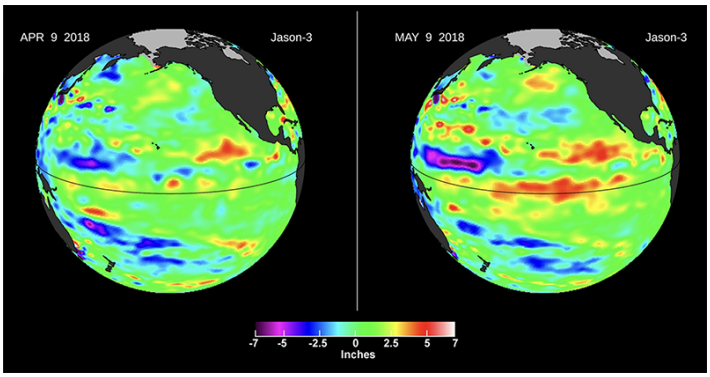
A Climate for Physicists

As concerns about climate change grow, researchers from fields ranging from gravitational-wave astronomy to condensed-matter physics are finding unexpected opportunities to contribute to climate research.

By **Sophia Chen**

Two and a half years into graduate school, Morgan O'Neill got scooped. A research team in another country published a nearly identical study before she could. "I was heartbroken," she says. At the time, O'Neill was studying tropical storms. She switched to studying Saturn instead.

The shift may sound dramatic, but O'Neill found the research pivot relatively smooth. The physics of Saturn's storms wasn't too different from that behind Earth's hurricanes. "I was able to borrow from tropical [meteorology] to develop a simple model and explanation of what's going on for Saturn," she says. For her PhD, O'Neill used computational models to study the Earth-sized cyclone at Saturn's north pole. Now a professor at the University of Toronto, O'Neill has come back full circle to studying storms on Earth.



Sea-level-height maps captured by a satellite in April (left) and May (right) of 2018. The red feature appearing along the equator in May is associated with a Kelvin wave.
Credit: NASA; JPL-Caltech

O'Neill's career trajectory illustrates the broad connections between climate science and more conventional fields of physics. During a **roundtable discussion** at this year's **Global Physics Summit** of the American Physical Society (APS) in Denver, O'Neill joined Brad Marston of Brown University in Rhode Island and Valerio Lucarini of the University of Leicester in the UK to discuss these connections. He and the other panelists argued that climate research can benefit in many ways from a physics perspective.

"A lot of climate scientists self-identify as physicists," says Marston, who is also the current APS president (APS is the publisher of *Physics Magazine*).

The panel came at a consequential time for climate action. In 2023, the Intergovernmental Panel on Climate Change (IPCC) released a report describing paths the world could take to limit global temperature rise to 1.5 °C compared to preindustrial levels. Even if warming is limited to 1.5 °C, the risks of extreme weather events, ocean acidification, and other climate impacts would increase. Yet compared with a 2 °C rise, the consequences would be substantially less severe and would require significantly less adaptation to climate change, according to the IPCC.

Achieving that target will require political commitment—and that commitment is uncertain, particularly in the US, the second biggest carbon emitter globally. The current US administration has cut funding for climate-science research; eliminated climate-science positions at the Environmental Protection Agency; and announced plans to dismantle the National Center for Atmospheric Research, an institution whose research includes climate science, meteorology, and space weather.

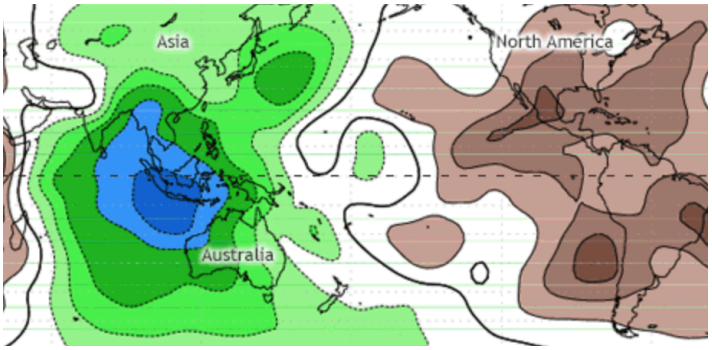
O'Neill anticipated the changing political environment when she decided, in 2023, to move her lab from Stanford University to the University of Toronto, where she sought the greater stability of climate-science funding in Canada. "I was pretty confident that Trump was going to win reelection, and I knew I would want to leave the country as a climate scientist," she says.

Despite the political uncertainty, some physicists are still looking for ways to contribute to climate science. Levi Schult, a 26-year-old PhD student at Vanderbilt University in Tennessee who studies gravitational waves, grew up aware of the of the vulnerability of New Orleans to rising seas and coastal flooding. "It feels so daunting and pressing of an issue," Schult says. She is now considering how to apply her modeling skills to climate science.

Condensed-matter physics, too, has surprising connections to climate science. Marston found that Earth's oceans and atmosphere can support flow patterns that are mathematically analogous to electron motion in an exotic state of matter known as a topological insulator. "There's a wave equation in both cases," he says. Electrons in a topological insulator follow the Schrödinger equation, whereas Earth's ocean dynamics follow classical wave equations under the influence of Earth's rotation.

In a topological insulator, electrons flow on the material's edges or surfaces, while the bulk remains insulating. Those edge currents are robust: They can persist in the presence of defects or disorder that would normally scatter electrons. This edge transport can make topological insulators a useful analogy for certain wave patterns in Earth's oceans and atmosphere.

On Earth's surface, the oceans support several types of giant equatorial waves, such as Kelvin waves and Yanai waves, whose wavelengths can extend for thousands of kilometers. Such waves, according to Marston, are mathematical analogues of the edge currents found in certain topological insulators in which an applied magnetic field deflects electrons. Instead of a magnetic force, it's the Coriolis force that deflects fluid motion on Earth's surface. Because the Coriolis force vanishes at the equator, the equator can be thought of as "the boundary between two topological insulators," Marston says. The result is Kelvin and Yanai waves that can travel long distances with little distortion.



The Madden-Julian oscillation involves the movement of large-scale patterns of enhanced (green) and reduced (brown) rainfall.
Credit: NOAA; Climate.gov

Now Marston is working with Brown University undergraduate Leopold Li to look for signatures of topologically protected waves in the Madden-Julian oscillation, a large-scale pattern of rainfall that circles the tropics every 30 to 60 days and that can affect monsoons in Asia and Australia and the timing of El Niño, among other things. Li is building a simple computational model to try to elucidate the mechanisms driving the oscillation. This impactful phenomenon isn't accurately captured by current weather and climate models.

While climate science's societal relevance appeals to Li, his primary motivation is understanding the scientific phenomenon itself. "It just so happens [that] many of the most fascinating problems that I've encountered in my life are geophysical in nature," Li says.

Statistical-mechanics concepts can also apply to climate science. Lucarini studies climate tipping points—thresholds beyond which a system abruptly shifts from one equilibrium state into another. Similar transitions occur throughout physics, from magnets losing their magnetization to water changing phase. "Statistical mechanics gives you a formal language to describe accurately what a tipping point is," Lucarini says.

Earth's climate appears to have undergone such transitions before. Drawing on both paleoclimatic records and theoretical models, researchers have found indications that Earth's past climate has tipped between different stable configurations,

Lucarini says. A dramatic example is Earth's "snowball" state, a period between 717 and 635 million years ago when ice may have covered nearly the entire planet. Geologic evidence of glaciers at the tropics, together with climate simulations, supports the idea that Earth entered—and eventually escaped—this globally frozen state.

If Earth's climate has tipped between stable states in the past, the question is whether it could do so again. Lucarini studies potential tipping points associated with rising carbon dioxide levels. One prominent candidate is the Atlantic Meridional Overturning Circulation, an ocean current that brings warm water from the tropics to northern Europe and returns cold water southward toward Antarctica. Evidence suggests that this current is slowing down, and some researchers worry that a major weakening could trigger drastic changes, including the cooling of currently fertile regions of northern Europe and shifts in tropical precipitation cycles.

The politicization of climate science can make the field look unusually contentious and uncertain compared to other scientific disciplines. Mohammad Ashraf Modares, a graduate student in O'Neill's group, thinks that the public discussions of climate science have unfairly demonized the associated uncertainties, treating them as weaknesses rather than normal features of the scientific method. "The uncertainties in climate studies seem normal compared to any kind of science," he says.

But physics is only one piece of the climate puzzle, and cross-disciplinary work can be difficult to communicate across research communities: Marston, for example, has had to choose between publishing in journals aimed at atmospheric scientists and those read by condensed-matter physicists, even when both audiences would find the work interesting.

To Marston, our planet's atmosphere and oceans command a sense of wonder comparable to that evoked by astronomy. Images from the JWST observatory "lead to this greater appreciation for our place in the Universe," he says. Climate physics could achieve something similar by offering people "an appreciation for the amazing beauty of the climate system," he says. And that sense of marvel may prove more powerful in shaping human behavior than facts and warnings alone.

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