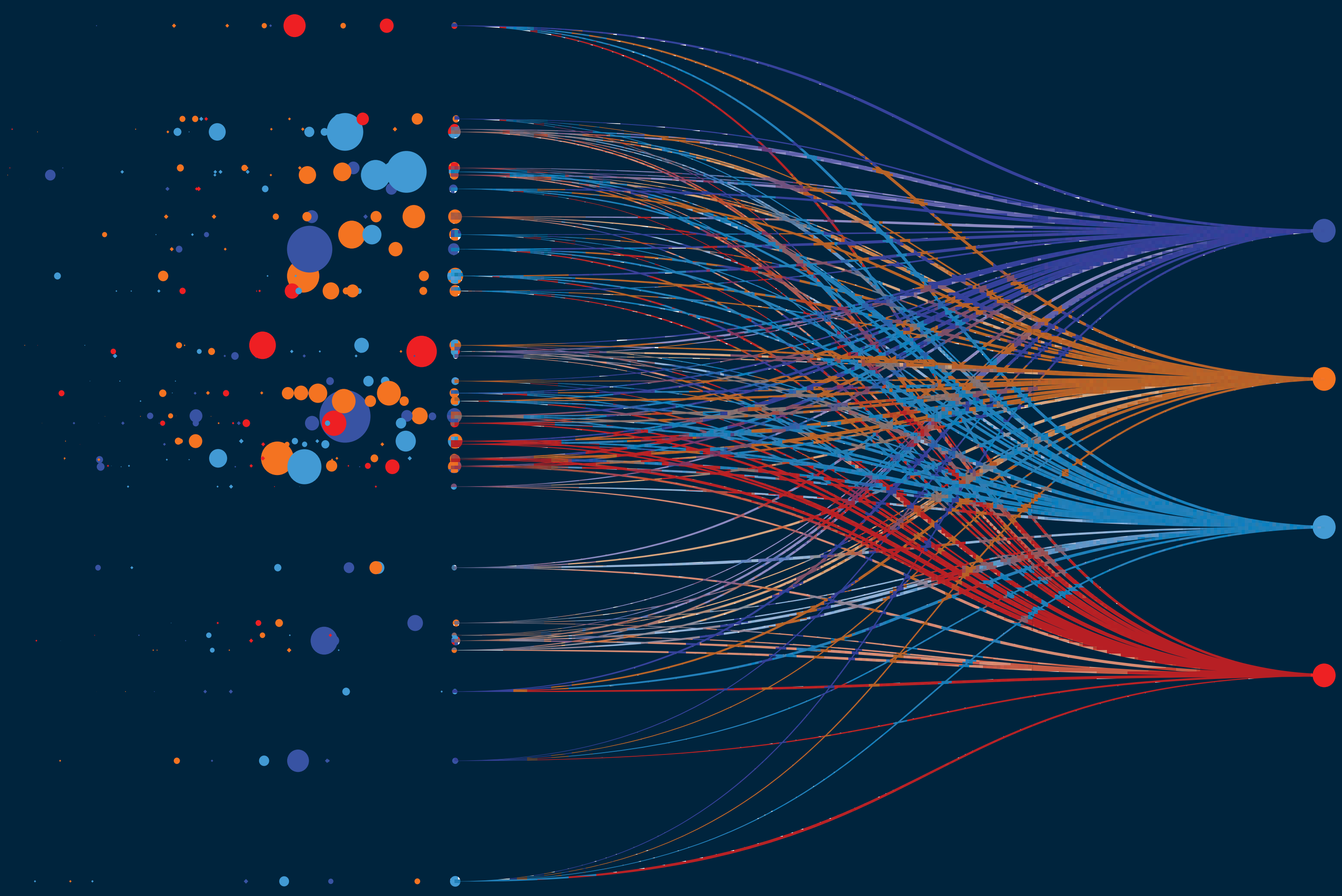
A Virtual Hackathon Fights Locusts

MH370's Search Reveals New Science

INNOVATIONS IN TECHNOLOGY GOT US INTO

THE DATA PROBLEM.

WE NEED AN EVOLUTION IN TECHNOLOGY TO GET US OUT.



AGU
ADVANCING EARTH AND SPACE SCIENCE

The Rise of Machine Learning

We cover the data problem here in *Eos* quite a bit. But "the data problem" is a misnomer: With so many ways to collect so much data, the modern era of science is faced not with one problem, but several. Where we'll store all the data is only the first of them. Then, what do we do with it all? With more information than an army of humans could possibly sift through on any single research project, scientists are turning to machines to do it for them.

"I first encountered neural networks in the 1980s," said Kirk Martinez, *Eos* science adviser for AGU's informatics section and a professor at the University of Southampton, United Kingdom, when he suggested the theme for our August issue. "Neural networks were a 'biologically inspired' way to make algorithms which could be trained to respond to certain inputs. Since then it has blossomed into a part of machine learning as we know it today."

Grappling with climate change research is one of the clearest places where machine learning will be crucial. "Currently, less than 5% of available environmental observational data are used in numerical models of Earth systems," writes Amy McGovern and colleagues in "Weathering Environmental Change Through Advances in AI" (p. 15). Recent innovations for artificial intelligence methods will allow researchers to harness more of those data, but realizing the full potential will require interdisciplinary collaboration to build the proper infrastructure.

What then? Residents in the U.S. Great Plains are already getting AI weather forecasts that give 36 hours of notice before a hailstorm, write McGovern et al. AI is mapping ecological provinces in the ocean (see p. 14), and soon it could even decode alien atmospheres (see p. 7), if scientists can overcome "the curse of dimensionality."

Machine learning, said Martinez, is going to be an essential part of data analysis in Earth and space sciences. "It gives us a way to classify images and signals that we would have struggled to process before," but we also need to understand its limitations.

The discoveries machine learning can help scientists make come at a cost. The processing power required for these algorithms requires massive amounts of energy—and many in the geoscience community are clamoring for even more powerful supercomputers. In "A Greener Earth Model" (p. 18), Richard Loft writes about the irony of creating a significant carbon footprint to build climate models that tell us what burning all that carbon is doing to climate. Instead, he urges scientists to lead by example, offering several ways to think about—and lower—the energy requirements of these systems.

On the theme of analyzing and interpreting data, don't miss Stephanie Zeller's and David Rogers's "Visualizing Science: How Color Determines What We See" (p. 28). They write, "Visualization's single most effective encoder—color—remains vastly understudied," but here they offer a masterful introduction of the many considerations involved when conveying data. Needless to say, the images illustrating the article are page turners.

We hope you enjoy this issue on data and machine learning and that it makes you think about the ways in which you might use it—or improve its use—in your own work.

Heather Goss, Editor in Chief

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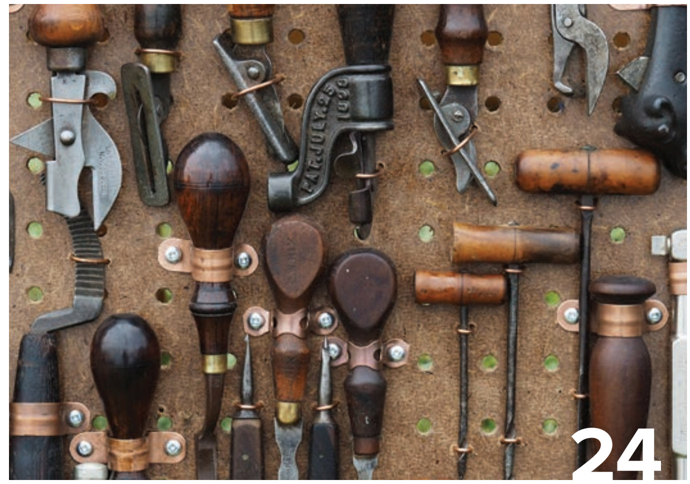
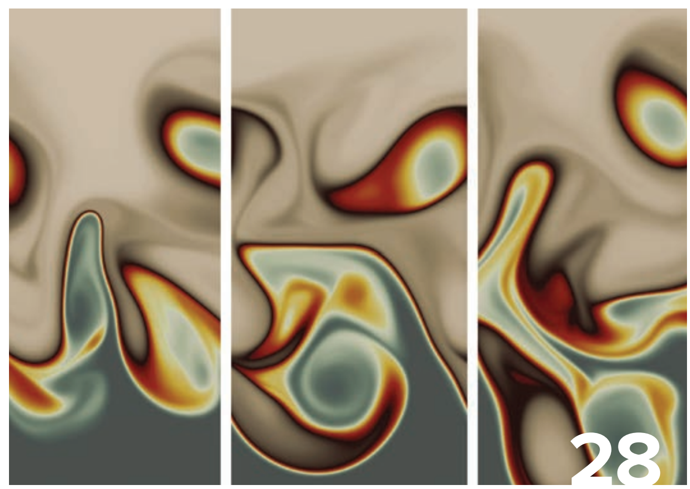




Features

On the Cover

Credit: iStock.com/GarryKillian

Columns

Europe Launches Biodiversity Strategy for the Coming Decade

Ancient woodlands, such as the conifer forest in Sweden's Ycke Nature Reserve, are biodiversity hot spots. Credit: iStock/thomasmales

As world governments draw up recovery plans in response to the coronavirus 2019 (COVID-19) pandemic, environmental concerns risk being shunted aside as leaders default to business-as-usual solutions to revive their economies. But in Europe, researchers and policy analysts have recently voiced cautious optimism, as the European Union (EU) appears to be sticking by commitments outlined in its Green Deal.

Devised and rolled out last year, the European Green Deal is a policy framework to achieve net zero carbon emissions by 2050 within the bloc of 27 EU nations.

The EU has pushed ahead with the launch of its Biodiversity Strategy for 2030, which will help shape how the Green Deal is implemented over the next decade (see bit.ly/2030-strategy). Key commitments include increasing the amount of legally protected land, restoring degraded ecosystems, and creating new green spaces in urban environments.

Currently, only 26% of the EU's land and 11% of its marine zones are legally protected areas; both will increase to 30% under the new plans. A third of these protected zones, including all remaining primary and old-growth forests, will be subject to even stricter protections.

To help rejuvenate freshwater ecosystems, the plans propose that at least 25,000 kilometers of rivers be restored to free-flowing status by 2030. This restoration includes the removal of obsolete dams and the restoration of floodplains and wetlands.

Protected Trees, Political Realities

Some ecologists and policy analysts, although positive about the Biodiversity Strategy, still have concerns about how it will work in practice.

"Targets to place more areas of land under protection make a good headline and intuitively make sense. But our questions are, Where will the space be found? Who might have to be moved or displaced—if anyone—to create them? And who will pay for it?" said Rosaleen Duffy, a political ecologist at the University of Sheffield in the United Kingdom and principal investigator at Biodiversity and Security (BIOSEC), a project funded by the European Research Council.

Duffy is concerned that it may be cheaper and more politically acceptable to establish protected areas in Eastern Europe, placing a disproportionate onus on rural communities in those EU nations.

Currently, the EU provides roughly 60 billion euros per year in farming subsidies through its Common Agricultural Policy. Much of the money is spent on increasing production. With its Biodiversity Strategy, the EU is introducing policies and funding that address some of the negative impacts of farming on the environment, such as clamping down on chemical pesticides. The strategy states that at least 20 billion euros per year should be provided to help with this transition, with a significant chunk coming from programs in the next long-term EU budget (2021–2027).

This budget commitment has been praised by the World Wide Fund for Nature (WWF), which urged the EU to make this spending commitment more concrete and to involve citizens and nonprofit organizations to implement the plans. "The Biodiversity Strategy spells out what WWF deeply believes in: that nature protection and restoration will only lead to lasting positive change if it is planned and implemented with genuine participation across society," said Irene Lucius, WWF's regional conservation director for Central and Eastern Europe.

András Báldi at the Centre for Ecological Research in Budapest, Hungary, welcomed the new strategy: "I am optimistic it is finally a real step with target numbers and significant funding for the protection of our biodiversity."

Péter Ódor, one of Báldi's colleagues, believes that legally protecting Europe's oldest woodlands is a crucial step in preserving European biodiversity. Undisturbed forests contain "dead wood that is the main microhabitat for about 40% of the forest biota," he said. After logging or other disturbances, "the restoration and creation of dead wood in relatively young secondary forests could not substitute for these old-growth stands."

In Europe, old-growth forests account for roughly 0.7% of the continent's forests, with the majority found in Finland, the Balkans, and the Carpathian Mountains. Each nation classifies its forests differently, and this inconsistency will likely intensify debate with the introduction of this new legislation, according to Duffy and colleagues on the BIOSEC team. They are concerned that without adequate compensation mechanisms, nations are unlikely to rush to designate forests as protected areas.

By **James Dacey** (@JamesDacey), Science Writer

Teaching Machines to Detect Climate Extremes

Extreme weather events, whether scorching temperatures that ruin crops or killer storms that drown coastal towns, are likely to become more frequent and more powerful with climate change. Quantifying the increase in these extreme events (and their economic and public health costs) requires combing through thousands of gigabytes of data that climate models generate every day.

Scientists can't just look at the results of their climate models and count hurricanes or droughts. Instead, they are turning to machine learning to find such extreme weather events in their models' data.

For decades, modelers have relied on heuristics—mathematical definitions of an object of interest—to pinpoint extreme weather events. But heuristics cannot capture the complexity and variability of weather, which are very difficult to condense into a set of values and threshold conditions. Although many algorithms based on heuristics can detect atmospheric rivers (air currents that transport water from the tropics to the poles), for instance, their results tend to be unreliable, with large discrepancies between algorithms. Researchers hope to replace them with a new generation of artificial intelligence (AI) algorithms.

Computer Visionaries

To build better algorithms, climate scientists have turned to a particular subset of machine learning techniques known as deep learning. Deep learning systems do not require a set of human-defined rules and values to guide their output. Instead, researchers "train" a system with hundreds or thousands of solved examples that the system then analyzes to create its own relevant rules.

Deep learning was first developed in the 1970s in the field of computer vision, with the goal of training computers to "see" or recognize certain objects in digital images.

"In the '80s, '90s, and 2000s, people kept coming up with heuristics for defining what makes a pedestrian, what makes a car, what makes a face, and so on and so forth," said Prabhat, a computer scientist who leads big-data initiatives at the Lawrence Berkeley National Laboratory in California. "In the last 10 years, it has been conclusively proved that AI and, in particular, deep learning techniques are truly well suited for solving [the computer vision] problem. We felt that we could apply the same idea to finding extreme weather patterns."

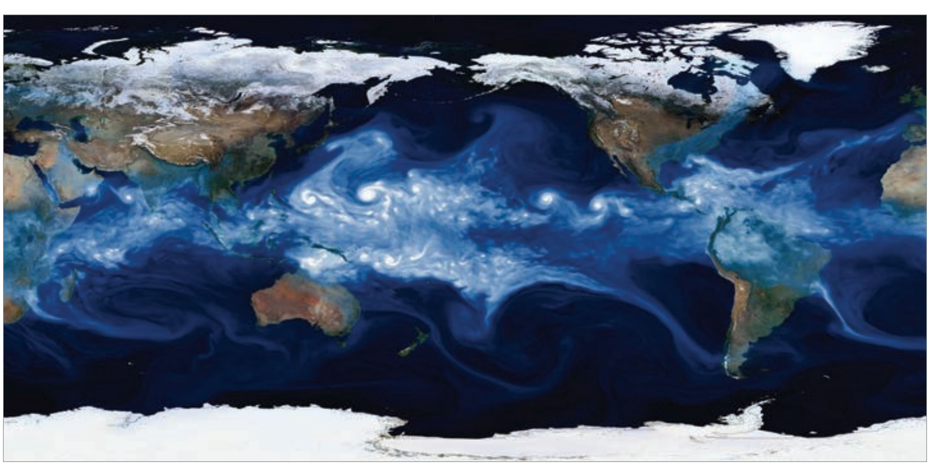
To test this approach, Prabhat and his colleagues attempted to train a deep learning network to recognize and draw labels around two types of extreme weather in high-resolution simulation data: tropical cyclones and atmospheric rivers, both of which are associated with heavy rainfall. After being trained with over 500 labeled examples, their system can detect most atmospheric rivers and tropical cyclones in simulation data it has never seen before. Their work is described in a preprint of an article submitted to the open-access journal *Geoscientific Model Development* (see bit.ly/detect-extreme-weather).

Experienced climate scientists have been "very convinced that the deep learning network is identifying the right patterns," said Karthik Kashinath, a machine learning scientist leading the project at the National Energy Research Scientific Computing Center in Berkeley, Calif. That's not to say the project is perfect—the system still yields a number of false positives and false negatives—but the researchers hope it can be improved with more training data.

Generating Training Data

Obtaining reliable training data is one of the main challenges for deep learning applications. For extreme weather patterns, the labeling has to be done by experts in the field. "We're going directly to the climate experts, the meteorologists, who have been looking at these patterns for many years, so they have a good sense of what they look like," Kashinath said. But labeling these images is a tedious and time-consuming process.

> **"In the last 10 years, it has been conclusively proved that AI and, in particular, deep learning techniques are truly well suited for solving [the computer vision] problem."**



This image shows a Community Atmospheric Model (CAM) high-resolution simulation used in attributing changes in the risk of extreme weather and climate. Credit: U.S. Department of Energy

To speed things up, Kashinath and Prabhat, with many collaborators, created ClimateNet (see bit.ly/climate-net), a crowdsourced extreme weather training database for deep learning networks. The goal is to share the labeling effort by opening it to other researchers and institutions around the world. The team also created an online labeling tool called ClimateContours, which allows other scientists to upload their own data sets and label them.

"If a dozen institutions around the world can provide labels corresponding to maybe a dozen [extreme weather] patterns, then we can just solve these problems once and for all, and we can move on to the next set of problems," Prabhat said.

"The unique aspect to ClimateNet is that instead of relying on one definition of what an atmospheric river or tropical cyclone is, it crowdsources the information using experts, all with subtly different ideas on how these features should be defined in data sets," said Christine Shields, a climate scientist at the National Center for Atmospheric Research in Boulder, Colo. "All of those viewpoints are then used as a way to train the deep learning algorithm, thus incorporating, implicitly, these different definitions."

Better data sets will lead to better AI models and could unlock untapped results from climate simulations, said Claire Monteleoni, an associate professor in computer science at the University of Colorado Boulder who has applied AI to hurricane track prediction but wasn't involved in this project. "Much of the data output by climate models hasn't been analyzed, so AI is really the cheapest way, without having to run new climate model simulations, to gain more insights to help with predicting climate and extreme weather events."

Enabling High-Precision Analysis

The most basic thing researchers will be able to do with a successfully trained deep learning network will be to count how many extreme events a model calculates will happen in the future and compare the result with present-day numbers. Even so, Prabhat said, that would barely scratch the surface of what these systems will allow.

Researchers can look at underlying data for each event in the model data and extract information such as how much precipitation is expected to fall in a specific area. This information can be used in many ways, including estimating insurance costs in high-risk areas and managing future drought. In places like California, which depend on rain delivered by atmospheric rivers, authorities could be alerted that they should make contingency plans if those rivers are going to be diverted, Prabhat said.

"It's not that you could have never answered these questions" without resorting to AI, Prabhat explained, but the new approach will likely make it easier and faster—and possibly better than with heuristics.

"We are able to do precision analytics and get these very high quality results," he said, which heightens the credibility of climate models' results and the plans that rely on them for preparing for the extreme weather events of the future.

By **Javier Barbuzano** (@javibarbuzano), Science Writer

Hackathon Participants Solve Global Problems—from Home

Data journalist Winnie Kamau knew she wanted to join the desert locust hackathon team after a friend shared video of the locust devastation in her childhood home of Meru, Kenya.

"That made me think, 'Wow, this is coming closer [to] home,'" said Kamau, who now lives in Nairobi. The practicality of working on a project that could directly help Kenyan farmers—and others—made her more curious about the opportunity. According to the Food and Agriculture Organization of the United Nations, East Africa (especially Ethiopia, Kenya, and Somalia) is currently facing an unprecedented threat to its food security because of locust swarms.

Coming up with ways to help farmers during locust swarms was one of the challenges for this year's INSPIRE Hackathon, an annual competition dedicated to solving problems around the globe with open data, volunteered geographic information, and citizen observations.

Kamau's team, which won the event, used imagery from the European Space Agency's Sentinel-1 and -2 satellites to map and study the effects of desert locust swarms.

"We know that there's a global pandemic that has taken over the world right now, and we are all fighting an unseen enemy. But in East Africa and the Horn of Africa, we are also fighting an enemy that we can see," Kamau said during a presentation on 6 May.

The nations of East Africa are enduring an invasion of desert locusts, which are threatening food security and economic activity in areas like Samburu National Reserve in Kenya. Credit: iStock.com/Jennifer Watson

Virtual Hackathon for a Sustainable Africa

In 2019, the INSPIRE Hackathon was held in Nairobi with more than 200 participants. This year's hackathon was supposed to have been hosted in Kampala, Uganda, but with recent lockdown orders associated with the coronavirus-2019 (COVID-19) pandemic, an in-person hackathon just wasn't possible.

However, moving the event online didn't seem to deter participants, said hackathon organizer Bente Lilja Bye. Frequent webinars helped participants get to know each other and share ideas. Webinars also helped the hackathon recruit even more participants, with some participants joining multiple teams, Lilja Bye said.

Kamau actually preferred the virtual format. Instead of dealing with the hassle of airports, hotel reservations, and jet lag, not to mention the limited time of an in-person event, the virtual format "[gave] us more time and space to be able to be more creative," Kamau said.

Other hackathon attendees ranged from students to big-data experts. Each team was required to make use of freely available Earth observation data to approach challenges like maintaining food security, balancing open land use and transportation infrastructure, anticipating ways climate change might affect agriculture, and helping farmers plan for and mitigate devastating locust swarms. Each team was provided a mentor, an expert to consult on whatever issue they were trying to solve.

Although the hackathon is over now, Kamau and her teammates still meet regularly. They're even publishing their report with the Global Open Data for Agriculture and Nutrition initiative, an INSPIRE Hackathon partner that supports open-data efforts around the globe (www.godan.info/).

Both Kamau and Lilja Bye stressed the importance of a hackathon-style event in bringing people together to solve problems.

"I think the common denominator is, you have a concentrated work on something, just to solve something, identify a problem and solve something," Lilja Bye said.

By **JoAnna Wendel** (@JoAnnaScience), Science Writer

Machine Learning Can Help Decode Alien Skies—Up to a Point

iStock.com/robertiez

Future telescopes like the James Webb Space Telescope (JWST) and the Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL) are designed to sample the chemistry of exoplanet atmospheres. Ten years from now, spectra of alien skies will be coming in by the hundreds, and the data will be of a higher quality than is currently possible.

Astronomers agree that new analysis techniques, including machine learning algorithms, will be needed to keep up with the flow of data and have been testing options in advance. A study that has been accepted by *Monthly Notices of the Royal Astronomical Society* trialed one such algorithm against the current gold standard method for decoding exoplanet atmospheres to see whether the algorithm could tackle this future big-data problem (bit.ly/machine-learning-exoplanets).

"We got really good agreement between [the answers from] our machine learning method and the traditional Bayesian method that most people are using," said Matthew Nixon. Nixon is the lead researcher on the project and an astronomy doctoral student at the University of Cambridge in the United Kingdom.

However, he said, "as we increased the parameter space, the computational efficiency of our method dropped.... As we started to add more parameters, we started to get hit by the curse of dimensionality."

A Random Forest Breathing in Exotic Air

Astronomers measure the spectrum of an exoplanet's atmosphere when starlight shines through it or when heat from the planet lights up the atmosphere from within. In either scenario, the atmosphere imprints its chemical signature on the light and is detected by our telescopes.

The current front-runner for best deciphering a planet's spectrum is called atmospheric retrieval. It uses statistical inference to calculate the likelihood that given an observed spectrum, an exoplanet's atmosphere has a certain composition, temperature, level of cloud cover, and heat flow. The technique has so far proven very reliable but can be computationally expensive.

"The more detailed the data, the more detailed the model needs to be," said Ingo Waldmann, an astrophysicist at University College London in the United Kingdom who was not involved with this study. "Perhaps unsurprisingly, the more detailed the model, the longer it takes to compute its results. Today we are rapidly reaching a stage where our traditional techniques become too slow to compute these increasingly complex models."

"As we started to add more parameters, we started to get hit by the curse of dimensionality."

Nixon and his adviser and coauthor, Nikku Madhusudhan, also at the University of Cambridge, tested a type of supervised machine learning algorithm called a random forest, which is made up of thousands of decision trees. Each decision tree makes its prediction for a likely combination of atmospheric properties, and then the algorithm generates an artificial spectrum that has those properties. The algorithm compares each artificial spectrum with the real one and chooses the closest match. This is a new and modified application of the random forest algorithm for exoplanetary atmospheres that was originally developed by astronomers at the University of Bern in Switzerland.

The researchers tested their algorithm on two exoplanets with exceptionally well studied atmospheres and found that the random forest's solution matched the one from atmospheric retrieval. Moreover, "the authors achieve a much faster interpretation of the data than otherwise possible with traditional techniques," Waldmann said.

However, the two exoplanets in question, WASP-12b and HD 209458b, are both very hot Jupiter-sized planets. The algorithm could easily simplify its decision because each planet's atmosphere consists mostly of hydrogen and helium, Nixon said.

"Generally speaking," Madhusudhan explained, "it is going to be slightly harder to retrieve atmospheric properties of cooler and smaller planets," for example, super-Earths or Earths. "This is because the spectral signatures are expected to be smaller for such planets, which makes it harder to extract the same amount of information as we have for hot Jupiters currently." For planets with faint signals and those whose base constituents are unknown—an ocean world, super-Earth, or temperate-zone planet—the random forest would lose its computational edge.

A Balanced Approach for the Way Forward

This study adds to a growing effort by exoplanet scientists to find an efficient way to handle the upcoming deluge of atmospheric data. "It is great to see a growing group in the community using machine learning methods and cross-checking each other's results and claims," said Daniel Angerhausen, an astrophysicist at ETH Zürich in Switzerland who was not involved with this research.

Missions like JWST and ARIEL are first at bat, but Angerhausen is also thinking about missions that will come after those. Astronomers will need to strategize the most efficient ways to observe interesting targets. "This problem is predestined for a [machine learning] approach," Angerhausen said. A random forest approach is just the "tip of the iceberg" for algorithms to try.

Nixon agreed and said that "going forward, looking at different machine learning algorithms is definitely a positive [step], and also looking at how we can combine these machine learning approaches into hybrid methods to really boost these retrievals to the next level."

As exoplanet atmosphere research moves into the big-data era, machine learning will become an increasingly important research tool scientists should be trained to use, Madhusudhan said. Some graduate programs are already integrating more data science learning into students' training. (Nixon's doctorate work is supported by one such program in the United Kingdom.)

"On the other hand," Madhusudhan added, "it also needs to be recognized that while machine learning is a great research tool in various areas, there are also important areas of research where other numerical, statistical, and analytic approaches are more suitable for some important problems. Therefore, I believe the right balance needs to be met while integrating machine learning into graduate programs in the right research areas."

"Machine learning may never replace an atmospheric expert," Waldmann said, "but I'm certain that artificial intelligence will certainly play a role as a helping hand."

By **Kimberly M. S. Cartier** (@AstroKimCartier), Staff Writer

Search for MH370 Revealed Ocean Crust Waves

The M/V Fugro Equator, *seen here, was one of three ships that collected sonar data from June 2014 to June 2016 while searching for Malaysia Airlines Flight 370 (MH370). Those data led to a new high-resolution bathymetry map of an area near the Southeast Indian Ridge. Credit: Justin Baulch, Australian Transport Safety Bureau, CC BY 4.0 (bit.ly/ccby4-0)*

Malaysia Airlines Flight 370 (MH370) disappeared on 8 March 2014 somewhere in the southern Indian Ocean. The tragic loss of all 239 people aboard led to a multinational, multiyear search to find and recover the plane. Despite this effort, it remains missing.

As part of that search effort, three survey vessels collected multibeam bathymetry data using hull-mounted sonars. These data were used to create maps of the seafloor that span roughly 88,000 square kilometers near the Southeast Indian Ridge west of Australia.

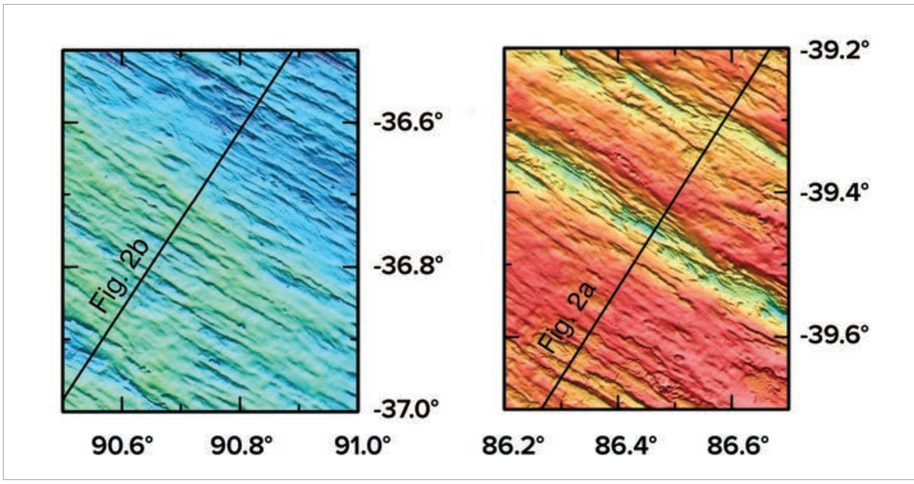
The bathymetry, at a resolution 15 times sharper than previous maps of the area, did not reveal MH370's final resting place. However, a recent analysis of those seafloor maps showed that the ocean crust surrounding the ridge grew at a rate that ebbed and flowed on a timescale of hundreds of thousands of years. The results, published in *Geophysical Research Letters* (see bit.ly/oceanic-crustal-formation), will help scientists better understand the processes that control ocean crust formation over millions of years.

Waves on the Seafloor

Most of the ocean floor is only very roughly mapped. "Earth is about 70% ocean floor," said Joyce Sim, "but we really don't know the bathymetry of the ocean floor, and it's really hard to have this sort of high-resolution data on all of it." Sim is a coauthor on the study and a geodynamics postdoctoral researcher at the Earth and Planets Laboratory at the Carnegie Institution for Science in Washington, D.C. "It takes quite a while just to cover a pretty small patch of the ocean" with mapping vessels and costs millions of dollars per expedition.

Moreover, the seafloor accumulates layers of sediment that can prevent sonar from seeing the ocean crust in detail. The area that was searched for MH370, however, has a thinner-than-average sediment buildup that makes the crust underneath visible to sonar.

The scans for MH370 revealed that the ocean crust rises and falls in waves that start at the Southeast Indian Ridge and continue outward.



Two sections of the bathymetry map that covers part of the MH370 search area. Shown are variations in ocean crust depth around 3.5 kilometers below sea level (left), and crust about 4 kilometers below sea level (right). In both maps, the seafloor is spreading along the solid black line from bottom left to top right. Small grooves are abyssal hills. The more widely spaced ridges are evidence that porosity waves helped form the ocean crust. Credit: Parnell-Turner et al., 2020, https://doi.org/10.1029/2020GL087349

The scans for MH370 revealed that the ocean crust rises and falls in waves that start at the Southeast Indian Ridge and continue outward. The ridge spreads about 35 millimeters in opposite directions every year, and the wave crests, where crust grew faster, are more than 100 kilometers long and repeat every 10–14 kilometers. The researchers estimated when each wave formed by comparing the bathymetry maps to independent measurements and models of the crust's magnetic field.

The ocean crust is like "a magnetic tape recorder," said lead author Ross Parnell-Turner, a marine geophysicist at Scripps Institution of Oceanography in La Jolla, Calif. Crustal rocks record the polarity of Earth's magnetic field as they form, allowing scientists to trace the age of different sections of ocean crust.

"You might expect that oceanic crust is formed in this constant process, so you might have a uniform thickness, for example, of oceanic crust being formed," he said. "What we found, actually, is that the pace at which new crust is formed varies on this...characteristic timescale of 300,000–400,000 years." The wavy pattern repeated for 12 million years.

It's not so strange that ocean crust topography has some periodicity, Sim explained. It would be much odder for the crust to form perfectly flat for millions of years.

What is odd about these waves, however, is that the characteristic timescale doesn't match up with glacial cycles that are governed by changes in Earth's orbit around the Sun and its axis of rotation. So-called Milankovitch cycles regulate ice coverage and sea level on timescales of 23,000, 41,000, and 100,000 years.

It's been fiercely debated in recent years, Parnell-Turner explained, whether the waxing and waning of sea level modulate how quickly new crust forms at seafloor ridges. Data from oceanic crust not far from the MH370 search site support this theory.

But for the Southeast Indian Ridge, at least, that appears not to be the case. "We have a very long record of crustal accretion over a very large area," Parnell-Turner said. "We did not find any evidence for cycles of crustal accretion on those Milankovitch timescales."

"These kinds of studies drive home the point that exploration-driven science is as valuable as hypothesis-driven science."

Melted Mantle Through Thick and Thin

Seeking an alternate explanation, the researchers tested whether the periodicity could be caused by variations in how melted the magma is when it comes up through the seafloor. Using simplified computer simulations, the team found that the phenomenon, called porosity waves, created variations in ocean crust topography at timescales similar to those seen in the bathymetry.

"As the mantle upwells, it starts to melt due to decompression melting" and becomes a fluid-like magma, Sim explained. "What you see are melt-rich pockets forming in waves and moving toward the ridge axis where the oceanic crust is created."

"The authors of this paper make a convincing case for a longer-scale structure...and plausibly attribute such features to mantle processes," said John A. Goff, a senior research scientist in seafloor mapping at the University of Texas at Austin. "What really makes that possible is the exceptionally long record in terms of crustal ages from the MH370 search." Goff was not involved with this research.

This bathymetry map, although a significant leap forward in resolution, can't tell the team for sure whether porosity waves, glacial cycles, or something else like mantle composition is truly behind ocean crust waves. The fact is, it's just one location where the seafloor is spreading.

"We don't have very good data in a lot of the deep ocean," Parnell-Turner said. "Collecting more bathymetry data like this in areas where we have the crust exposed would be helpful" in figuring out the extent to which each process might regulate crust formation.

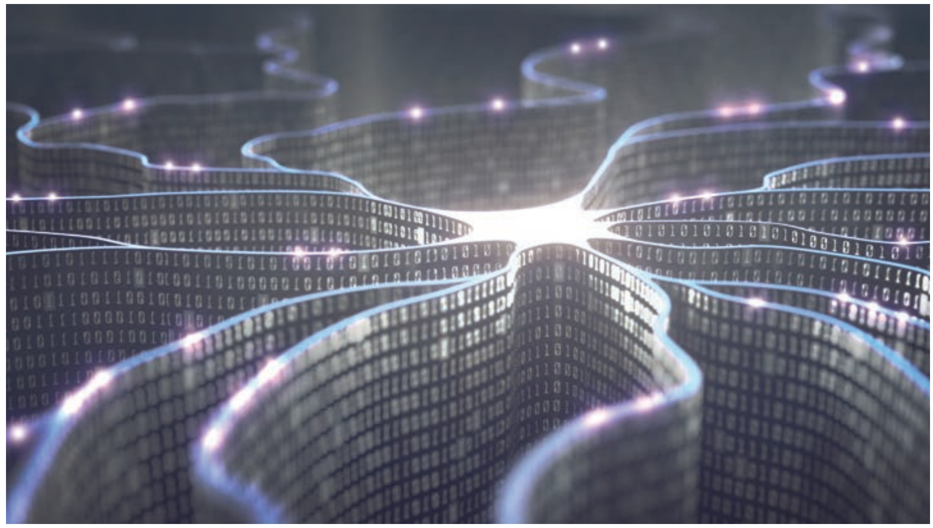
"These kinds of studies drive home the point that exploration-driven science is as valuable as hypothesis-driven science," Goff said.

By **Kimberly M. S. Cartier** (@AstroKimCartier), Staff Writer

The Future of Big Data May Lie in Tiny Magnets

The use of artificial intelligence and machine learning is now widespread, with practical applications in many Earth science domains, including climate modeling, weather prediction, and volcanic eruption forecasting. This revolution in computing has been driven largely by rapid improvements in software and algorithms.

But now we're approaching a second computing revolution of redesigning our hardware to meet new challenges, said Jean Anne Incorvia, a professor of electrical and computer engineering at the University of Texas at Austin.



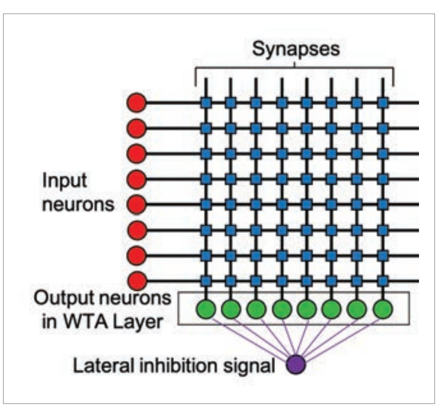
An artificial neuron, artistically rendered here, that can mimic properties of a biological neuron could accelerate developments in big-data computing. Credit: iStock.com/ktsimage

Traditional silicon-based computer hardware (like the computer chips found in your laptop or cell phone) has bottlenecks in both speed and energy efficiency, which may impose limits on its use in increasingly intensive computational problems.

To break these limitations, some engineers are drawing inspiration from biological neural systems using an approach called neuromorphic computing. "We know that the brain is really energy efficient at doing things like recognizing images," said Incorvia. This is because the brain, unlike traditional computers, processes information in parallel, with neurons (the brain's computational units) interacting with one another.

Incorvia and her research team are now studying how magnetic—not silicon—computer components can mimic certain useful aspects of biological neural systems. In a new study published in the journal *Nanotechnology* (bit.ly/neural-systems), her team reports that physically tuning the magnetic interactions between the magnetic nanowires could significantly cut the energy costs of training computer algorithms used in a variety of applications.

"Now we're approaching a second computing revolution of redesigning our hardware to meet new challenges."



In this diagram of an artificial neural network implementing a "winner-take-all" (WTA) machine learning algorithm, neurons (blue) are the computation units receiving data input (red) with synapses that interconnect them. The final computational output neurons (green) are inhibited by a lateral inhibition signal (purple). Credit: University of Texas at Austin

"The vision is [creating] computers that can react to their environment and process a lot of data at once in a smart and adaptive way," said Incorvia, who was the senior author on the study. Reducing the costs of training these systems could help make that vision a reality.

Lateral Inhibition at a Lower Cost

Artificial neural networks are one of the main computing tools used in machine learning. As the name implies, these tools mimic biological neural networks. Lateral inhibition is an important feature of biological neural networks that helps improve signal contrast in human sensory systems, like vision and touch, by having more active neurons inhibit the activity of the surrounding neurons.

Implementing lateral inhibition in artificial neural networks could improve certain computer algorithms. "It's preventing errors in processing the data so you need to do less training to tell your computer when it did things wrong," said Incorvia. "So that's where a lot of the energy benefits come from."

Lateral inhibition can be implemented with conventional silicon computer parts, but at a cost.

"There is peripheral circuitry that is needed to implement this functionality," said Can Cui, an electrical and computer engineering graduate student at the University of Texas at Austin and lead author of the study. "The end result is that as the size of the network scales up, there's much more difficulty in the design of the circuit and you will have extra power consumption."

Researchers in the new study are using magnetic nanowires and their innate physical properties to more efficiently produce lateral inhibition. These devices create small, stray magnetic fields, which are typically a nuisance in designing computer parts because they can disturb nearby circuits. But here, "this kind of interaction might be another degree of freedom that we can exploit," Cui said.

By running computer simulations, the researchers found that when these nanowires are placed in parallel and next to one another, the magnetic fields they produce can inhibit one another when activated. That is, these magnetic parts can produce lateral inhibition without additional circuitry.

Researchers found that when nanowires are placed in parallel and next to one another, they can produce lateral inhibition without additional circuitry.

The researchers ran further computer modeling experiments to understand the physics of their devices. They found that using smaller nanowires (30 nanometers wide) and tuning the spacing between pairs of nanowires were key to enhancing the strength of lateral inhibition. By optimizing these physical parameters, "we can achieve really large lateral inhibition," said Cui. "The highest we got is around 90%."

The Challenge of Real-World Applications

Training machine learning algorithms is a large time and energy sink, but building computer hardware with these magnetic parts could mitigate those costs. The researchers have already built prototypes of these devices.

However, there are still open questions about the practical applications of this technology to real-world computing challenges. "While the study is really good and combines the hardware-software functionality very well, it remains to be seen whether it is scalable to more large scale problems," said Priyadarshini Panda, a professor of electrical engineering at Yale University who was not involved in the study.

But the study is still a promising next step and shows "a very good way of matching what the algorithm requires from the physics of the device, which is something that we need to do as hardware engineers," Panda added.

By **Richard J. Sima** (@richardsima), Science Writer

Long Live the Laurentian Great Lakes

LIVING IN GEOLOGIC TIME

From some vantage points, the Great Lakes feel more like vast inland seas than freshwater lakes. But the 6 quadrillion gallons (~23 quadrillion liters) sloshing in Superior, Michigan, Huron, Ontario, and Erie represent one fifth of the planet's fresh water.

How long will the Great Lakes retain their honor of being the largest collection of freshwater lakes on the planet? Thanks to some ancient rifting events, probably for a very long time to come.

Ancient Rifts and Ice Age Lakes

The story of the Great Lakes began over 1 billion years ago, when the ancient supercontinent Laurentia began splitting in half. Over the course of about 10 million years, the Midcontinent Rift System opened a massive fissure on its way to becoming a new ocean basin. But for reasons geologists don't entirely understand, the rift failed and no ocean was formed, leaving a 3,000-kilometer-long scar across what is now North America.

Eons of erosion have hidden this scar, which runs in two forks from Lake Superior down to Alabama and Oklahoma. "A billion years is a very long time, even by geologic standards," said Seth Stein, a geophysicist at Northwestern University in Evanston, Ill.

Evidence of the rift is visible at Lake Superior, which is ringed by cliffs of billion-year-old basalt that erupted into the active rift, giving the largest lake a uniquely rugged shoreline. "Lake Superior looks very different from the rest of the Midwest," where volcanic rocks are rare, Stein said.

Lake Superior sits within the Midcontinent Rift scar, but all five Great Lake basins were carved out by glaciers during the last glacial period, when the region was buried under the Laurentide Ice Sheet. As the ice age came to a close, the glaciers retreated, and the lake basins filled with meltwater to form the five Great Lakes as we know them by around 10,000 years ago. Today some scientists refer to the Great Lakes by their more formal name, the Laurentian Great Lakes.

A few summers ago, I drove hundreds of kilometers out of my way to visit Superior's billion-year-old rocks on a backpacking trip through Porcupine Mountains Wilderness State Park in Michigan, on the south shore of Lake Superior. Unfortunately, the pilgrimage

Lake Superior's towering basalt cliffs stand in contrast to the sandy beaches that ring the other Great Lakes. Credit: Seth and Carol Stein

Holland Beach, on Lake Michigan is one of many sandy swimming beaches around the Great Lakes. Credit: Mary Caperton Morton

was rushed. The moment we parked at the trailhead, clouds of mosquitoes swarmed the car. It was mid-June, and the bloodsuckers were so relentless—biting through bug spray, layers of clothes, a smoky fire, and a tent—that we cut our 4-day loop in half. Next time I visit, I'll avoid peak mosquito season.

The Great Lakes offer a lifetime's worth of hiking opportunities: I have my eye on the Superior Hiking Trail, a 499-kilometer-long, 2- to 4-week backpacking trip along the northwestern shore of Lake Superior in Minnesota. Isle Royale, a large island in Lake Superior, "offers arguably the best backpacking in the Midwest," Stein said.

More Water, More Problems

The Great Lakes have been a nexus of migration, transportation, fishing, and trade for thousands of years, with a series of lakes, rivers, and waterways connecting the upper Midwest to the Atlantic Ocean. Records that began in 1918 show lake levels fluctuating seasonally, with the annual water budget controlled by inputs from rivers and outputs to the Atlantic Ocean and by evaporation.

In 2014, after years of drought and higher temperatures triggered increased evaporation, water levels in the Great Lakes reached all-time lows. "For a long time, the dominant climate change narrative was that lake levels were going to drop drastically," said Richard Rood, a climate scientist at the University of Michigan in Ann Arbor. "That narrative ended abruptly in 2015," when lake levels started rising because of heavy rainfall and flooding across the Midwest.

By 2019, lake levels had drastically reversed course, exceeding their highest recorded levels. High water in the Great Lakes leads to shoreline flooding and erosion, which in turn threaten homes, industrial buildings, and port infrastructure.

"Now the narrative is that we will need to be able to cope with both highs and lows in lake levels," with those extremes persisting for longer time periods, perhaps several seasons in a row, Rood said.

Higher influxes of water into the Great Lakes also bring more pollutants, including nitrogen and phosphorus from agricultural runoff and *Escherichia coli* bacteria from overworked water treatment systems. Algal blooms and toxic water quality issues have increased.

The sheer size of the individual Great Lakes means that pollutants can stay in the system for a long time: A water droplet or molecule of pollutant will reside in Lake Superior for as long as 191 years, in Lake Michigan for 99 years, and in Lake Huron for 22 years, whereas the smaller Lakes Ontario and Erie have residence times of 6 and 2.6 years, respectively.

"Smaller lakes with shorter residence times can respond more quickly to changes than bigger lakes," said Dale Robertson, a research hydrologist at the U.S. Geological Survey in Middleton, Wis. That means there's hope for Lake Erie, where toxic algal blooms feeding off nutrients delivered by the Maumee River create water quality issues each summer. But larger lakes, like larger boats, cannot change course as quickly. It may take decades before we know how the larger lakes will respond to climatic changes, Robertson said.

Currently, around 35 million people rely on the Great Lakes for drinking water, and an additional 56 billion gallons are extracted each day for municipal, agricultural, and industrial use.

Those staggering numbers are likely to increase, Rood said, as people displaced from other regions of the country by climate-related impacts seek refuge in the Great Lakes Megalopolis.

"Compared to some places, like south Florida, the Great Lakes are going to look like a climate winner," Rood said. "We need to be prepared for how those migrations will change our communities and water usage in the coming decades."

Long Live the Great Lakes

The long-term trajectory of large freshwater lakes often depends on their outlet: Endorheic, or terminal, lakes such as the Great Salt Lake have no exit to another body of water, and the majority of their water balance is lost through evaporation, making them saltier over time.

The Great Lakes are not an endorheic basin; the outlet that connects them to the Atlantic Ocean has a 535-million-year-old history that's unlikely to peter out anytime soon. The Saint Lawrence Seaway, along with the basins that hold Lakes Erie and Ontario, sits inside the Saint Lawrence Rift, a 1,000-kilometer-long scar that dates back to the opening of the Iapetus Ocean between the paleocontinents of Laurentia, Baltica, and Avalonia.

Unlike the long dead and buried Midcontinent Rift System, the Saint Lawrence Rift System is still seismically active, capable of generating earthquakes with magnitudes 5 or greater. As long as water flows into the Great Lakes Basin and out through the Saint Lawrence Seaway, the Great Lakes are likely to retain their status as the world's largest—and hopefully freshest—lakes for eons to come.

By **Mary Caperton Morton** (@theblondecoyote), Science Writer

Living in Geologic Time *is a series of personal accounts that highlight the past, present, and future of famous landmarks on geologic timescales.*

Are Geysers a Signal of Magma Intrusion Beneath Yellowstone?

Steamboat Geyser erupts on 4 June 2018. Credit: Jamie Farrell, USGS

Steamboat Geyser in Yellowstone National Park is an enigma. It is the tallest currently active geyser in the world, sometimes blasting superheated water over 90 meters (300 feet) into the air. Yet unlike the more famous Old Faithful, Steamboat Geyser runs on its own rhythm. Sometimes the geyser is quiet for decades and then suddenly bursts back to life. It is a mystery exactly why Steamboat has such behavior. After a new period of activity that started in 2018, we might have more clues about what drives these steam-and-water explosions.

Yellowstone caldera is a geologic wonderland. It is the source of three of the largest explosive eruptions in the past 3 million years. The caldera itself covers over 1,500 square kilometers (580 square miles) in the northwestern corner of Wyoming. As Charles Wicks from the U.S. Geological Survey (USGS) put it, "Yellowstone's roots seem to extend all the way to the core-mantle boundary. In that dimension, it's a magmatic system of continental scale."

Yellowstone caldera is packed with geothermal features like geysers, hot springs, mud pots, and geothermal pools. This hydrothermal activity is driven by the vast reservoirs of heat beneath the Yellowstone area, most of which comes from the magma found many kilometers underneath the caldera. All of this heat and water cause the land surface at Yellowstone to rise and fall frequently, meaning that Yellowstone is best described as a "restless caldera."

Modeling a Deformation

A new study by Wicks and colleagues in the *Journal of Geophysical Research: Solid Earth* examines this restless behavior to try to understand what drives the deformation and how it might be linked to Steamboat Geyser. (see bit.ly/magma-intrusion). It turns out that the rising and falling of the land, the behavior of some geysers, and the introduction of new magma underneath Yellowstone could all be linked.

The north rim area and caldera floor at Yellowstone have been deforming for decades. The ability to monitor this deformation has greatly improved with GPS and interferometric synthetic aperture radar techniques. Wicks and others looked at the North Rim Uplift Anomaly (NRUA) and used deformation data from these techniques to model potential sources of these changes.

Magma, volatiles released from magma, or hydrothermal fluids could all cause the surface to rise or fall. Wicks and others used data from 2000 to 2018 to examine how much the NRUA either inflated or deflated. What they found is that the deformation in the NRUA may represent the accumulation of magmatic volatiles from a basaltic intrusion that occurred around 2000.

Steamboat Geyser might be a pressure gauge for these intrusions and accumulations of volatiles. The geyser is in the midst of one of its most active periods on record, having erupted 79 times between 2018 and 1 July 2020. This activity appears to correlate with the deformation cycle in the NRUA, which to Wicks suggests a connection between the cause of the deformation (magmatic volatiles) and Steamboat Geyser.

Small Sample Size

Mike Poland, scientist-in-charge of the USGS Yellowstone Volcano Observatory who was not involved in the study, thinks that the connection is more complicated: "Why would just a single geyser respond to processes beneath Norris [Geyser Basin]? Wouldn't that impact all the geysers?" One explanation might be that Steamboat Geyser likely has a more complex and deeper system than many geysers at Yellowstone.

Wicks admitted that so far, scientists have a limited data set for Steamboat Geyser. "With only two episodes of observed deformation near Norris, the eruption frequency appears to respond to the surface deformation. Of course, that's a very small sample size, so the apparent connection might be happenstance," he said. Any connection between Steamboat Geyser's activity and the accumulation of gases near the surface could heighten the risk of hydrothermal explosions, one of the most significant geologic hazards for tourists visiting the national park.

Wicks suggested that the ability to have constant geochemical monitoring of the hydrothermal fluids from geysers and hot springs would help scientists create more accurate models: "Continuous monitoring of volatile flux rates is really needed to put the geophysical models in context. If surface inflation is caused by accumulation of pressurized fluids and deflation occurs when those fluids escape to the surface, we might be able to detect changes in volatile flux over time."

The ability to link deeper processes like magmatic intrusion with surface phenomena is tantalizing for geoscientists monitoring an active caldera like Yellowstone. Wicks and Poland both agreed that understanding the connection between the magmatic and hydrothermal systems at Yellowstone is fundamental for better hazard models. They might end up being more directly linked than geoscientists have previously thought.

By **Erik Klemetti** (@eruptionsblog), Science Writer and Associate Professor of Geosciences, Denison University, Granville, Ohio

How Machine Learning Redraws the Map of Ocean Ecosystems

On land, it's easy for us to see divisions between ecosystems: A rain forest's fan palms and vines stand in stark relief to the cacti of a high desert. Without detailed data or scientific measurements, we can tell a distinct difference in the ecosystems' flora and fauna.

But how do scientists draw those divisions in the ocean? A new paper has proposed a tool to redraw the lines that define an ocean's ecosystems, lines originally penned by the seagoing oceanographer Alan Longhurst in the 1990s. The paper uses unsupervised learning, a machine learning method, to analyze the complex interplay between plankton species and nutrient fluxes. As a result, the tool could give researchers a more flexible definition of ecosystem regions.

Using the tool on global modeling output suggests that the ocean's surface has more than 100 different regions or as few as 12 if aggregated, simplifying the 56 Longhurst regions. The research could complement ongoing efforts to improve fisheries management and satellite detection of shifting plankton under climate change. It could also direct researchers to more precise locations for field sampling.

Beyond the Human Eye

Coccolithophores, diatoms, zooplankton, and other planktonic life-forms float on much of the ocean's sunlit surface. Scientists monitor plankton with long-term sampling stations and peer at their colors by satellite from above, but they don't have detailed maps of where plankton live worldwide.

Models help fill the gaps in scientists' knowledge, and the latest research relies on an ocean model to simulate where 51 types of plankton amass on the ocean surfaces worldwide. The latest research then applies the new classification tool, called the systematic aggregated ecoprovince (SAGE) method, to discern where neighborhoods of plankton and nutrients appear.

The SAGE method relies, in part, on a type of machine learning algorithm called unsupervised learning. The algorithm's strength is that it searches for patterns unprompted by researchers.

To compare the tool to a simple example, if scientists told an algorithm to identify shapes in photographs like circles and squares, the researchers could "supervise" the process by telling the computer what a square and a circle look like before it began. But in unsupervised learning, the algorithm has no prior knowledge of shapes and will sift through many images to identify patterns of similar shapes itself.

Using an unsupervised approach gives SAGE the freedom to let patterns emerge that the scientists might not otherwise see.

"While my human eyes can't see these different regions that stand out, the machine can," first author and physical oceanographer Maike Sonnewald at Princeton University said. "And that's where the power of this method comes in." This method could be used more broadly by geoscientists in other fields to make sense of nonlinear data, said Sonnewald.

Desert of the Ocean

Applied to model data, SAGE noted 115 distinct ecological provinces, which can then be boiled down into 12 overarching regions.

One region appears in the center of nutrient-poor ocean gyres, whereas other regions show productive ecosystems along coasts and the equator.

"You have regions that are kind of like the regions you'd see on land," Sonnewald said. One area in "the heart of a desert-like region of the ocean" is characterized by very small cells. "There's just not a lot of plankton biomass." The region that includes Peru's fertile coast, however, has "a huge amount of stuff."

If scientists want more distinctions between communities, they can adjust the tool to see the full 115 regions. But having only 12 regions can be powerful too, said Sonnewald, because it "demonstrates the similarities between the different [ocean] basins." The tool was published in the journal *Science Advances* (see bit.ly/sage-method).

Oceanographer Francois Ribalet at the University of Washington, who was not involved in the study, hopes to apply the tool to field data when he takes measurements on research cruises. He said that identifying unique provinces gives scientists a hint of how ecosystems could react to changing ocean conditions.

"If we identify that an organism is very sensitive to temperature, then we can start to actually make some predictions," Ribalet said. Using the tool will help him tease out an ecosystem's key drivers and how it may react to future ocean warming.

By **Jenessa Duncombe** (@jrdscience), Staff Writer

Weathering Environmental Change Through Advances in AI

The world's need for accurate, usable predictions of atmospheric and oceanic phenomena—and their impacts—has never been greater. Climate change is affecting weather patterns and sea levels are rising, putting more and more people at risk from environmental disasters. At the same time, the quantity and quality of modeling systems and Earth observations—from satellite platforms, cell phones, connected vehicles, and many other sources—are increasing dramatically, offering a deluge of data so rich that only automated intelligent systems can fully exploit them.

Improving society's long-term sustainability with respect to limited environmental resources while ensuring health and safety is a "wicked problem," a term coined to describe complex real-world challenges that have severe societal consequences, cannot be studied by trial and error, and do not have clear-cut solutions. Addressing this wicked problem effectively will require new artificial intelligence (AI) methods for knowledge discovery and prediction driven by convergent collaborations across multiple sectors involved in research and enterprise.

Convergent research could lead to the development of trustworthy artificial intelligence methods based on environmental data that help individuals, officials, and others make quick decisions during high-impact events like tornadoes. Credit: sshepard/E+/Getty Images

Artificial intelligence is poised to help us harness the power of the big-data frontier by exploiting untapped environmental observations and enhancing Earth system modeling in cost-effective ways.

Collaborating to Tap AI's Potential

Currently, less than 5% of available environmental observational data are used in numerical models of Earth systems. Better models that leverage additional data are essential to improving our understanding of and ability to predict atmospheric and oceanic phenomena and their impacts, as well as to assist individuals, businesses, and governments in making better decisions to reduce harm to people, livelihoods, ecosystems, and economies.

AI has demonstrated value throughout the observing, predicting, and impact modeling process, from preprocessing to postprocessing and improving forecasts. And with recent computational hardware innovations like graphics processing units (GPUs) and tensor processing units, as well as innovations in AI methods themselves, AI is poised to help us harness the power of the big-data frontier by exploiting untapped environmental observations and enhancing Earth system modeling in cost-effective ways.

Developing AI approaches that revolutionize our understanding of and ability to predict a wide range of environmental phenomena accurately, and that address society's needs in the process, calls for a convergent effort across research and operational sectors. Each sector provides unique expertise, resources, and viewpoints that when deeply collaborating, can result in synergistic and substantial progress.

Broadly speaking, academia provides rich expertise and research programs that with funding from government or industry can sustain their focus on a problem for many years. Academia also trains new generations of scientists, engineers, and policy makers. Both industry and government benefit when students develop appropriate interdisciplinary knowledge and skills and gain experience with hands-on problem-solving.

To achieve environmental and public health goals, governments develop and enforce laws, policies, and regulations informed by environmental sciences. They provide long-term funding for research and development in science deemed essential to the public interest, and coordination at a scale otherwise unachievable. Governments are uniquely able to deploy large-scale, long-term operational environmental sensing systems such as radar, satellite, and buoy networks. Within the U.S. weather enterprise, the federal government also employs and trains forecasters and has the primary responsibility to issue watches and warnings.

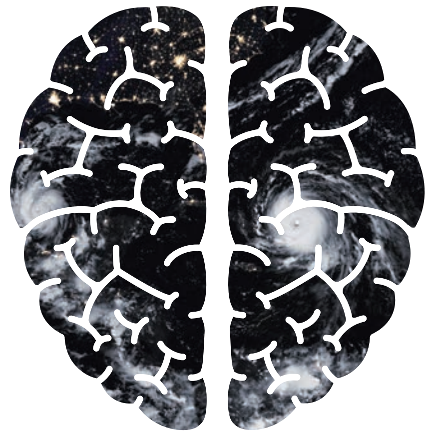
Opposite: Unsplash/Marek Okon

The private sector has a wide reach and a profit motive to rapidly develop and implement new technology that can help people, organizations, and governments make better decisions. The private sector can often move more quickly and with more flexibility than other sectors, which can lead to faster adaptation. However, this agility is often driven by quarterly financial reports, which can make it difficult to devote internal resources to lengthy research projects that may take years to mature. Partnering with academia and government allows industry to identify problems of high practical value, to fund and guide external research and development, and to adopt resulting products that prove valuable and widely useful. Many private companies can also offer collaborators access to unique data and computational resources.

Multinational companies like IBM and Google are deeply ingrained in nearly every industry and have global perspectives on what environmental science information is needed and actionable, on what timescales, as well as on how this information can be distributed efficiently to the media, the public, or individual clients. These companies typically focus on simplicity and pragmatism, cost-benefit ratios, data latency, user experience, and maintainability more than academia and government do. Injecting this perspective into academic and government research and development helps ensure that high-value knowledge is developed and that methods, software, and algorithms are suitable for quick and effective use, including in commercial tools and industry-specific decision platforms. New types of deep collaboration have the potential to accelerate such research-to-operations transitions.

Trustworthy AI for Environmental Sciences

Realizing the full potential of AI to yield improved understanding and predictions of environmental phenomena requires convergent research to develop methods that earn the trust of decision-makers, including individuals, households, business owners and private companies, and officials at all levels of government. This trustworthiness is especially critical for extreme and high-impact environmental phenomena—ranging from tornadoes to heavy snowfall during rush hour—in which life-or-death and other protective decisions must be made quickly and reliably. Having skillful, user-trusted AI predictions of these hazards can, for example, help people decide when to take shelter or when they should (or should not) drive.



Artificial intelligence can help put the massive and growing amount of Earth observations to use in creating accurate, usable predictions of atmospheric and oceanic phenomena and in improving society's long-term sustainability. Credit: NASA Earth Observatory (image); J. Henry Pereira (design)

What makes environmental science AI methods trustworthy to different stakeholders varies depending on their expertise and experience, however, and it is important to understand their diverse viewpoints. Generally, physical and computer science researchers in academia pay more attention to the theoretical performance of AI-based models and less to human aspects of trust. AI researchers develop new models and score them using objective metrics. Meteorologists also use performance diagrams and case studies, examining an algorithm's ability to reproduce observations and effects of known past events, often extreme or societally impactful events, to assess an AI model's performance. Although AI researchers generally evaluate new models in a research setting, operational meteorologists care about what additional guidance value and physical consistency the algorithm provides in comparison with the other sources of information available to them.

Definitions and metrics for assessing reliable and trustworthy methods can be very different for private industry and government. Government forecasters may prioritize the reliability of AI techniques across weather regimes, for example, whereas private industry is incentivized to ensure that products are tailored to specific clients, with client needs driving the measures of trustworthiness.

By working across sectors and disciplines, the applied needs of end users in government and industry drive the development of new fundamental tools and techniques. Academics have developed tools such as explainable AI, which enables researchers to dive into the black box of machine learning methods and highlight what the models have learned, as well as interpretation and visualization techniques. But these tools have most often been tested on novices or on high-level users, such as other researchers, rather than on decision-making end users in government and industry. Critical end user feedback should help clarify design choices and priorities for future explainable AI systems.

Developing AI tools that earn the trust of all types of end users requires fundamental research on their different needs and perceptions. Identifying these varying needs and learning more about the dynamics of communicating model results and uncertainty, as well as about users' risk perceptions and trust in AI, are essential to the success of AI integration across disciplines and sectors.

Cross-Sector Collaboration in Action

Integrative approaches have already proven successful as force multipliers in a variety of efforts.

In the U.S. Great Plains, hailstorms cause significant property damage each year. The University of Oklahoma collaborated with the U.S. National Oceanic and Atmospheric Administration's (NOAA) Storm Prediction Center (SPC) to operationalize AI hail forecasting, producing hail forecasts 12–36 hours in advance. Operational forecasters (the meteorologists who produce weather reports like those seen on the news) considered the early AI-generated hailstorm probabilities produced by this system to be too high compared with forecasts traditionally issued by NOAA's SPC. As a consequence, the AI forecasts were rethought and reformulated to produce probabilistic forecasts that were more in line with what human forecasters expected. This collaboration highlighted the need to work closely with end users to develop AI that they consider trustworthy.

In a collaboration among academic organizations, federal and state agencies, and the private sector, Texas A&M University–Corpus Christi created an operational AI-based forecasting system to help save sea turtles that found themselves in cold water along the Texas coastline. Strong cold fronts can decrease water temperatures quickly in coastal bays and lagunas. As a result, thousands of threatened and endangered sea turtles can become lethargic and require rescue to survive. AI-based water temperature predictions allow managers to anticipate impacts on sea turtles and save most of them by mobilizing resources, gathering and organizing volunteers, diverting watercraft, and interrupting other coastal activities such as shipping. By developing a reliable AI method through collaborations and agreements among the relevant federal, state, and local governments and the private sector, researchers have significantly reduced sea turtle deaths.

On the other side of the world, Google is collaborating with the government of India to provide end-to-end flood forecasts, including AI-based precipitation forecasting and hydrological and inundation modeling. A partnership between the Indian Central Water Commission and Google Crisis Response delivers alerts. When AI is integrated into the warning system, these alerts are more personalized to individual users and their specific locations and needs. More than 1.5 million alerts were issued in 2019, and there are plans to expand coverage tenfold in 2020.

AI approaches can also make hyperlocal weather forecasts accessible to more regions around the world. In a multiyear effort, IBM worked with the National Center for Atmospheric Research (NCAR) and the American technology company Nvidia to optimize NCAR's state-of-the-art Model for Prediction Across Scales (MPAS) weather model to run on a GPU-equipped POWER9 supercomputer. IBM also worked with the University of Washington to develop AI methods to clean and correct millions of pressure measurements gathered from opted-in cell phone users so the measurements could be assimilated into the model. The resulting IBM Global High-Resolution Forecast System (IBM GRAF) runs hourly and produces forecasts at 3-kilometer resolution. This type of high-resolution, rapidly updating forecast was previously available only in industrialized countries but is now available to consumers and businesses around the world, including more than 300 million users of the Weather Channel mobile app.

Although some of these collaborations are just beginning, they highlight the ability of convergent multisector research to create trustworthy AI, enabling improved understanding and prediction of a broad range of environmental phenomena. These tools will be useful to decision makers for years to come, helping improve the sustainability and safety of our world.

Acknowledgments

The views expressed here are those of the authors and do not necessarily represent those of their employers, NOAA, or the U.S. government.

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▶ **Read the article at bit.ly/Eos-AI**

A GREENER EARTH MODEL

BY RICHARD LOFT

As weather and climate models grow larger and more data intensive, the amount of energy needed to run them continues to increase. Are researchers doing enough to minimize the carbon footprint of their computing?

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SOME PROJECTIONS INDICATE THAT BY 2030, ELECTRICITY USAGE BY COMMUNICATION TECHNOLOGY COULD CONTRIBUTE UP TO 23% OF GLOBAL GREENHOUSE GAS EMISSIONS.

Recently, the National Center for Atmospheric Research (NCAR), where I serve as director of technology development in the Computational and Information Systems Laboratory, conducted a carbon footprint analysis. The organization was quite pleased with the results, until it realized that the analysis neglected to account for carbon dioxide emissions related to the lab's modeling activities. When these emissions were included, the overall picture looked considerably less green.

How could this oversight have happened? In part, it's because modern society is very good at obscuring the environmental impacts of its activities, whether these are impacts from food production, manufacturing, or many other activities. The same is true of the information technology (IT) industry. Carbon dioxide emissions from the IT industry already rival those of the prepandemic airline industry, and some projections indicate that by 2030, electricity usage by communication technology could contribute up to 23% of global greenhouse gas emissions [*Andrae and Edler,* 2015].

In his book *How Bad Are Bananas? The Carbon Footprint of Everything,* Mike Berners-Lee estimates that the energy required to transmit a typical email generates 4 grams of carbon dioxide equivalents. That number may give pause to some, while for others it may represent an acceptable cost of doing business in the modern world. Regardless, unlike a gasoline-powered car with an exhaust pipe, there's nothing about the act of sending an email that makes it obvious that we're causing carbon dioxide emissions, so the environmental cost is easy to overlook. With the continuing growth of cloud computing and the Internet of Things, more emissions, like those from computing and the communication of data, will be further virtualized.

Within the Earth system sciences (ESS) community, many initiatives around the world are planning the next generation of global weather and climate models that will be capable of resolving storms and, ultimately, clouds. Examples of these include the Climate Modeling Alliance (CliMA) model, the Energy-efficient Scalable Algorithms for Weather and Climate Prediction at Exascale (ESCAPE-2) model, and the Energy Exascale Earth System Model (E^3SM). The repeated calls from the community [*Shukla et al.,* 2010; *Palmer,* 2014] to build powerful supercomputing machines to tackle long-standing model biases in the water cycle and improve predictions seem to be coming to fruition. All of these long-running, high-resolution models, and the big computers needed to run them, will require investments from governments and philanthropic organizations. For example, in February, the United Kingdom announced £854 million in funding to develop its next-generation computer, and the U.S. National Oceanic and Atmospheric Administration announced that it was tripling the size of its investment for weather- and climate-related computing.

In this context, the ESS community should consider the question, What is our collective responsibility to reduce carbon emissions related to these large-scale modeling activities?

Leading by Example

In discussions with colleagues, three counterarguments have been offered: first, that weather and climate modeling activities are only a small contributor to societal emissions overall; second, that ESS research is too important to let it be slowed by these considerations; and third, that even raising the subject of emissions from ESS computing provides ammunition to both ends of the political spectrum to attack the research goals.

The central processing unit–based Cheyenne supercomputer, went into service in 2017 at the National Center for Atmospheric Research (NCAR)–Wyoming Supercomputing Center. Credit: University Corporation for Atmospheric Research (UCAR), Carlye Calvin, CC BY-NC 4.0 (bit.ly/ccbync4-0)

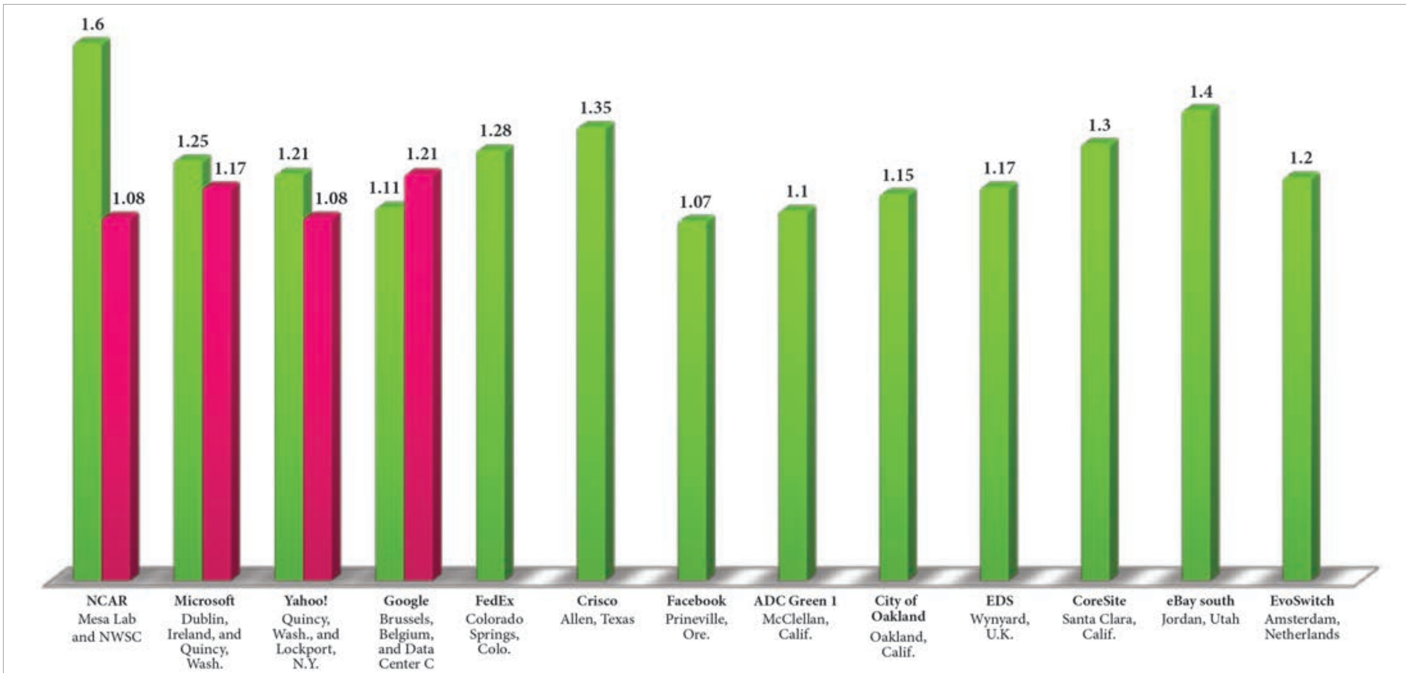

Fig. 1. A comparison of power usage efficiency (PUE) at a variety of energy-efficient data centers. All of these data centers were built within the past few years, with the exception of NCAR's Mesa Laboratory, which was built in 1967. The average PUE in 2019 among more than 600 data centers surveyed by the Uptime Institute was 1.67.

To be sure, studying the impacts of human activity on our planet is both an important and, of late, a risky area of research: Scientists studying climate, for example, are frequently caught in political crosshairs and are also subjected to trolling and other forms of harassment. But the first two arguments above sound like rationalizations that might be made by anyone when they are first confronted with their carbon footprint.

Certainly, it seems this is an opportunity for the ESS community to lead by example. So perhaps a more productive question is, Have we done everything we can to minimize the carbon footprint of our computing activities?

In answering this question, it's useful to separate considerations about decarbonizing utilities from those of reducing the "energy to solution," a metric for comparing high-resolution atmospheric models that accounts for the total energy needed to run a model simulation from start to finish [*Fuhrer et al.,* 2018]. In this way, questions about the merits of carbon offset schemes or the locations of facilities, for example, can be considered apart from questions about how to reduce the energy consumed by our research activities.

Components of Computing's Carbon Footprint

Energy sources: Switching to renewable energy sources like wind, solar, and biogas must be part of the solution to mitigate climate change, and we should laud and try to emulate organizations that do so. It is worth considering, however, that the environmental side effects of a future decarbonized energy portfolio are not well understood [*Luderer et al.,* 2019], and switching to renewable energy sources often means buying credits, which can be traded, thereby obfuscating the actual source of the energy powering a computing facility.

THIS IS AN OPPORTUNITY FOR THE ESS COMMUNITY TO LEAD BY EXAMPLE. HAVE WE DONE EVERYTHING WE CAN TO MINIMIZE THE CARBON FOOTPRINT OF OUR COMPUTING ACTIVITIES?

In the meantime, one way to address the problem without creating more problems or sacrificing transparency is to improve the efficiency of the modeling enterprise. This idea is perhaps best expressed by the Japanese expression "mottainai," often interpreted to mean "waste not, want not."

We can consider the challenge of improving the energy efficiency of modeling as an infrastructure stack to be optimized, where the components are the computing facilities (the data center), the computing infrastructure (the computer and data system), the software (the model), and the data motion (the workflow).

Computing facilities: According to a recent report from the Uptime Institute, "Efforts to improve the energy efficiency of the mechanical and electrical infrastructure of the data center are now producing only marginal improvements. The focus needs to move to IT." The commonly used measure of facility efficiency is power usage efficiency (PUE), which is basically the total power a facility uses divided by the power used to run the infrastructure within the facility. Whereas older computing facilities still have room for improvement in PUE, recently built data centers are, for the most part, already quite efficient (Figure 1). For example, the NCAR-Wyoming Supercomputing Center (NWSC), which my organization operates for the ESS research community on behalf of the National Science Foundation, has a PUE of 1.08, meaning that if the facility were perfect, with no energy usage overhead, it would yield only an 8% improvement in PUE compared with its present state. Still, as efficient as it is, since the facility's commissioning in 2012, the computers that NWSC houses have emitted roughly 100,000 metric tons of carbon dioxide—roughly the mass of a modern aircraft carrier. In such cases, the best path to further optimization isn't the facility.

Computing infrastructure: Supercomputers on the scale that will be required for high-resolution Earth system models are being deployed by the U.S. Department of Energy.

The Summit supercomputer at Oak Ridge National Laboratory and the planned Aurora system at Argonne National Laboratory, for example, will each consume on the order of 10 megawatts, annually producing carbon dioxide emissions equivalent to those from more than 30,000 round-trip flights between Washington, D.C., and London (calculated using the Avoided Emissions and Regeneration Tool (AVERT) and the MyClimate initiative). Using values of standard system performance benchmarks—specifically the High Performance Conjugate Gradients (HPCG) and High Performance Linpack (HPL) benchmarks—from published sources, such as the top500.org list of the 500 fastest supercomputers, we find, for example, that the graphics processing unit (GPU)-based Summit supercomputer system is 5.7 and 7.2 times more power efficient on HPCG and HPL, respectively, than NCAR's roughly contemporaneous central processing unit (CPU)-based Cheyenne system at NWSC. GPUs look like an energy-efficient alternative to CPUs for reducing energy to solution.

The software: In its report, the Uptime Institute notes that optimizing energy-efficient software is the least frequently used best practice suggested by the European Code of Conduct (CoC) for Data Centre Energy Efficiency. Could Earth system models, which have been designed to run on CPUs predominantly, be optimized for GPUs? Experience with atmospheric models that have been adapted, or ported, to run on GPUs, like the Consortium for Small-scale Modeling (COSMO) model and most recently the Model for Prediction Across Scales (MPAS), has shown that significant energy savings can be achieved. However, refactoring legacy models for GPUs is labor intensive, creating an obstacle to this potential energy savings. And because of the substantial complexity of ESS code, Earth system modelers have not shown much appetite for adopting these power-efficient devices.

Data motion: Also relevant to the carbon footprint of ESS modeling is data motion. Moving a petabyte of data around a data center requires roughly the amount of energy contained in half a barrel of oil; burning this much oil produces about 215 kilograms of carbon dioxide emissions. These figures explain the economics of Amazon's Snowmobile, a low-tech but effective "sneakernet" solution to the big-data problem in which a data center on wheels—in the form of a semitruck—plugs in to your data center, transfers data to onboard storage devices, and drives them to Amazon for storage in the cloud. Yes, it is actually more efficient and faster to load data into a truck and drive them across country than to transfer them via the Internet. Given that a single 1-kilometer 3D atmospheric field will produce roughly half a terabyte in single precision, data movements of this magnitude surely will be required routinely in an exascale computing complex.

The Path to Efficiency

I propose five steps the ESS modeling community should take to move toward a more energy efficient and lower-emissions future.

First, although many modern computing centers are already very efficient, there may still be ways to improve PUE of older facilities that should be examined. Also, when possible, use renewable energy sources to power facilities.

Second, regarding modeling software, you can't improve what you don't measure. Publishing the energy consumed per simulated day when reporting benchmarking results, particularly for high-resolution models requiring large-scale computing resources, would help raise awareness about energy efficiency in ESS modeling, and through competition could foster developments leading to further energy savings. This approach should be integrated into existing model intercomparison projects, such as the Dynamics of the Atmospheric General Circulation Modeled on Non-hydrostatic Domains (DYAMOND) initiative from the Centre of Excellence in Simulation of Weather and Climate in Europe.

EXPERIENCE WITH ATMOSPHERIC MODELS THAT HAVE BEEN ADAPTED, OR PORTED, TO RUN ON GPUS HAS SHOWN THAT SIGNIFICANT ENERGY SAVINGS CAN BE ACHIEVED.

Third, porting existing models to, and developing models for, new computing architectures must be made easier. Researchers seeking to program the current generation of energy-efficient GPUs can attest to the difficulty of achieving this feat. This difficulty comes from multiple sources: the inherent complexity of Earth system model codes, the lack of workforce trained in programming new technology, the underresourcing of such programming efforts, and the inherent architectural complexity of the heterogeneous computing systems currently available.

Fourth, chip manufacturers and supercomputer vendors should make it easier for users to measure the actual amount of power drawn during execution of models. For some models, the actual power draw can be as much as 40% less than the "nameplate" power of the systems on which they're run. Currently, the tools to make these measurements are often poorly documented and are architecture dependent. They are also typically used only by computer science teams.

Fifth, the ESS community should increase research into techniques that could lead to energy savings, including reducing floating point precision computation; developing machine learning algorithms to avoid unnecessary computations; and creating a new generation of scalable numerical algorithms that would enable higher throughput in terms of simulated years per wall clock day.

Achieving higher scientific throughput with reduced energy consumption and reduced emissions is a mottainai approach that is not only defensible but is also one of which everyone in the ESS community could be proud.

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CREATING DATA TOOL KITS THAT EVERYONE CAN USE

BY ZHONG LIU, VASCO MANTAS, JENNIFER WEI, MENGLIN JIN, AND DAVID MEYER

Earth scientists need to make the growing wealth of data more accessible and build data services meant for interdisciplinary use.

As Earth science and the technologies it uses evolve and improve, the data and services that support the science also change and become more complex, often spanning multiple disciplines. The ability to easily find and seamlessly access these data and services in an open and integrated environment is essential to facilitating interdisciplinary research and applications and to broadening data user communities.

The sheer amount of available data is growing rapidly as the science community adopts the Findable, Accessible, Interoperable, and Reusable (FAIR) data principles [*Wilkinson et al.*, 2016] and emerging technologies such as cloud computing. Even with recent advances in data archiving and services (e.g., more data sets and related information are available online with customized data services and multiple data access methods), accessing heterogeneous inter-

Multiple special or discipline-oriented tools, often with steep learning curves, are required to handle heterogeneous, complex, and evolving Earth science data sets in interdisciplinary research and applications. Credit: Pixabay/Deborah Breen Whiting disciplinary data sets (e.g., those with nonuniform data types and formats) still poses challenges to users globally.

To address these challenges in Earth science interdisciplinary data services, we organized and led sessions titled "Data and Information Services for Interdisciplinary Research and Applications in Earth Science" at AGU Fall Meetings 2018 and 2019; at both meetings, this was one of the largest of the Earth and Space Science Informatics sessions. Groups of international participants presented data, tools, and services for Earth science interdisciplinary research and applications, as well as work on other topics related to big data, artificial intelligence (AI), machine learning (ML), and natural language processing.

Six Challenges

As a result of the presentations, discussions, and feedback from our AGU Fall Meeting sessions, we identified the following questions that address challenges in making Earth science data and data services more accessible and useful:

- How can we make Earth science interdisciplinary data sets needed for a specific research project or application easier to find?
- How do we eliminate the need for the many special tools, some with steep learning curves, that are currently required to handle heterogeneous and interdisciplinary data sets?
- What data services can we provide in the cloud environment, where unprecedented access to data sets and data analytics is available?
- What data services can we provide to facilitate AI/ML activities?
- How can we collect metrics to help development and enhancement of data services and to benchmark the performance and societal impacts of a project or mission?
- How do we ensure the scientific reproducibility of Earth sciences research?

Finding and Accessing the Data

Data users typically consult various sources (e.g., the Internet, conference proceedings, colleagues, professors) to find where data are archived and distributed among many repositories around the world. However, access websites for different data resources are often designed differently, and as a result, only those who are already familiar with the repositories can easily locate data sets and information. Finding the right data and information for a specific research project or application is another challenge, especially for inexperienced data users who may not be familiar with data sets outside their own disciplines and for people searching across disciplines.

The variety of access website designs can impede data and information searches by users who are unfamiliar with specific repositories. For example, NASA's Earth Observing System Data and Information System (EOSDIS) has 12 discipline-oriented Distributed Active Archive Centers (DAACs) that archive and distribute NASA Earth data sets from satellite missions and projects, each with its own unique web interface. For users doing interdisciplinary research that requires data from multiple DAACs, it can be difficult to become familiar with all of the interfaces.

One solution is to develop an integrated and uniform web interface for data access. At present, NASA EOSDIS is developing such an interface, called Earthdata, which serves as a gateway for all data sets and services at the 12 NASA DAACs. When the interface is finished, users will be able to search all NASA Earth science data, along with data services and information, in one place. Building this type of one-stop shop for accessing complex and heterogeneous data, services, and information is a major challenge in improving interdisciplinary research and applications.

Access websites for different data resources are often designed differently, and as a result, only those who are already familiar with the repositories can easily locate data sets and information.

Another barrier to easy access is that discipline-oriented websites currently exist for their own special disciplinary requirements. To unify these different websites, an integrated data system must address both general and discipline-specific requirements. On a larger scale, Earth science data from various U.S. federal agencies, countries other than the United States, private companies, and citizen scientists must also be easily accessible in an integrated environment. Ideally, all of these data would be accessible without the need to visit different websites, but making this a reality requires collaboration from domestic and international data scientists, developers, and stakeholders to address such issues as disciplinary vocabulary, data standards, and usability.

At present, many websites rely on sorting and filtering of search results. In satellite data services, for example, search suggestions, research subject, measurement, satellite source, and processing level are often used to narrow the list of search results. Users' success in finding the data they need can vary significantly in such systems, depending on the web design, the users' knowledge, and many other factors. Websites that focus on a single project or mission and contain only a few data sets can eliminate the need for sorting or filtering. For more comprehensive resources, inexperienced users often need human assistants or a help desk to interact with them, find out more about what they need, and provide recommendations for data products or services. Therefore, incorporating human expertise with AI/ML technologies such as natural language processing in the system may improve the user experience of finding data for a specific need.

Simplifying the Tool Kit

Because interdisciplinary data sets are complex, and their formatting and data structures are not uniform, multiple tools are needed to handle such data sets for research and applications. For example, more than 61 data tools are available at the 12 discipline-oriented NASA DAACs for search and order; data handling; subsetting and filtering; geolocation, reprojection, and mapping; and data visualization and analysis. It can be a daunting task for a user to learn all of these tools for interdisciplinary activities.

Heterogeneous data can also present challenges to users and stakeholders without access to complex data set processing capabilities. For many users, acquiring dedicated software, using multiple tools, and performing programming-based data analyses are not viable. The use of standards like uniform data formatting may address the problem of heterogeneous data often requiring many tools to handle. Data tools that integrate more data processing capabilities may also help in reducing the number of tools. Meanwhile, data repositories can go beyond their existing services (e.g., providing original data as they are) by offering data interoperability services to provide data that meet users' research or application requirements with respect to data format, projection, model grid, and spatiotemporal resolution, for example.

Putting New Capabilities to Work

Cloud computing provides new opportunities to address issues related to the unprecedentedly large amount of data and data analytics available. Governmental and private organizations are putting significant efforts toward developing cloud-based data services. The NASA Goddard Earth Sciences Data and Information Services Center (GES DISC) plans to launch its popular online visualization and analysis tool Giovanni in the cloud, creating the potential to scale up and expand its current capabilities by, for example, including Earth science data sets from other NASA DAACs, improving performance, and providing new data analytics.

Best practices, including user-friendly features and services, should be carried over to the cloud environment. These practices can facilitate a smooth or seamless transition from on-premises data services to the cloud and ensure a satisfactory user experience in the cloud-based environment. One such initiative currently under development is the NASA EOSDIS Cumulus Project, a cloud-based framework for NASA EOSDIS data collections. This project is designed so that users will not notice any difference between on-site and cloud-based data services.

Cloud computing isn't the only area in which new technologies are introducing significant changes. In recent years, the Earth science community, like many other sectors and scientific fields, has experienced a surge in research and applications using AI/ML techniques. Identifying and adopting the features that data repositories can provide to facilitate AI/ML activities are pressing and challenging issues. For example, natural language processing–based data systems could simplify access for users who want only visualizations (e.g., images, maps), facts, or information. These systems handle the interactions between computers and humans using natural language—ordinary human speech in the form of voice or text rather than arcane computer commands. On the other hand, more advanced users expect data repositories to provide analysis-ready or customized data (e.g., training data) for AI/ML activities. Down the road, standard or customized AI/ML services—running AI algorithms such as deep learning or random forests, for example—can be integrated into data repositories, allowing users to conduct AI/ML activities without leaving the system. Cloud computing may be able to host such services in the future.

Measuring Performance and Impact

Data metrics are frequently used to measure user and system activities—data access and usage in research and applications, for example—that are related to the life cycle of a data set and play an important role in Earth science. For example, in the satellite community, data usage metrics are used to benchmark a mission's or project's success and its societal impacts.

Among their many applications, data metrics supply key information to satellite data service providers for designing new data services and improving existing ones. Satellite product developers rely on data metrics to understand how their products are used. Thus, collecting data metrics is an essential part of a satellite mission or project.

One key challenge is to develop metrics that accurately describe a wide range of data-related activities in research and applications. Another is to develop metric standards for different disciplines so that metrics are interoperable in interdisciplinary activities.

But Is It Reproducible?

Scientific reproducibility is a cornerstone of Earth science (and of all scientific fields). Providing trustworthy data and results is one of the most challenging and pressing issues in the science community. Reproducing Earth science research requires documentation of all elements in the life cycle, including data, algorithms, software, computing environment, and other factors.

Several research projects and workshops have focused on ways to improve reproducibility by, for example, collecting best practice guidelines—like the community guidelines for open and reproducible workflows that the geoscience research modeling community has worked to develop [*Mullendore et al.,* 2020]. Earth science users are also increasingly using open-source software, open standards, and services such as Jupyter Notebook to exchange workflows. For interdisciplinary research and applications, the scope is much larger, requiring participation and collaboration from the entire Earth science community and from stakeholders (e.g., journal publishers). Major challenges include the development of standards for the framework and for interoperability.

Going Far, Together

There are many challenges to improving Earth interdisciplinary data services. Emerging technologies like cloud computing and AI/ML can potentially enable significant progress in all aspects of interdisciplinary data services. However, tackling the challenges will also depend on active participation and collaboration from all involved parties in the community. In the wake of AGU Fall Meeting 2019, we are continuing our follow-up activities, which include assembling a special issue in the journal *Computers and Geosciences* (with a submission deadline of 15 September) to report current advances and address the challenges as well as planning another session at AGU Fall Meeting 2020.

Acknowledgments

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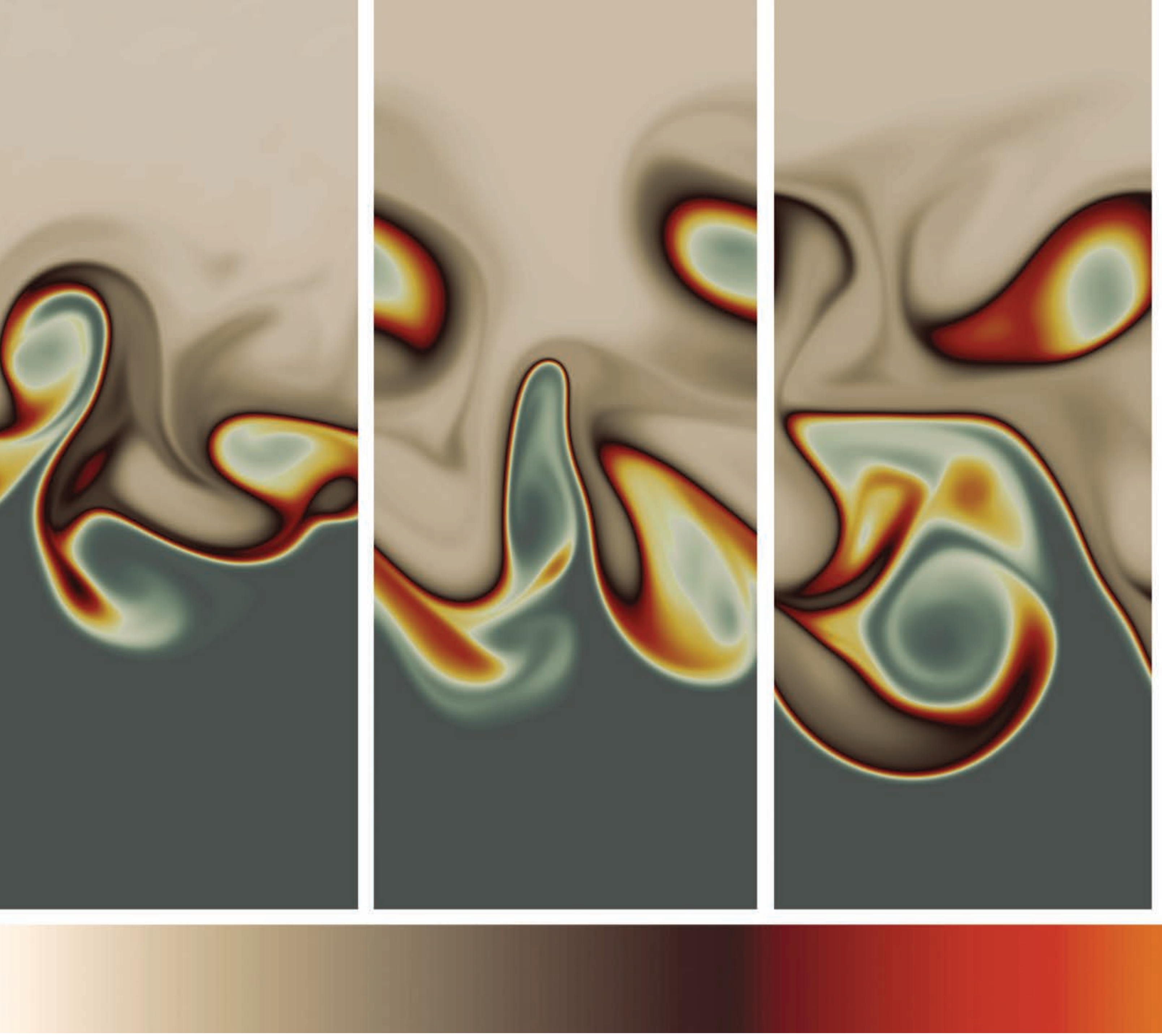
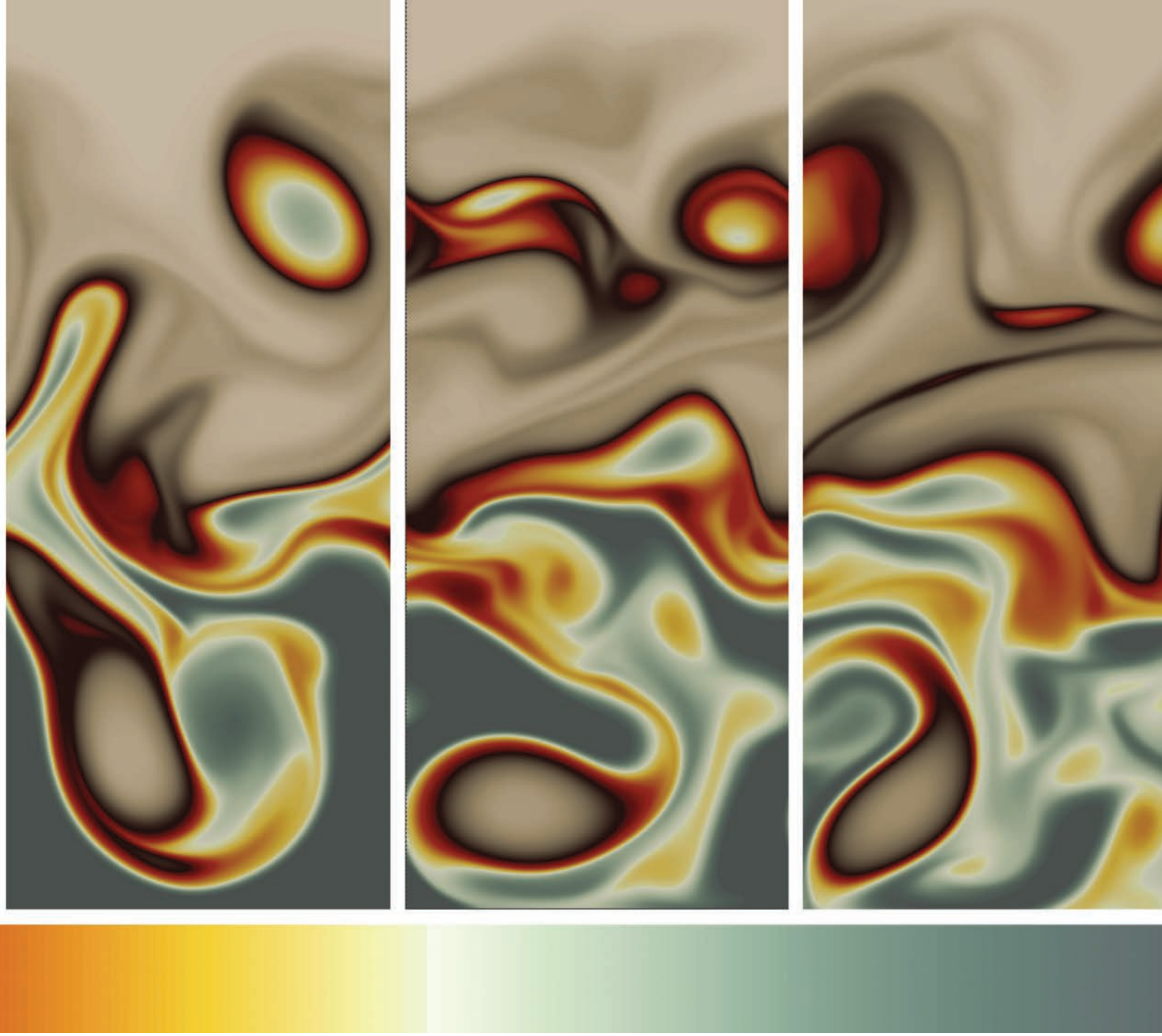


VISUALIZING SCIENCE: HOW COLOR DETERMINES WHAT WE SEE

By Stephanie Zeller and David Rogers



Color plays a major role in the analysis and communication of scientific information. New tools are helping to improve how color can be applied to data more accurately and effectively.

In a "wave" colormap like this one, selective saturation is used to isolate and "foreground" specific data ranges so these data are easier to follow over time. In the colormap, desaturated colors surround a saturated section to focus attention while providing context. Credit: Graphic created by Francesca Samsel with data processed and provided by M. Petersen, LANL, using MPAS-Ocean

Color strongly influences the way we perceive information, especially when that information is dense, multidimensional, and nuanced—as is often the case in scientific data sets. Choosing colors to visually represent data can thus be hugely important in interpreting and presenting scientific results accurately and effectively.

"Language is inherently biased, but through visualization, we can let the data speak for [themselves]," said Phillip Wolfram, an Earth system modeler and computational fluid dynamicist at Los Alamos National Laboratory. At Los Alamos, data visualizations are as ubiquitous as the sagebrush that embroiders the nearby desert. Every day, expert teams wrangle, render, and color encode swaths of data for interpretation with the lab's Earth and computer scientists. Choosing colors to represent various properties of the data, a step that ranges from an iterative, responsive process to a hasty afterthought, is the final barrier between painstaking data collection and well-anticipated analysis and discovery.

Most visualization software comes equipped with colormaps—a selection of standard color-encoding gradients that researchers can apply, in a matter of seconds, to display and evaluate their data. But not all data visualizations are created equal, and despite a proliferation of literature denouncing standard maps like the traditional rainbow colormap [e.g., *Borland and Taylor,* 2007], they pervade visualizations from basic bar graphs to complex depictions of biogeochemical data.

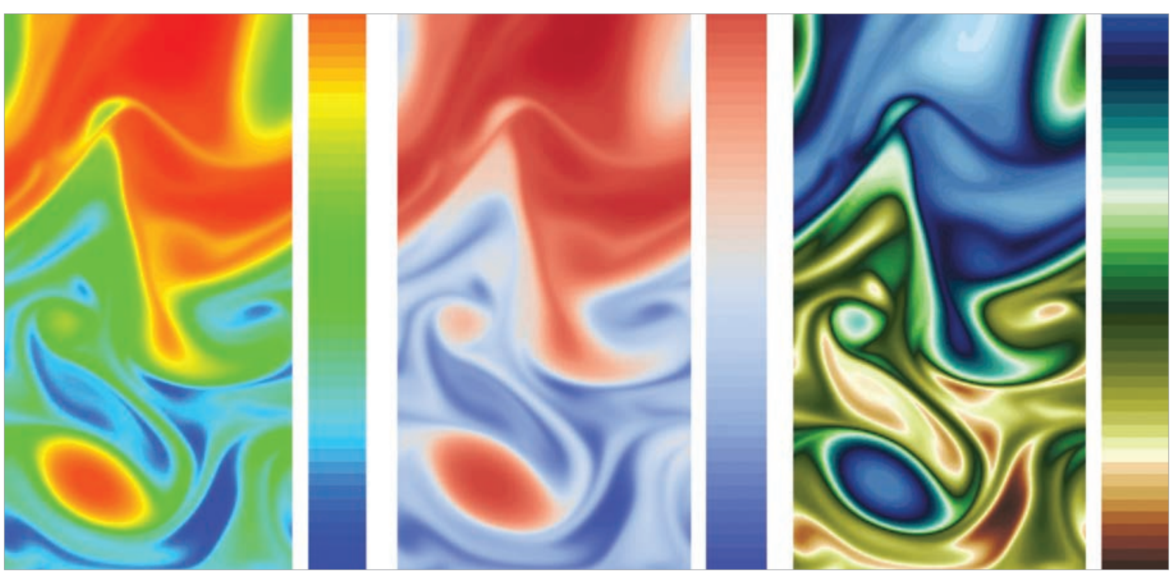
At AGU's Fall Meeting 2019, row upon row of posters in the convention center's vast main hall featured the same bright, standard colormaps adorning visualizations of temperature scales, chlorophyll concentrations, land elevations, and a host of other data.

"The same colormap applied to a diverse array of data gets monotonous and confusing," said Rick Saltus, a senior research scientist with the Cooperative Institute for Research in Environmental Sciences (CIRES) at the University of Colorado Boulder. "You're trying to communicate both effectively and efficiently, and that's impeded if the viewer is presented with a variety of concepts, all illustrated using identical color mappings."

Color researchers and visualization experts around the world are working to change this status quo. A number of groups are developing new tools to help scientists image increasingly complex data sets more accurately and intuitively, and with higher fidelity, using context as a guide to ensure an appropriate balance of hue, luminance, and saturation.

How We See Color

More than a century ago, Albert H. Munsell built upon the work of Isaac Newton and Johann Wolfgang von Goethe to compose



This image shows a comparison of the same data set displayed using the traditional rainbow colormap (left), a cool–warm colormap (middle), and a "wave" colormap, illustrating how visible detail can change when data are portrayed with different color gradients. Credit: Graphic created by Francesca Samsel with data processed and provided by M. Petersen, Los Alamos National Laboratory (LANL), using MPAS-Ocean

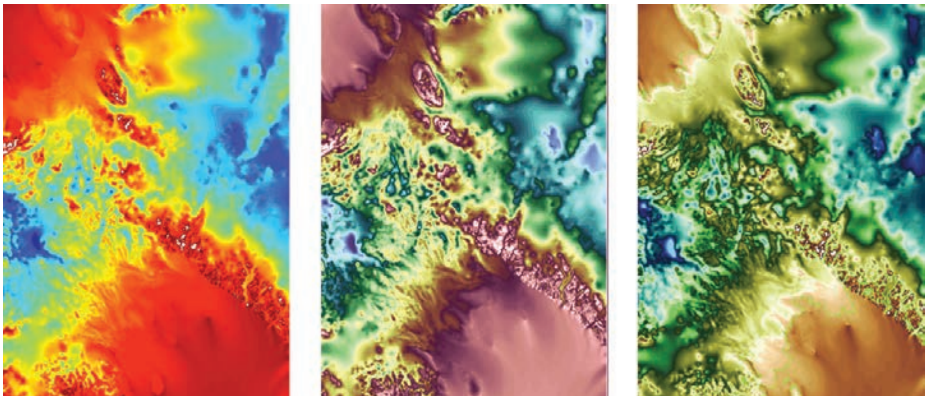


Fig. 1. Detail of topography between the Filchner-Ronne and Ross Ice Shelves in West Antarctica. This image illustrates the effects of simultaneous contrast within the traditional rainbow colormap (left), increased detail in a desaturated version of the traditional rainbow (middle), and an analogous color palette for greater aesthetic quality as well as discriminatory power (right). Credit: Graphic created by Francesca Samsel with data processed using E^3SM

our modern concept of color mapping [*Munsell,* 2015]. Munsell's research produced the first perceptually ordered color space—a three-dimensional plot in which the axes represent hue (color), value (lightness or darkness), and chroma (intensity of color) [*Moreland,* 2016].

Around the same time, in the early 1900s, Hermann Grassmann's theory of linear algebra decrypted abstract math, revealing the origami-like properties of higher dimensions. Grassmann thereby created the concept of vector space, allowing for the approximate calculation of perceived color within a defined area [*Grassmann,* 1844]. The study of color no longer depended on approximation but could rather be coded numerically, plotted along a parabola. This level of accuracy is necessary because color perception is a subjective experience dependent on light, simultaneous contrast (the phenomenon of juxtaposed colors affecting each color's appearance; see Figure 1), and rod and cone photoreceptors within the viewer's eyes [*Albers,* 2006; *Itten,* 1970].

In the Eye of the Beholder

Contemporary color spaces (Figure 2) can be divided into two categories: absolute and nonabsolute. Absolute color spaces define

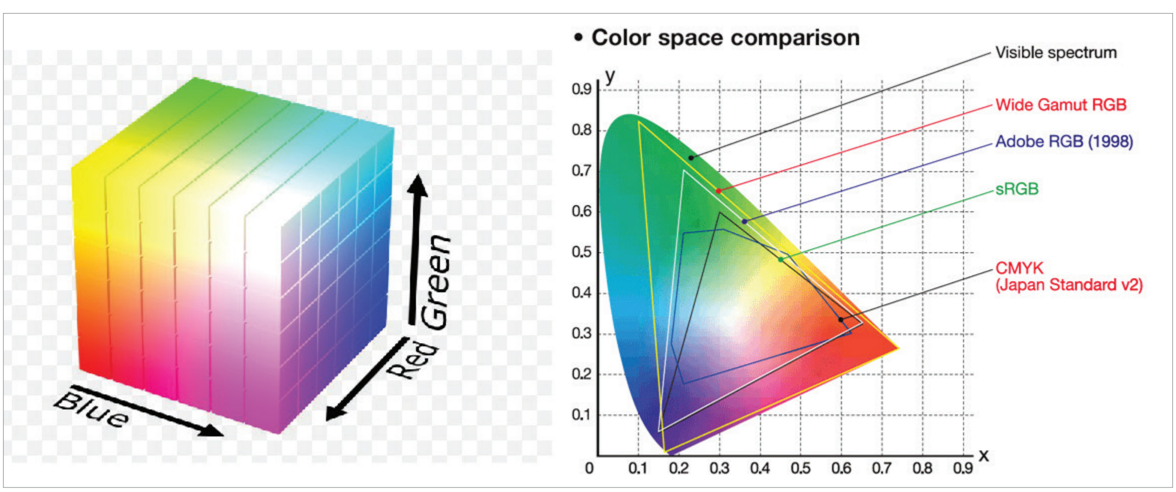


Fig. 2. Two types of color space established by the International Commission on Illumination (CIE) in 1931: the nonabsolute red–green–blue (RGB) color space illustrated using a cube (left), and the CIELAB color space (right), one of the most widely used absolute color spaces. The full parabola of CIELAB color space illustrates the full visible spectrum of hues typically discernible by the human eye. Within this parabola, the white triangle encloses all hues available in Adobe RGB color space. (CIELAB is a three-dimensional space shown in two dimensions here for simplicity.) Credit: SharkD, CC BY-SA 4.0 (bit.ly/ccbysa4-0) (left); public domain (right)

color in terms of human perception. More familiar nonabsolute color spaces such as red-green-blue (RGB) and cyan-magenta-yellow-black (CMYK) define color based on self-contained models that rely on either input devices, like a camera, or output devices, like a monitor or printer.

The popular rainbow map was defined within a nonabsolute color space—its gradient spans many highly saturated hues without consideration for their mathematical separation within an absolute (perceptual) space. This arrangement creates extremely high contrast between hues, visually demarcating different values in a data set and thereby propelling the rainbow map to default status among most scientists.

In recent years, however, researchers have challenged the rainbow's status and common usage, which proliferated without full consideration of its influence on data representation. Rainbow mapping can wash out oceans of data in glaring neon green, creating false artifacts, color interference, and attention bias (see, e.g., the left-hand graph in the image on p. 30) [*Borland and Taylor,* 2007; *Liu and Heer,* 2018; *Ware et al.,* 2019, 2017]. Perceptual scientists have attempted to remedy this issue through "perceptually equalized colormaps"—maps made with uniformly spaced values in absolute color space—but these maps, along with the rainbow colormap and its cousins, were all created independent of the data they are used to represent. This means they were made for general use as opposed to considering each data set's unique properties and needs. In an age of rapidly growing and increasingly complex data, many visualization experts agree that their utility is limited.

Rainbow mapping can wash out oceans of data in glaring neon green, creating false artifacts, color interference, and attention bias.

Balancing Familiarity with Clarity

Scientists and visualization professionals attempting to heed the latest color mapping research struggle, however, to break away from standard, data-independent maps like the traditional rainbow, viridis, the cool-warm divergent, Jet, and Turbo (Google's increasingly popular next-generation rainbow). Impeding the adoption of this research are scarcities of convenient and user-friendly color mapping resources, available expertise and guidance, precedents within the community, and time available to researchers to familiarize themselves with new color conventions [*Moreland,* 2016].

"When people approach a visualization, they have expectations of how visual features will map onto concepts," said Karen Schloss, a psychologist at the University of Wisconsin–Madison and the Wisconsin Institute for Discovery. Schloss and her team are working to tackle these implementation issues and understand trade-offs between deeply ingrained, communal familiarity and the next generation of color tools.

"We refer to these expectations as inferred mappings," she said. "If someone has been working in a particular field their whole [life], they have this inferred mapping for colors and the values they represent. We are trying to understand these biases while also being careful about recommending that these experts just abandon their conventions completely. We need to find a balance."

In search of that balance, visualization experts are focusing their efforts on understanding what scientists need from their data and on how to address those needs without compromising the information contained in the data themselves.

What Do Scientists Need?

Francesca Samsel, a research scientist at the Texas Advanced Computing Center (TACC) at the University of Texas at Austin, and her team describe scientists' needs with respect to data visualization using three categories—feature identification, exploration, and communication—as well as subcategories of pinpointing outliers and determining relationships. When interpreting a large data set, scientists are usually looking for specific features (e.g., the direction of flow of ocean currents or water temperatures in certain locations) within known data ranges; exploring the data holistically to make general observations; or looking to communicate specific properties of the data to colleagues, peers, or the public. Occasionally, a researcher may be interested only in outliers, or in the way one variable affects another—for example, how water temperatures change when two currents meet.

Visualization is how scientists interact with the quantitative outcomes of their research and how they make data-based arguments, said Wolfram. He regularly uses

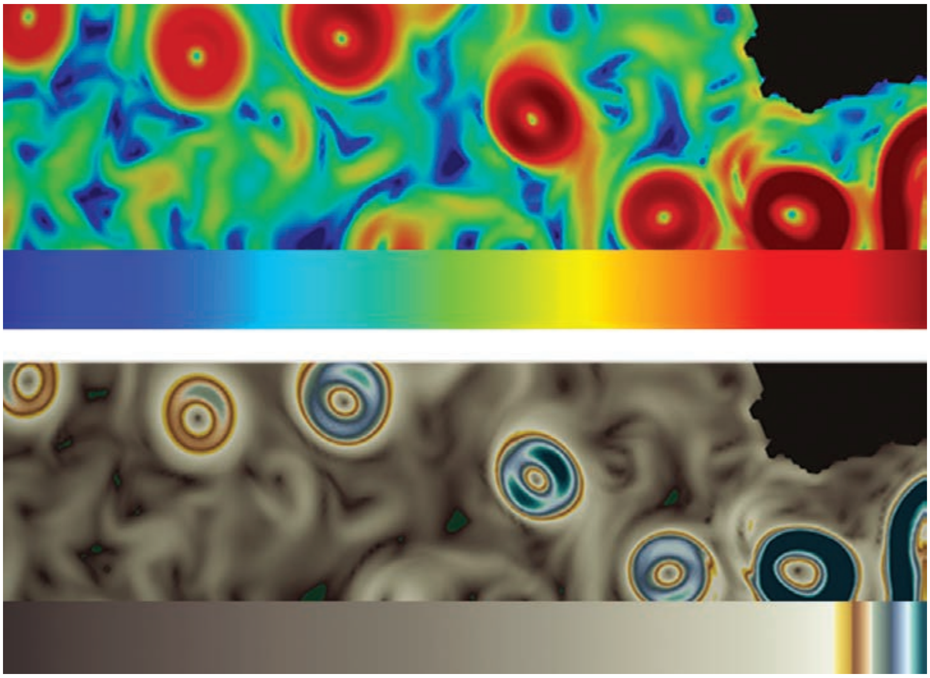


Fig. 3. Comparison of the same data portrayed with a desaturated rainbow colormap (top), which is often used to increase visual detail, and with a colormap designed to provide detail in outlying data ranges (bottom). The specialized colormap provides detailed information about the kinetic energy within eddies in the Agulhas Current, a major current in the Indian Ocean, whereas the rainbow colormap simply identifies the eddies. Credit: Graphic created by Francesca Samsel with data processed and provided by M. Petersen, LANL, using MPAS-Ocean

visualizations, including overhead plots, representing the view from above (e.g., from satellites) to explore Earth systems and climate data in his work at Los Alamos. "What I'm looking for is tightly coupled to the science question," he said. "I'm typically trying to understand geospatial relationships, particularly in overhead plot data, for surface features like [ocean] eddies." Advanced color mapping tools help prevent significant losses of feature detail in the data Wolfram analyzes, unlike standard maps like Jet (Figure 3).

Samsel and others argue that non-data-dependent color mapping strategies can perpetuate bias if the hues are not arranged in a familiar order (e.g., rainbow order), if the luminance is not specifically accounted for, or if multiple gradients within a map are not arranged for a specific data set [*Borland and Taylor*, 2007]. The importance of visualization throughout the research process necessitates high-level tools that maximize information and minimize obstruction caused by any of these color-related issues. Researchers Samsel, Schloss, and Danielle Szafir, an assistant professor and director of the VisuaLab at the University of Colorado Boulder, have taken concrete steps to create such tools, maintaining the goal of intuitive operation.

A New Set of Color Tools

Samsel, who was trained and worked for 25 years as an artist before pivoting to visualization, uses her knowledge of color theory in tackling the perceptual challenges of crafting colormaps. "We've discovered in the course of our research that presenting scientists with perceptually equalized colormaps is not always the most beneficial solution" for providing the kind of resolution scientists need within their data, Samsel said. There are nuance and complexity in color interaction that affect a viewer's associative response and how they derive the relative importance of different features within the data, she explained.

The importance of visualization throughout the research process necessitates high-level tools that maximize information and minimize obstruction.

Samsel's research spurred the creation of ColorMoves [*Samsel et al.*, 2018], an applied tool for interactively fine-tuning colormaps to fit the needs of different data sets. The online interface for the tool provides sets of maps focused on achieving increased discriminative power [*Ware et al.*, 2019] while reflecting the palette of the natural world—something called semantic association. For example, many people associate blue with ocean data and green with land data.

Beginning in the 1990s, perceptual researchers established that the human eye is more sensitive to differences in luminance (perceived brightness) than to hue when distinguishing patterns within densely packed data points [*Ware et al.*, 2019; *Rogowitz*, 2013]. Samsel and her colleagues have reaffirmed these findings, in part through color theory. Using this information in concert with gradations of hue and saturation, Samsel created linear (one hue gradient), divergent (two hue gradients that meet in the middle), and what she calls wave colormaps—maps that cycle through luminance distribution across many hues (see image on pp. 28–29). "This creates a greater density of contrast throughout the map, which resolves many more features on continuous data," said Samsel.

"How can we capture designer practices without asking them to distill their entire field down to an extremely simplified, and therefore incomplete, set of rules?"

The ColorMoves interface enables users to drop multiple colormaps onto their data and adjust the result interactively, seeing the changes on their data in real time and allocating hue and contrast wherever appropriate. "It wasn't necessarily intended as a tool for data exploration, but scientists have identified that as a priority" and have been using it for exploration, said Samsel.

Schloss, who runs the Visual Reasoning Lab at the University of Wisconsin–Madison, focuses on making visual communication more effective and efficient through the study of color cognition, targeting the trade-offs in color mapping between high contrast and aestheticism. "People see customization as a huge asset for creating visualizations," she said, "and I think making that capability easily accessible may encourage people to take more care in how they are color encoding and presenting their data."

As part of an effort to optimize colormaps for visualizations, Schloss and her colleagues created a tool called Colorgorical. The tool features a series of adjustable sliders for customizing a palette based on perceptual distance between hues, the differences between hue names, how close together the hues are on the color wheel, and the specificity of hue names (e.g., peacock or sapphire versus blue) [*Heer and Stone*, 2012]. Users can also select a hue and luminance range within which the custom palette should fall, and they can construct a color palette around a "seed color."

Designer in a Box

Schloss, Samsel, and Szafir agree that future research in this area lies in producing automatically generated colormaps that are based on the custom work of designers and that are ready to integrate with the visualization software scientists are already using.

Szafir and her team at the ATLAS Institute's Department of Computer Science are already on the path to making this vision a reality. "We started thinking about how to meet the user where they are," Szafir said. The attention to detail and creativity that individual designers can offer are unfortunately not very scalable, so Szafir's team wondered whether they could create a product that was effectively a "designer in a box."

"How can we capture designer practices without asking them to distill their entire field down to an extremely simplified, and therefore incomplete, set of rules?" Szafir asked.

Szafir and her colleagues constructed machine learning models based on 222 expert-designed color gradients and used the results to automatically generate maps that mimic designer practices. The final maps "support accurate and aesthetically pleasing visualizations at least as well as designer [maps] and...outperform conventional mathematical approaches" to colormap automation, Szafir and colleagues wrote in a recent study [*Smart et al.*, 2020].

Despite her team's progress, complete automation has drawbacks, Szafir said. An algorithm needs a set of data to "train" on—in this context, a batch of colormaps with similar curves in 3D color space. The algorithm derives a set of rules based on this group of maps, then generates new maps based on those rules. However, "a lot of what comes out of the artistic community that is truly expressive, creative, and engaging comes from breaking these conventions," she said. "An artist knows where and when and how to break those rules, and we don't know if we can produce that level of comparable variation [in a program] successfully."

Both Samsel and Schloss are seeking avenues to merge their diverse expertise with Szafir in the near future, continuing to structure their respective work around the data visualization needs of scientists. "We see a future of using new tools to measure the spatial density of data, creating an automation process that interpolates, aligns, and allocates contrast within a colormap to match [those] data," said Samsel. Such a program would concentrate variance in hue and luminance where the data are densest, allowing a scientist to visualize nuance and detail where they count.

Conveying an Accurate Message

Scientific visualizations play multiple roles of helping people quantify, interpret, evaluate, and communicate information. Their importance in the exploration and discovery of data is immense and is growing with advances in computational power, yet visualization's single most effective encoder—color—remains vastly understudied. Although the macroscale effects of such neglect on public perception of issues like climate change are yet unknown, many groups are beginning to devote greater resources to designing their visualizations with the public in mind.

Ed Hawkins, a lead author of the upcoming sixth Intergovernmental Panel on Climate Change (IPCC) report and creator of the now-viral "Warming Stripes" graphic, said the IPCC pays multiple graphic designers to transform complex visualizations into simplified graphics. "We have to be able to reach a very broad audience," Hawkins added. "Not just for general communication but also to inform policy decisions and to help people respond to risks that threaten their way of life." Hawkins and his team spend "a lot of time" focusing on color blindness issues in addition to readability and semantic understanding of color.

Keeping in mind the difference in perception between those publishing reports and those reading them is imperative, according to Lyn Bartram, a professor in the School of Interactive Arts and Technology at Simon Fraser University and director of the Vancouver Institute for Visual Analytics. "Rather than engaging people in the experience of understanding big data, we just sort of throw the facts out there and wash our hands of the affair," she said. "Data visualization is a language, and, foundationally, you're trying to tell a story. Color is a huge part of this."

If researchers do not behave as if they are in conversation with their audience, Bartram said, their work will have little impact. "The democratization of data visualization means that it has become media; it is no longer just a means to an end for scientists," she said. "Visualization has become so much more than just a tool. It is now a part of our conversations and decision-making as a society at large."

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In Appreciation of AGU's Outstanding Reviewers of 2019

AGU Publications recognizes a number of outstanding reviewers for their work in 2019, as selected by the editors of each journal.

Peer review is central to communicating and advancing science. Although there have never been more ways to distribute ideas and research outputs online, a robust peer review ensures that we maintain the highest integrity in our scientific discourse. The peer review process is organized by our journal editors, but every article decision relies on individuals who take time out from their own research to volunteer their expertise. The work of these reviewers ensures proper evaluation of thousands of articles each year. We are truly thankful for their efforts.

As the uses for scientific literature have grown, so has the complexity of papers, which now typically include more authors bringing more techniques, data, simulations, and results. This increase in complexity, in turn, has increased the challenge and role of reviewing. The outstanding reviewers listed here have all provided in-depth evaluations, often over more than one round of revision, that greatly improved the final published papers. Their contributions have helped to raise the quality of submissions received from around the world, providing valuable feedback that elevates the prominence of our journals to the high standards that align with AGU tradition.

The outstanding reviewers listed here have all provided in-depth evaluations, often over more than one round of revision, that greatly improved the final published papers.

Many Reviewers: A Key Part of AGU Journals

Although we note these few outstanding reviewers here, we also acknowledge the broad efforts by all AGU reviewers in helping ensure the quality, timeliness, and reputation of AGU journals. In 2019, AGU received over 16,700 submissions, up from 15,600 submissions received in 2018, and published over 7,000, up from 6,600 articles in 2018. Many of these submissions were reviewed multiple times—in all, 18,173 reviewers completed 39,368 reviews in 2019 compared with 37,674 reviews completed in 2018.

This increase happened in the past year while each AGU journal worked to shorten the time from submission to first decision and publication or maintained already industry-leading standards. Several AGU journals regularly return first decisions within 1 month of submission, and most others do so now within 2 months. Reviewers represent a key part of this improvement. We look back at 2019 here, but we have already seen that in 2020, during the pandemic and unrest, members of our amazing community have continued to accept invitations to peer review article submissions.

Editorials in each journal (some already published, some upcoming) express our appreciation along with recognition lists. Our thanks are a small recognition of the large responsibility that reviewers bear in improving our science and its role in society.

Additional Thanks

In addition, we are working to highlight the valuable role of reviewers through events (though they may be virtual) at Fall Meeting and other meetings.

Each reviewer also receives a discount on AGU and Wiley books. We will continue to work with the Open Researcher and Contributor Identification (ORCID) network to provide official recognition of reviewers' efforts, so that reviewers receive formal credit there. As of 5 May, we have over 59,962 ORCIDs linked to GEMS user accounts, compared with 49,000 at this time last year.

Our thanks are a small recognition of the large responsibility that reviewers bear in improving our science and its role in society.

Getting Your Feedback

We are working to improve the peer review process itself, using new online tools. We conducted a full survey earlier in 2020, and we continue to provide a short questionnaire for feedback after each review is completed.

We value your feedback, including ideas about how we can recognize your efforts even more, help improve your experience, and increase your input on the science.

We look forward to hearing from you. If you'd like to respond directly, feel free to take our survey.

Once again: Thanks!

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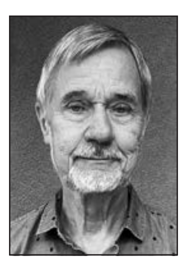

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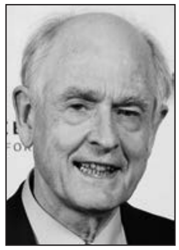

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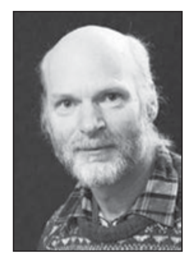

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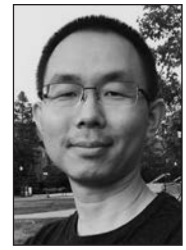

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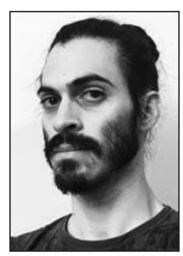

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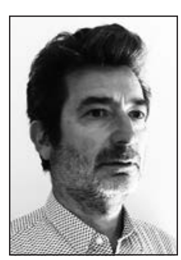

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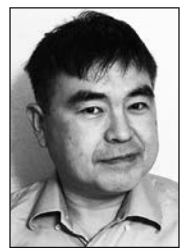

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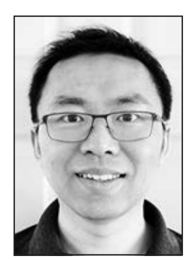

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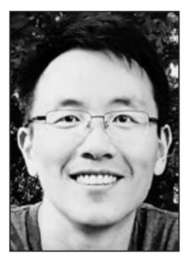

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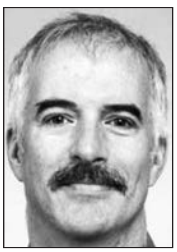

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How Much Modification Can Earth's Water Cycle Handle?

Portions of Europe (foreground) and North Africa are seen in this view from the International Space Station. Human activities at local and regional scales all over the planet influence the global water cycle. Credit: NASA

Earth's fresh water is essential: It helps regulate climate, support ecosystems, and sustain human activities. Despite its importance to the planet, humans are modifying fresh water at an unprecedented scale, and because of their damming rivers, pumping groundwater, and removing forests, humans represent the primary source of disturbances in the world's freshwater cycle.

Extensive modifications to the water cycle and perturbations to other Earth processes prompted the development of the planetary boundaries framework roughly a decade ago. The framework defines the "safe operating space" for essential Earth system processes, including fresh water, and sets limits beyond which we risk rapidly and maybe irreversibly disrupting critical global systems.

In a new study, *Gleeson et al.* argue that the current definition of the planetary boundary related to fresh water—and the methodology for determining it—is insufficient, neither capturing water's role in Earth system resilience adequately nor offering a way to measure perturbations on a global scale. The authors provide an overview of how water supports Earth's resilience and propose an approach for analyzing and better understanding global water cycle modifications focused on three central questions: What water-related changes could lead to global tipping points? How and where is the water cycle particularly vulnerable? And how do local changes in water stores and fluxes affect regional and global processes, and vice versa?

The authors delve into each of these questions. In addressing the second question, for example, they examine where ecological regime shifts would alter the water cycle. As a case study, they assess the Amazon rain forest. Research has suggested that if the Amazon loses between 10% and 40% of its current forested extent, it may transition permanently into savanna and disrupt water and carbon cycles. By understanding the limits of the Amazonian ecosystem—and other ecosystems around the world—we can shape policy to avoid reaching tipping points that would undermine the planet's resilience.

The study invites scientists to meet the scientific and ethical grand challenge of examining how water cycle modifications affect Earth system resilience. In outlining the grand challenge, the authors suggest initiatives that can be addressed immediately by collaborative working groups to illuminate better the current extent of water modifications and the state of the water cycle. (*Water Resources Research,* https://doi.org/10.1029/2019WR024957, 2020) **—Aaron Sidder,** *Science Writer*

Improving Atmospheric Forecasts with Machine Learning

Weather forecasting has improved significantly in recent decades. Thanks to advances in monitoring and computing technology, today's 5-day forecasts are as accurate as 1-day forecasts were in 1980. Artificial intelligence could revolutionize weather forecasts again. In a new study, *Arcomano et al.* present a machine learning model that forecasts weather in the same format as classic numerical weather prediction models.

Previously, the team developed an efficient machine learning algorithm for the prediction of large, chaotic systems and demonstrated how to incorporate the algorithm into a hybrid numerical machine learning model for dynamical systems like atmospheric conditions. In the new proof-of-concept study, the researchers build on their previous work by using a reservoir computing–based model, rather than a deep learning model, to reduce the training time requirements for their machine learning technique.

The researchers trained their model using data from the European Centre for Medium-Range Weather Forecasts and prepared 171 separate 20-day forecasts, each of which took just 1 minute to prepare. They compared the machine learning forecasts to three benchmark forecasts: daily climatology; a persistence model, which assumes that the atmospheric state will remain constant throughout the forecast; and the Simplified Parameterizations, Privitive-Equation Dynamics (SPEEDY) model, a low-resolution version of numerical weather prediction models.

They found that the machine learning model typically forecast the global atmospheric state with skill 3 days out. It outperformed both daily climatology and the persistence model in the extratropics, though not in the tropics, and bested the SPEEDY model in predicting temperature in the tropics and specific humidity at the surface in both the tropics and the extratropics. However, the SPEEDY model still outperformed the machine learning model for wind forecasts more than 24 hours out. The authors note that overall, the reservoir computing–based machine learning model is highly efficient and may be useful in rapid and short-term weather forecasts. (*Geophysical Research Letters,* https://doi.org/10.1029/2020GL087776, 2020) **—Kate Wheeling,** *Science Writer*

Cumulonimbus clouds advance over the Baltic Sea. Incorporating machine learning techniques into weather and climate models could improve both. Credit: Arnold Paul, CC BY-SA 2.5 (bit.ly/ccbysa2-5)

Machine Learning Improves Weather and Climate Models

Both weather and climate models have improved drastically in recent years, as advances in one field have tended to benefit the other. But there is still significant uncertainty in model outputs that are not quantified accurately. That's because the processes that drive climate and weather are chaotic, complex, and interconnected in ways that researchers have yet to describe in the complex equations that power numerical models.

Historically, researchers have used approximations called parameterizations to model the relationships underlying small-scale atmospheric processes and their interactions with large-scale atmospheric processes. Stochastic parameterizations have become increasingly common for representing the uncertainty in subgrid-scale processes, and they are capable of producing fairly accurate weather forecasts and climate projections. But it's still a mathematically challenging method. Now researchers are turning to machine learning to provide more efficiency to mathematical models.

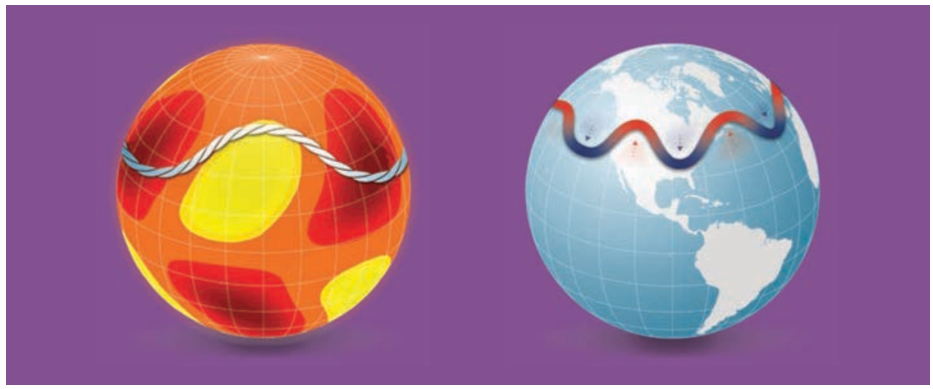
Here *Gagne et al.* evaluate the use of a class of machine learning networks known as generative adversarial networks (GANs) with a toy model of the extratropical atmosphere—a model first presented by Edward Lorenz in 1996 and thus known as the L96 system, which has been frequently used as a test bed for stochastic parameterization schemes. The researchers trained 20 GANs, with varied noise magnitudes, and identified a set that outperformed a hand-tuned parameterization in L96. The authors found that the success of the GANs in providing accurate weather forecasts was predictive of their performance in climate simulations: The GANs that provided the most accurate weather forecasts also performed best for climate simulations, but they did not perform as well in off-line evaluations.

The study provides one of the first practically relevant evaluations for machine learning for uncertain parameterizations. The authors conclude that GANs are a promising approach for the parameterization of small-scale but uncertain processes in weather and climate models. (*Journal of Advances in Modeling Earth Systems (JAMES)*, https://doi.org/10.1029/2019MS001896, 2020) **—Kate Wheeling,** *Science Writer*

Space Weather Forecasting Takes Inspiration from Meteorology

Every so often, the Sun unleashes powerful bursts of plasma particles and magnetic field structures toward Earth. These solar storms can wreak havoc on power grids, satellites, and other infrastructure, but they are difficult to predict more than a few days in advance.

In a new review, *Dikpati and McIntosh* showcase mounting evidence that solar storms arise from solar Rossby waves, a type of wave associated with rotating fluids. Just as the 1939 discovery of Rossby waves in Earth's atmosphere paved the way to accurate weather prediction, Rossby waves in the Sun could be key to predicting disruptive space weather in time to prepare for it.



Large-scale Rossby waves propagating around the Sun may play a role in triggering solar storms (yellow and deep red regions indicate where sunspot activity is unlikely and more likely, respectively). These waves are akin to Rossby waves in Earth's atmosphere, which influence weather, including potential heat waves (red arrows) and cold snaps (blue arrows). Credit: Simmi Sinha, University Corporation for Atmospheric Research

On Earth, atmospheric Rossby waves arise from the planet's rotation, and these large-scale meandering features help transport warm air toward the poles and cold air toward the tropics. Earth's Rossby waves sometimes have extreme effects, such as those from 2019's polar vortex.

Rossby waves in the solar plasma arise from the star's rotation and originate within a transitional layer known as the tachocline. Unlike Earth's Rossby waves, solar Rossby waves are strongly influenced by powerful magnetic fields. Recent observations and theoretical modeling suggest that these magnetically modified Rossby waves interact with the differing rates of rotation of the Sun's plasma to trigger solar storms.

The researchers suggest that computational techniques developed for meteorology could inform strategies to improve solar storm predictions. In the future, scientists could use observations of the Sun's surface as indicators of Rossby wave dynamics deep below, potentially revealing harbingers of solar storms weeks, months, or even a few years ahead of their eruption. (*Space Weather,* https://doi.org/10.1029/2018SW002109, 2020) —**Sarah Stanley,** *Science Writer*

Hardwood Forest Soils Are Sinks for Plant-Produced Volatiles

Biogenic volatile organic compounds (BVOCs) are carbon-containing molecules released into the air by plants. They act as signaling molecules between trees, in a kind of airborne chemical communication, and play important roles in larger climate processes by facilitating aerosol formation and ozone production. Forest soils can store BVOCs and influence the compounds' exchange with the atmosphere, functions that are affected by variables that scientists are keen to understand, such as the types of trees present and associated fungi growing in the soil.

In a new study, *Trowbridge et al.* analyzed BVOCs in situ from two types of soil within a hardwood forest in south central Indiana. The first type was beneath trees that associate with arbuscular mycorrhizal fungi (AM), a type of symbiotic fungus that penetrates the cells of tree roots to form a network of nodes where sugar, gas, and nutrients are exchanged. The second type of soil was beneath trees that associate with ectomycorrhizal fungi (ECM), which form tiny exchange nets around plant roots but do not breach the root cells themselves. Scientists often find substantial differences in soil biogeochemistry between AM- and ECM-dominated forest stands. For example, AM-associated tree species drop litter that decays more rapidly and cycle nutrients faster than ECM-associated tree species.

Overall, the new analysis shows that both soil types studied work as net BVOC sinks during the growing season; however, other factors, like temperature and moisture, are critical to understanding the larger picture. ECM soils absorbed more BVOCs than AM soils, especially as temperatures warmed. ECM soils were also much more active when moisture levels were higher. Finally, ECM soils showed stronger seasonality, acting as sources of BVOCs before the growing season but then becoming strong sinks after leaf out. AM soils, on the other hand, were weak BVOC sinks year-round.

The scientists conclude that characterizing forest soil by tree-associated mycorrhizal associations may be a good first step in capturing landscape-scale variation in BVOC transport between the land and the atmosphere. (*Journal of Geophysical Research: Biogeosciences,* https://doi.org/10.1029/2019JG005479, 2020) —**David Shultz,** *Science Writer*

How Long Was Venus Habitable?

Earth and Venus are "sister worlds," sharing a similar size, mass, and bulk composition. You wouldn't want to visit modern-day Venus, though, with its atmosphere of carbon dioxide and nitrogen and surface temperatures hovering around 450°C. But our neighbor probably wasn't always so inhospitable.

Deciphering what early Venus looked like isn't easy—in part because the planet's surface is relatively young, just 300–700 million years old—but indications from the Pioneer Venus mission suggest that its atmosphere once contained more water than it does today. Venus also might have hosted liquid water at its surface, as well as plate tectonics and a stable, temperate climate; some studies even indicate that Venus's climate may have been more stable than early Earth's, avoiding Earth's icy snowball periods.

Theories abound about what led to Venus's drastic transformation: A gradually warming Sun may have left the planet hot and desiccated after a short period of habitability, or a very early magma ocean and an atmosphere of carbon dioxide and steam could have given way to the planet's current state nearly 4 billion years ago.

In a new study, though, *Way and Del Genio* provide evidence that a shallow water ocean and habitable conditions may have persisted on Venus for as long as 3 billion years, until volcanic large igneous provinces (LIPs) emerged simultaneously and ended the planet's temperate period.

The team ran several simulations of Venus's history using NASA's ROCKE-3D (Resolving Orbital and Climate Keys of Earth and Extraterrestrial Environments with Dynamics) general circulation model to examine how variations in the planet's rotation rate and surface water levels might have influenced its early climate. Assuming that Venus's early atmosphere, like early Earth's, was carbon rich and cool and that its rotation rate was slow, the team found that Venus's climate could have been stable for most of the planet's more than 4-billion-year history—a strike against the gradually warming Sun theory.

The authors believe that simultaneous eruptions of LIPs over the past few hundred million years could have led to a runaway greenhouse effect by releasing large amounts of carbon dioxide into the atmosphere. The resultant drying of the planet's surface could have driven it into a new interior-surface dynamics regime, with newly exposed basalts—evident on Venus today—acting as an efficient oxygen sink.

In Earth's past, LIPs have emerged sequentially in a random stochastic process rather than simultaneously, which the authors note is "fortuitous for life as we know it today." But not enough is known about Venus's interior to speculate whether an uninhabitable end state is the inevitable product of internal processes on Venus-like planets or even on Earth, for that matter. Researchers need more observations from Venus's surface to better constrain its early history and further challenge the magma ocean theory.

Ultimately, a better understanding of Venus's history will provide insights into both terrestrial processes and those of exoplanets, including whether the window of habitability is wider than currently thought. (*Journal of Geophysical Research: Planets,* https://doi.org/10.1029/2019JE006276, 2020) **—Kate Wheeling,** *Science Writer*

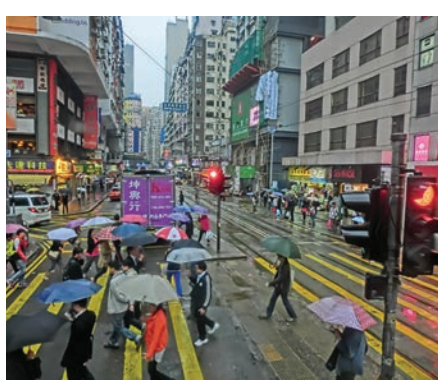
Chinese Swamp Core Reveals 47,000 Years of Monsoon History

Every summer, one third of the world's population receives rainfall from the East Asian monsoon. Variations in monsoon behavior can pose flood or drought risk, so understanding how it has changed over time could help clarify future risks. *Wei et al.* now provide new insights into 47,000 years of East Asian monsoon history.

The new research addresses a lack of long-term, high-resolution data on past monsoon variability from southern China. To help fill this gap, the researchers collected an 8.6-meter-long sediment core from Dahu Swamp in the Nanling Mountains of southern China; the region's topography makes it particularly sensitive to shifts in monsoon rainfall patterns.

The research team took samples of material every 2 centimeters along the length of the core and analyzed each sample's magnetic properties to produce snapshots of mineral composition in the swamp at different time periods. These snapshots provided clues to the hydrologic and climatic processes in play when the materials were deposited.

Findings from the mineral-magnetic analysis enabled the scientists to reconstruct patterns of fluctuation between relatively wet and dry periods in the region over the past 47,000 years. These monsoonal rainfall patterns are consistent with data from northern China and are in line with past climate changes resulting from gradual shifts in Earth's orbit and orientation.



New insights into ancient trends in East Asian monsoon rainfall could help refine predictions of flood and drought risk as global warming progresses. Credit: Kamiswlswoo, CC BY-SA 3.0 (bit.ly/ccbysa3-0)

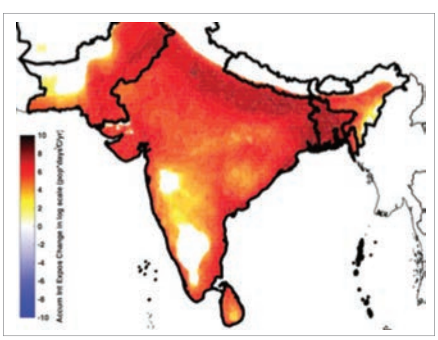
The results also add to mounting evidence contrary to the traditional view that climate processes at high latitudes were the primary driver of paleoclimate monsoon trends. The new findings suggest that tropical climate patterns associated with the El Niño–Southern Oscillation have played an important role in driving long-term monsoon rainfall patterns.

This research could help refine climate models and improve predictions of future shifts in monsoon rainfall patterns as climate change progresses. (*Paleoceanography and Paleoclimatology,* https://doi.org/10.1029/2019PA003796, 2020) **—Sarah Stanley,** *Science Writer*

Health Concerns from Combined Heat and Pollution in South Asia

Rising global temperatures and, correspondingly, increasing incidences of extreme heat events are occurring across most of the world. This is even more concerning in South Asia, with many other geographic factors leading to prolonged periods of hazardous weather. The examination of potential health exposure by *Xu et al.* is unique. The researchers studied projections for heat events in combination with one aspect of air quality—particulate matter—for the current and projected climate of India and a few other countries in South Asia.

The authors show that such jointed events will increase by 175% in frequency by midcentury. The fraction of land exposed to prolonged high particulate pollution increases by a factor of more than 10 in 2050. The alarming increases in health exposures over just a few decades in South Asia pose great challenges to adaptation. Action addressing the combined impacts of climate change is needed across the world. (*AGU Advances,* https://doi.org/10.1029/2019AV000103, 2020) **—Donald Wuebbles**



Decadal variability in the ocean carbon sink is attributed to (a) slowing of the partial pressure of carbon dioxide (pCO_2) in the atmosphere in the 1990s (black line) and the rapid cooling and slower warming recovery in response to the eruption of Mount Pinatubo (red arrows) and (b) increasing atmospheric pCO_2 in the 2000s (black line). The strength of the ocean carbon sink (black arrows) was reduced by conditions in the 1990s and strengthened by conditions in the 2000s. Credit: McKinley et al.*, 2020*

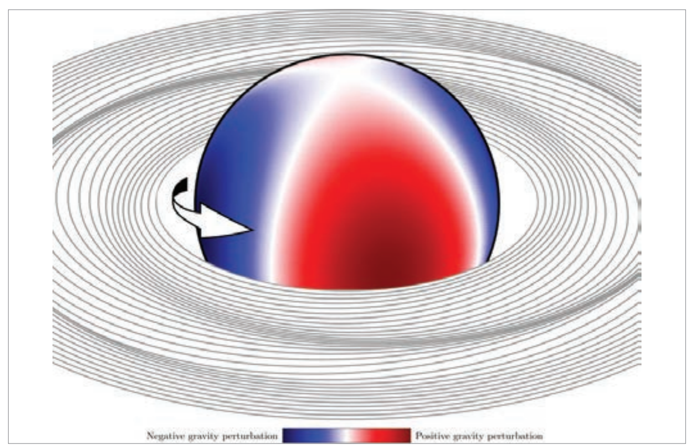
Eruption and Emissions Take Credit for Ocean Carbon Sink Changes

The ocean's capacity to take up carbon is a balance between the amount of carbon dioxide in the atmosphere and the state of the ocean. Reduced emissions in the 1990s resulted in lower atmospheric carbon dioxide, which slowed the ocean's uptake of carbon. At the same time, the eruption of Mount Pinatubo in 1991 produced cooler sea surface temperatures followed by warming in the latter part of the decade that changed the state of the ocean, which, in turn, shifted the timing of the carbon sink's slowing.

McKinley et al. now provide a model-based analysis that evaluates the ocean's response when these two effects coincided, to explain the slowing of the ocean carbon sink during the 1990s. The confluence of these events yielded a net carbon uptake by the ocean that was less than expected. These results highlight the importance of external processes in controlling decadal variability in the ocean carbon sink and point to the uncertainty introduced by extreme events. (*AGU Advances,* https://doi.org/10.1029/2019AV000149, 2020) **—Eileen Hofmann**

Using Saturn's Rings as a Seismometer

Seismology is a powerful tool for probing a planet's or star's interior structure. Almost 40 years ago, it was recognized that internal oscillations in Saturn could produce wave patterns in its rings: The rings could act as a seismometer. Now, as Mankovich describes in a Commentary, 20 such patterns are known and lead to two surprising conclusions.



Schematic of how oscillations (colors) inside Saturn generate spiral density waves in the rings. In reality, the waves are much more tightly wound. Observations of these waves can be used to probe Saturn's internal structure. Credit: Mankovich, *2020*

The first is that the interior half of Saturn is not convecting, as was expected, but is stably stratified. The explanation is most likely a deep but diffuse rock-rich region. The second conclusion is not only that Saturn is rotating somewhat faster than was previously thought but also that the rotation rate varies with depth. The use of rings as seismometers is still in its infancy, and more is likely to be learned as modeling techniques become more precise. Furthermore, this work opens up the possibility of using similar approaches elsewhere, notably in the ring system of Uranus. (*AGU Advances,* https://doi.org/10.1029/2019AV000142, 2020) **—Francis Nimmo**

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POSITIONS AVAILABLE

Atmospheric Sciences

The Faculty Mathematics and Natural Sciences invites in cooperation with the Leibniz Institute of Atmospheric Physics Kühlungsborn (IAP) applications for a W3-Professorship in Atmospheric Physics at the IAP and the Institute of Physics, starting at the earliest possible date (within budget considerations).

We are looking for an outstanding scientist in the field of atmospheric physics. Emphasis should be on the experimental or theoretical exploration of the stratosphere, mesosphere and lower thermosphere. The main task is leading the Leibniz Institute of Atmospheric Physics (IAP). In addition, the candidate is expected to collaborate with the Institute of Physics of the University, to participate in joint projects and to contribute to the activities of the Interdisciplinary Faculty. The teaching duties comprise courses and seminars in atmospheric physics for master and PhD programs.

Additional Information:
Prof. Dr. Stefan Lochbrunner
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email: stefan.lochbrunner@uni-rostock.de

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Qualifications are as per §58 of the Higher Education Act of the State of Mecklenburg-Vorpommern (LHG M-V): completed university studies, doctoral degree, post-doctoral thesis ("Habilitation"), teaching experience or equivalent qualifications, usually earned within the context of junior professorship.

A special focus is placed on academic achievement and teaching qualifications as well scientific organization and academic administration. For this reason, candidates should describe previous teaching results, ideas regarding future teaching (including didactic lesson planning) and their prior experience in academic and scientific management.

Applications with the usual documents (full CV, a complete list of academic and professional background, publications, teaching experience, any additional qualifications, a summary of grants and sponsored research activities and a description of future research plans) should be sent no later than 31st July 2020 to the University of Rostock, Dean of the Faculty of Mathematics and Natural Sciences, Wismarsche Straße 45, 18057 Rostock or by e-mail to dekan.mnf@uni-rostock.de.

The Desert Research Institute (DRI) Division of Atmospheric Sciences is seeking a Postdoctoral Fellow or an Assistant Research Professor to advance a research program on air quality topics such as PM2.5, ozone, deposition, and visibility. We are looking for an expert in emissions modeling, dispersion modeling, chemical transport modeling, data visualization, and advanced data analysis techniques. This position is located in Reno, NV. The successful candidate will have demonstrated expertise in simulation of atmospheric systems (hypothesis setting and testing using simulations; analysis and exposition of simulation results; application of Eulerian air quality models), manipulating large datasets (e.g., observations collected using aerometric instruments, emissions data, and model output data), and conducting experiments with numerical models that are guided by empirical data. The research activities associated with this position will also build the knowledge base related to air quality management strategies.

Required Qualifications

• Ph.D. in chemical engineering, mechanical engineering, civil engineering, atmospheric science, chemistry, or a related discipline from an accredited institution.

• 2-year minimum experience in atmospheric or closely related science research (candidates with less or no experience will be considered for a postdoctoral fellowship).

• Demonstrated expertise in using regional air quality models such as CMAQ and CAMx including ability to use emissions processing software as well as post-processing of model results.

• Demonstrated ability to conduct sensitivity simulations using brute-force methods or using various sensitivity tools available with the regional air quality model.

For more detailed information about DRI, please visit the careers section of our website at www.dri.edu.

SUSTech (http://www.sustech.edu.cn/en) was founded in 2011 with public funding from the Municipal Government of Shenzhen. A thriving metropolis of over 20 million people bordering Hong Kong, Shenzhen has often been referred to as the "Silicon Valley of China" with strong telecommunication, biotechnology and pharmaceutical sectors. Widely regarded as a pioneer of higher-education reform in China, SUSTech aims to become a top-tier international university that excels in interdisciplinary research, talent development and knowledge discovery. In the latest Times Higher Education (THE) World Universities Rankings 2020, SUSTech was ranked as the 9th among the mainland China universities and the No. 1 young university under 50-year old. Internationalization is a hallmark of SUSTech where

1. OVERVIEW OF SUSTECH

Shenzhen, also known as The Great Eagle City, is China's first Special Economic Zone and recognized as the driving force for the reforming and opening up of the Chinese economy over the past thirty-forty years. In 2017, Shenzhen was selected by the Chinese Government to develop into one of the two International Ocean Cities in China.

Southern University of Science and Technology (SUSTech is a public research university established in 2011, funded by Shenzhen Municipality. Widely regarded as a pioneer and innovator in collectively moving China's higher education forward to match China's growing role in the international arena, SUSTech aspires to become a globally-renowned university that contributes significantly to the advancement of science and technology by excelling in interdisciplinary research, nurturing creative future leaders and creating knowledge for the world. More information can be found in website: **http://www.sustech.edu.cn.**

2. OVERVIEW OF DOSE

The Department of Ocean Science and Engineering (DOSE) was founded in July 2015, aiming to build a team of high quality and international faculty, an "Into the deep ocean" scientific research platform, an international research program in Oceanography, and an internationally leading center in Ocean Engineering. Our long-term vision is to station in Shenzhen, devote our research to the three oceans of the globe!

Research areas in Ocean Science include Marine Geophysics/Geology (Solid), Physical Oceanography (Liquid) and Microbial Oceanography/Biogeochemistry etc. Those in Ocean Engineering include Offshore and Coastal Engineering, Offshore Energy & Resource and Ocean Acoustic & Fiber Technology etc.

As in January 2020, DOSE has 17 faculty staff, including five Chair Professors, two Professors, one Associate Professor and nine Assistant Professors. Our plan is to increase the number to 40 within a short period of time.

3. OCEAN SCIENCE & FACULTY OPENINGS

We plan to appoint a **Chair Professor in Physical Oceanography** (**Liquid**), and about **10 Assistant/Associate/Full Professors** in all fields in Ocean Science.

4. OCEAN ENGINEERING & FACULTY OPENINGS

Ocean Engineering is a strategic discipline for development in DOSE and SU Tech. We plan to appoint at least **12 faculty staff at all levels including Assistant/Associate/Full/Chair Professors** in the following areas:

· Structural Engineering
· Fluid mechanics
· Wind engineering
· Wave-structure interaction
· Geotechnics
· Ocean Engineering materials
· Offshore Engineering & Resource
· Pipelines
· Ocean Acoustic & Fiber Technology
· Ocean Engineering equipment
· Ocean Engineering surveying

5. REMUNERATION & START-UP PACKAGES

I. Income and Benefits
1. Globally competitive (including US & HK) salary
2. Apartment inside campus (depending on remaining apartment quantity) or housing allowance of leasing outside;
3. Social Insurance: Retirement insurance, medical insurance, unemployment insurance, industrial injury insurance, maternity insurance and housing accumulation funds. Special health insurance negotiable.
4. Shenzhen living subsides of CNY 1.6~3 million and other living subsidies according to your talent level.

II. Lab space no less than 150 square meters.

III. SUSTech start-up fund of CNY 1 million and other research funds according to your talent level.

6. HOW TO APPLY

Candidates must have a proven and consistent track record of high-quality scientific publications, good communication skills and relevant teaching experience corresponding to their stages of career. English are required languages for teaching.

To apply, please submit the following materials electronically to **wangy9@sustech.edu.cn**: **1**) Cover letter; **2**) Curriculum vitae (with a complete list of publications); **3**) Statement of research, including justification of your suitability for being a faculty member in DOSE and your future research plan; **4**) Statement of teaching, including your teaching philosophy and teaching interests; **5**) Three representative full papers; and **6**) Names and contact information of five referees.

All applications will be considered shortly after received and offers will be made to those who are qualified.

English is a primary instructional language.

The SUSTech | School of Environmental Science and Engineering (ESE) (http://ese.sustc.edu.cn/en/) was established in May 2015. The mission of ESE is to become: an innovative training ground for cultivating top talent in environmental fields; an international center of excellence for environmental research; a leading platform for innovation and industrialization of advanced environmental protection technologies; and an influential think-tank for environmental sustainability. Currently, ESE has over 65 full-time faculty and research staff, including the recipients of numerous national and international awards and honors. ESE is organized into three broadly-defined groups (programs): Environmental, Water, and Global Change (including atmospheric science). The school is home to the State Environmental Protection Key Laboratory of Integrated Surface Water-Groundwater Pollution Control as well as the Shenzhen Institute of Sustainable Development.

Applications are invited for faculty positions at all ranks. Areas of interest include, but are not limited to, environmental toxicity, soil and groundwater contamination and remediation, ecohydrology and ecological restoration, environmental health, environmental microbiology and biotechnology, atmospheric chemistry and air pollution control, wastewater and solid waste treatment and recycling, remote sensing and environmental monitoring, earth system modeling, macroecology and biodiversity, global change and environmental sustainability. ESE is planning to fill additional two dozen tenure-track/tenured positions over the next 3-4 years to enhance and expand existing faculty and research strengths. Globally competitive (including US and Hong Kong) salaries and benefit packages will be offered. New hires may also be eligible for additional government support such as the Shenzhen City's Peacock Program and many others (http://www.sustech.edu.cn/en/faculty_en).

Applicants are required to have a Ph.D. in environmental science and engineering, earth and atmospheric sciences, or related disciplines. Postdoctoral experience is preferred but not required. Candidates must have a proven and consistent track record of high-quality scientific publications and good communication skills. To apply, submit the following materials electronically to iese@sustech.edu.cn: 1) Cover Letter; 2) Curriculum Vitae (with a complete list of publications); 3) Statement of research and teaching interest; 4) PDFs of three recent publications; and 5) Names and contact information for 3-5 references. All positions remain open until filled. For additional information, please contact Yuanyuan Su (email: suyy@sustech.edu.cn, phone: +86-755-8801-0822).

The Faculty of Mathematics and Natural Sciences at the University of Rostock is involved in a joint appointment procedure with the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt e.V.) (DLR) and invites applications for a University Professorship (W3) for Solar Terrestrial Physics to commence work at the earliest possible date. The successful applicant will be assigned to the University of Rostock as a university professor with a reduced teaching obligation (2 SWS) and in parallel will undertake the position of the Director of the DLR Institute for Solar-Terrestrial Physics in Neustrelitz.

Women with essentially equivalent qualifications will be given priority provided that the personal qualities of a male candidate are not better suited for the position.

Further information about the position, and application process can be found under https://www.uni-rostock.de/en/stellen/professuren/

Ocean Sciences

Postdoctoral Positions at iHESP, Texas A&M University

Overview: The International Laboratory for High-Resolution Earth System Prediction (iHESP, https://ihesp.tamu.edu) – a QNLM-TAMU-NCAR partnership seeks to hire two postdoctoral researchers in high-resolution climate modeling, analysis and prediction research. The postdocs will be supported and managed through the iHESP main office at Texas A&M University, College Station, Texas, but are expected to work closely with scientists at NCAR and QNLM.

Area of research: We seek candidates with strong background in ocean, atmosphere and climate dynamics, and/or high-performance scientific computing. Specific areas of expertise include, but are not limited to:

- Subseasonal-to-decadal climate prediction and predictability
- Weather and climate extremes
- High-performance scientific computing and data science in climate research

Appointment: Each position will be supported for two years, contingent upon funding availability and satisfactory performance.

Application Instructions: Applications must include the following:

1. A cover letter containing a statement of interest.
2. A curriculum vitae.
3. Three references with complete contact information.

Review of applications will begin immediately and the positions will remain open until filled. Application submission information can be found:

https://tamus.wd1.myworkdayjobs.com/en-US/TAMU_External/job/College-Station-TAMU/Postdoctoral-Research-Associate-3_R-017416-1

https://tamus.wd1.myworkdayjobs.com/en-US/TAMU_External/job/Bryan-TAMHSC/Postdoctoral-Research-Associate-1_R-029797-3

iHESP is within the Department of Oceanography which is a part of the College of Geosciences at Texas A&M University along with Departments of Atmospheric Sciences, Geography, and Geology & Geophysics, as well as the Berg Hughes Center, the Texas Center for Climate Studies. The Department web site http://ocean.tamu.edu contains a full description of our program.

The Texas A&M System is an Equal Opportunity/Affirmative Action/Veterans/Disability Employer committed to diversity.

CLIMATE SCIENTIST

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The successful candidate will have a Ph.D. in a relevant natural or social science plus more than 10 years of research and media experience.

For more information, visit:
https://www.climatecentral.org/what-we-do/jobs#climatescientist.

Talofa from Ofu!

The U.S. Geological Survey (USGS) and the National Park of American Samoa (NPSA) are collecting data on Ofu, in the Manuʻa Islands of American Samoa. NPSA's Ofu unit contains more than 80 species of corals that are uniquely tolerant to thermal stress: Daily temperatures in the pools frequently exceed the local coral bleaching threshold of 30°C. Corals growing here provide insights into potential coral acclimatization and adaptation to climate change.

Ofu's pools are experiencing an outbreak of *Valonia fastigiata* algae that is overgrowing and killing healthy coral colonies, implying a shift in the local nutrient regime toward eutrophication. Submarine groundwater discharge (SGD) is increasingly recognized as an important vector for transporting nutrients into the coastal ocean, often leading to eutrophication and algal blooms. SGD is the dominant source of fresh water to Ofu's pools and is thus a likely pathway for transporting nutrients that may be driving the detrimental algal outbreak.

The photo shows Cordell Johnson tending to a USGS-developed radon-measuring buoy that enables scientists to quantify SGD rates to the coral reefs. The goal is to constrain the SGD-associated nutrient loading and identify the patterns of impact in Ofu's pools, thus leading to future management decisions to protect these important corals.

—**Curt Storlazzi,** Pacific Coastal and Marine Science Center, U.S. Geological Survey, Santa Cruz, Calif.

View more postcards at bit.ly/Eos-postcard