WHAT CAN WE DO ABO

By Dave Zobel

Here's a not-news flash: Earth's polar ice caps are melting.

The melting is largely due to a rise in the global mean temperature. Which is largely due to an increase in atmospheric greenhouse gases. Which is largely due to human activity. It's a domino chain, set tumbling by *Homo sapiens*, and the next time some dogmatist tries to tell you otherwise, you can say that Paul Wennberg told you so.

Wennberg, the R. Stanton Avery Professor of Atmospheric Chemistry and Environmental Science and Engineering at Caltech, is the acting director of the Ronald and Maxine Linde Center for Global Environmental Science, a consortium of close to 30 Caltech research labs that are attacking climate change from as many different angles. (The old saw that everybody talks about the weather but nobody does anything about it, observes benefactor Ronald Linde gleefully, is evidently no longer true.) The center's goal: to develop a quantitatively rigorous understanding of the mechanisms that determine Earth's climate—both past and future—and how that climate in turn influences the biosphere.

Why are so many investigators needed? Because, as Wennberg grimly acknowledges, the underlying problem is still poorly understood. "We have only a poor description of how clouds form and persist," he says, "and this ignorance limits our ability to predict the future climate. While we know that warming in the polar regions will reduce the extent of glaciation, the rate at which the ice melts—and the sea level increases—is highly uncertain. Perhaps least understood is how Earth's biosphere, both on land and in the ocean, will respond to changes in climate and CO_2."

Given such a chaotic landscape, no single piece of the puzzle solves the whole; no magic bullet offers a quick fix; no scientific discipline alone—and certainly no solitary researcher—holds the key. Instead, Caltech's chemists and physicists must work alongside its engineers and environmental scientists, its isotopic biogeochemists and molecular geomicrobiologists.

Mapping climate change's ubiquitous tendrils, Wennberg says, will require these scientists to make the most of the interdisciplinary tools and approaches available to them.

LOOK—UP IN THE SKY

Of all the footprints humans have left on the biosphere, perhaps the muddiest belong to the greenhouse gases. These include, in addition to media darlings carbon dioxide and methane, such culprits as carbon monoxide, nitrous oxide (no laughing matter in this context), and water vapor. The global warming they cause is real and measurable and can have wide-ranging effects on the environment.

JT CLIMATE CHANGE?

For example, we have ancient plants to thank for making our world habitable by producing much of the oxygen in our atmosphere. It's painfully ironic that, today, the descendants of those plants are experiencing climate change caused by atmospheric changes resulting from the burning of fossil fuels—the remains of those same ancient plants.

In hopes of gaining a better understanding of what exactly we're standing under, many Caltech researchers are studying the skies. Wennberg, for instance, has created and deployed the worldwide Total Carbon Column Observing Network (TCCON), which detects the fingerprints of various atmospheric components by measuring the spectroscopic bite they take out of the sun's incoming rays. One of TCCON's earliest successes was the discovery of more methane over Los Angeles than current models could account for. Can it be traced back to some local source of pollution, or is its origin more global? To find out, Wennberg is considering recruiting students to drive around the L.A. basin with methane-monitoring devices.

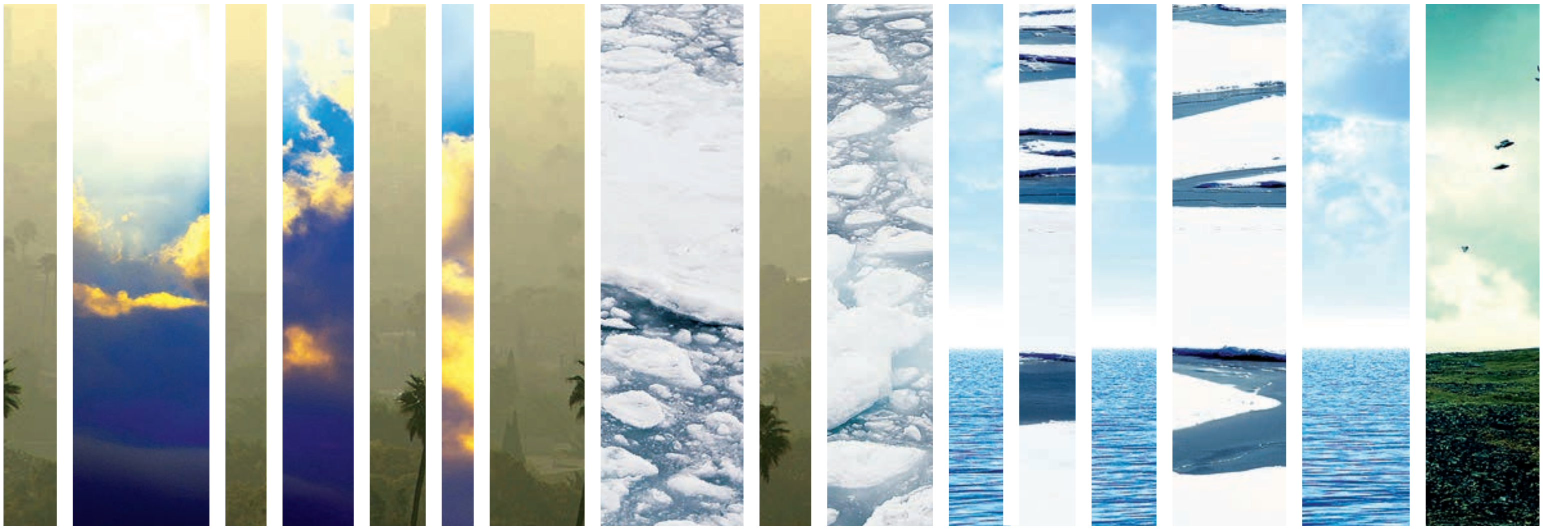
Climate change, incidentally, produces many effects, of which global warming is just one. For example, work done by environmental scientist Richard Flagan, the Irma and Ross McCollum–William H. Corcoran Professor of Chemical Engineering, points to climate change as the key to understanding a longstanding medical conundrum: How can pollen particles, which are too large to get past the nasal cavity, trigger asthma deep in the lungs? His studies have shown that when local wet/dry cycles are disrupted, pollen grains rupture on the plant—and the resulting bioactive microfragments are small enough to invade the lungs and wreak all manner of respiratory havoc.

In fact, the atmosphere is a complex, multilayered chemical laboratory. Even the stratospheric trace gases (found kilometers above us and as hardly more than faint wisps on a spectrograph) can exert their photochemical influence on the biosphere—i.e., us. This, says chemical physicist Mitchio Okumura, is an effect we cannot ignore.

THE MAIN CHALLENGE(S)

Actually, it's unfair to blame global warming solely on the greenhouse gases. The global heat engine, a system characterized by a continual flow of heat toward the poles, is regulated by a complex interplay of activities all over Earth's surface: on the sea and on the land as well as above and below them. One such activity is the movement of air and water, both in obvious local patterns and in larger, more stately dances that nonscientists rarely notice.

"People are often surprised to learn that there's something called the North American monsoon," remarks environmental scientist Simona Bordoni. "But it's a very real phenomenon, responsible



for summer thunderstorms and flash floods across the deserts of the Southwest and Mexico." Bordoni studies the interactions between mid- and large-scale atmospheric circulations. Using satellite observations of ocean-wave roughness to estimate surface wind velocity, she's traced broad changes in the monsoon's northernmost extent back to wind surges over the relatively narrow Gulf of California—a real-world butterfly effect.

Those butterfly wings may well be messing with the Greenland ice sheet as well. When warm winds—warmer than they should be, at least—cross the sheet's surface, they give rise to impromptu lakes of meltwater, which then drain away through cracks in the ice. Victor Tsai, who studies solid-earth geophysics, says that if this runoff reaches the underlying ground without refreezing, its lubricating effect might very well hasten the ice sheet's glacial march toward the shore. The result would be an increase in the iceberg calving rate, which, like adding ice cubes to a drink, could lower the average temperature of the Greenland Sea, kicking off yet another set of potential consequences.

Nothing evolves in isolation, particularly under the stresses produced by a constantly shifting climate.

While such a model is easy to visualize, Tsai cautions that at this point it's still only hypothetical. "The interactions between atmospheric warming, the ice sheet, and the ocean are intricate," he notes, "and that makes it challenging to understand the whole system."

Those sorts of interactions are similarly challenging for Andrew Thompson, a specialist in physical oceanography who is focusing on modeling the effect of climate perturbations on the circulation of ocean currents—a process that's actually far less straightforward than those looping arrow diagrams you remember from earth-science class. Consider the Antarctic Circumpolar Current, flowing perpetually eastward around Antarctica along a swath of latitude never interrupted by land. That fluke of geography sets up a fierce system of ocean jets that encircle the South Pole like a liquid skirt. These jets act as a gateway that controls the invasion of warmer water from equatorial latitudes as well as the escape across the ocean's abyssal plains of icy waters formed under ice sheets. This cold Antarctic Bottom Water is the densest seawater on the planet, and it influences everything from the amount of carbon dioxide in the atmosphere to the distribution of tiny krill, a keystone of the global food chain. The slightest imbalance in the system could have a ripple effect that substantially alters Earth's climate.

To model the oceanic effects of climate perturbations, Thompson sends autonomous robotic systems diving and drifting through the Southern Ocean, where they track their own positions via GPS and report local current data via satellite. "Using CITerra [a Caltech supercomputer cluster], we can compare these field observations with simulations of ocean circulations," he explains. "The results tell us how small-scale ocean flows govern ocean-ice interactions and feedback on sea level and other global aspects of climate."

Given such a sensitive global system, how can humankind hope to tweak the thermostat even the tiniest bit without triggering a catastrophe? Presumably, the first step is to identify the main stumbling blocks, of which each researcher seems to have a particular "favorite." For atmospheric scientist John Seinfeld, the John E. Nohl Professor and professor of chemical engineer-

ing, it's our limited understanding of two specific interrelated factors: the life cycles of aerosols, and the microphysics of clouds themselves. "Aerosols reside in the air for only a week or two, but that difference has a large effect on their climatic influence," he says. "That's because clouds form on these particles. Since the Industrial Revolution, the global level of aerosols has increased, and yet determining just how this increasing burden of particles has affected the world's clouds—and then how those clouds affect climate—remains one of the grand challenges in climate science."

Planetary scientist Andrew Ingersoll, on the other hand, is most focused on teasing apart the net-energy equation. "Of all the planets in the solar system with atmospheres, Earth absorbs the most energy per unit area, and yet it has the weakest winds," he says. That doesn't quite make sense, he adds, since air movement tends to be linked to and driven by differences in heat between ground and air. What's slowing down our winds? Nobody knows. "Clearly," Ingersoll says, "there's a lot we still don't understand about climate."

CLUES ALL AROUND US

One way to try to get a better idea of what is going on is to look to the past. Climate change is, it turns out, hardly an invention of modern humanity. Cores extracted from ancient corals and stalagmites by geochemists John Eiler and Jess Adkins reveal dramatic shifts and upheavals in the paleoclimate. Indeed, geobiologist Woody Fischer has found evidence in sedimentary rocks that correlates several mass extinctions—not just that of the dinosaurs—to climate-change events. And there's evidence that it was climatic pressure that drove ancient bacteria to evolve photosynthesis; by studying the chemical footprints they left behind, molecular geomicrobiologist Dianne Newman can trace the various branching pathways they took.

This suggests that an improved understanding of the complex interdependence between Earth and its inhabitants is vital. "We've known since Darwin that the evolution of species is shaped by the physical environment," explains biogeochemist Alex Sessions. "But it turns out that the relationship is reciprocal: under the influence of biology, the planet itself is evolving." An example: after a wildfire scours a grassy hillside, the resulting erosion deposits sediment downstream; as plants take root in the newly created wetlands, the soil's angle of repose increases, and new hills arise.

Nothing evolves in isolation, of course, particularly under the stresses produced by a constantly shifting climate. In this regard, it appears that one of the humblest organisms on the planet has much to teach the most advanced. Environmental microbiologist Jared Leadbetter has found that the termite would be unable to process lignocellulose—the substance that makes up the cell walls in wood—if its gut didn't harbor a digestive assembly line powered by a pair of cooperating bacterial species. Geobiologist Victoria Orphan is analyzing two cohabitating deep-sea microorganisms that work together in a chemical chain reaction for producing and consuming methane.

In both these cases, each microbial species holds the key to just one part of the process. Only through symbiotic cooperation are they able to pull their energy-transfer rabbit out of a hat.

And *that* makes a fitting analogy for the current state of climate-change research: where convergence is the watchword, where a new wave of portmanteau specializations has blurred the boundaries between scientific disciplines, and where Caltech's researchers, armed with a dazzling array of techniques and toolkits for bringing worldwide change to a changing world, are poised to uncover the answer to climate change.

Once they've worked out the question, that is. e&s

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