A new proxy for Earth's past energy imbalance

Oxygen-isotope measurements of ocean-bottom organisms are an excellent indicator of the atmosphere's radiation flux.

The amount of incoming solar energy that warms our planet today is greater than the energy radiated back to space. That radiation imbalance, predominantly attributable to anthropogenic fossil-fuel emissions, has heated Earth at an average rate of about 0.5 W/m^2 over the past 50 years.

To better understand present and future climate change, researchers study the geologic past—often during ice ages and other periods of extreme climate variations—using measurements from ice cores, sediment records, tree rings, and the like. (See, for example, the article by Toby Ault and Scott St. George, Physics Today, August 2018, page 44.)

Marine sediment records include the shells of micron-sized foraminifera, shown in figure 1. They're single-celled organisms, many of which live at or near the ocean bottom. To paleoclimate researchers, they're useful indicators of climate conditions. Foraminiferal $\delta^{18}O$ is the amount of the trace isotope oxygen-18 relative to the more abundant oxygen-16 in the organisms' shells. That geochemical signal primarily depends on the temperature of the ocean, which affects foraminifer biochemistry, and seawater $\delta^{18}O$, which depends on the volume of Earth's ice sheets and glaciers.

Now Princeton University's Sarah Shackleton and colleagues have combed through global foraminiferal $\delta^{18}O$ records[1] and found a new use for those data. The ocean temperature and ice-volume signals that contribute to the total $\delta^{18}O$ change are distinct. But when the signals are combined, they record global energy changes.[2]

Energy in, energy out

Daniel Baggenstos, who went to graduate school with Shackleton, published a paper in 2019 with her and other colleagues. They used an ice core, sediment records, and coral measurements to estimate Earth's radiation imbalance from the Last Glacial Maximum, about 20 000 years ago, to the present day.[3]

When more energy comes to Earth than goes out, it has to go somewhere: into the oceans, ice sheets, the atmosphere, or land surfaces. Today, a whopping 90% of the excess radiative flux is absorbed by the ocean. But what Baggenstos and colleagues found about past energy imbalance, says Shackleton, is that "warming the ocean and melting the ice sheets are really the only changes

FIGURE 1. MARINE INVERTEBRATES, like the many micron-sized species of foraminifera that form the tens of millimeter-sized shells shown here, are useful indicators of changes in ocean temperature and ice volume. (Photo by the Natural History Museum, London/Alamy Stock Photo.)

that matter." Every other process affected by the total energy imbalance has a much smaller contribution.

That study got Shackleton thinking about whether the foraminiferal $\delta^{18}O$ record would show similar trends to the results in the 2019 paper. "In any kind of Paleoclimate 101 class," says Shackleton, "one of the first things that you'll see is the $\delta^{18}O$ records, and they really are kind of a template for understanding the ice ages. Because they record changes in ice volume and ocean temperature, in the past several decades there have been a lot of efforts to interpret them in terms of either one of these properties." (For more about one recent reconstruction, see Physics Today, January 2022, page 14.)

Compared with the records that Baggenstos and colleagues used to construct 25 000 years of energy-imbalance history, foraminiferal archives have some advantages. For one, the plentiful number of the fossilized organisms in marine sediment cores make them a practically continuous record of change over time. And foraminiferal archives go back tens of millions of years, whereas ice-core records only extend back 800 000 years. (Efforts are underway to find even older ice in Antarctica; see Physics Today, April 2023, page 18.)

Two for one

Compared with the heavy ^{18}O, the light ^{16}O more readily evaporates from the ocean. Polar ice sheets, therefore, are enriched in ^{16}O and return the isotope to the ocean when they melt. Because the foraminiferal $\delta^{18}O$ record reflects the oxygen-isotope composition of seawater, it's a good proxy for ice volume. The foraminiferal $\delta^{18}O$ record is also affected by a temperature-dependent process during shell formation that separates ^{16}O from ^{18}O at chemical equilibrium, which makes it a useful ocean paleothermometer.

Rather than interpret the foraminiferal $\delta^{18}O$ record as a proxy for ice volume or ocean temperature, Shackleton and her colleagues considered whether it could be representative of Earth's energy imbalance. Their crucial insight was that melting ice and rising ocean temperatures have nearly the exact same effect on foraminiferal $\delta^{18}O$.

That is, when they modeled foraminiferal $\delta^{18}O$ as a function solely of ice-volume changes or ocean temperature, the energy changes associated with each variable were quite similar: 19×10^{24} J/ppt (parts per thousand) for ocean warming and 16×10^{24} J/ppt for ice-volume changes. "From what I understand," says Shackleton, "it's just a strange coincidence that they end up translating into similar total energies."

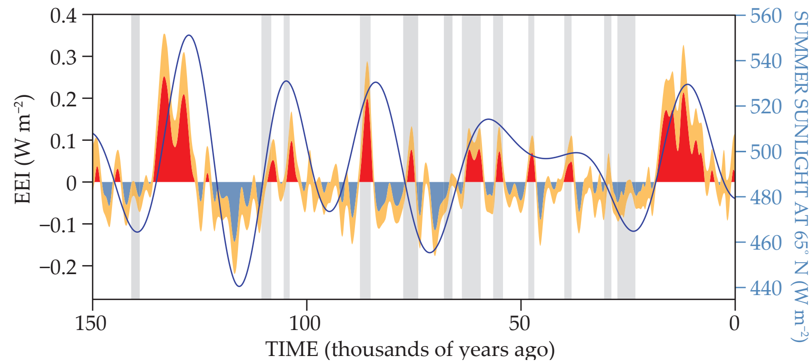

FIGURE 2. ISOTOPE MEASUREMENTS—made from the shells of some ocean-bottom-dwelling foraminifera similar to ones shown in figure 1—estimate Earth's energy imbalance (EEI, yellow line) over the past 150 000 years. Unlike most times with negative energy change (blue area), the periods of positive changes (red area) are associated with Heinrich events (gray shading), when icebergs broke off North America's Laurentide Ice Sheet into the ocean. The reconstructed energy imbalance largely follows the amount of sunlight Earth receives during the summer at 65° N (blue line). (Adapted from ref. 2.)

Thanks to that similarity, Shackleton and colleagues inferred the energy imbalance directly from foraminiferal $\delta^{18}O$ without needing to do the difficult task of deconstructing the isotope measurement into its constituent parts. The paleoclimate community already has independent records of ocean temperature and ice volume, but having a single record sensitive to both variables avoids some challenges, such as the need to carefully align different data to the same age model.

The researchers compared the energy imbalance calculated from foraminiferal $\delta^{18}O$ over the past 25 000 years with previous energy-imbalance predictions. Reassuringly, their results agree with an energy reconstruction based on ocean temperature from noble-gas measurements[3] and ice volume inferred from coral and sediment records.[4]

Figure 2 shows the new energy-imbalance calculation from the foraminiferal $\delta^{18}O$ data, and it extends back 150 000 years. The ups and downs in energy imbalance have a clear association with periods of abrupt climate change known as Heinrich events, when icebergs broke off into the ocean from the Laurentide sheet that once covered much of North America. "That was definitely very interesting, although not necessarily incredibly surprising, based on our understanding," says Shackleton. "But it was really nice to see that come out of the energy-imbalance reconstruction."

The new record also tracks strongly over time with another well-studied climate variable: the amount of sunlight Earth receives during the summer at 65° N, a bit south of the Arctic Circle. Previous research has linked variations in Earth's orbit to reductions of sunlight at that latitude and consequently the onset of global-scale ice ages. Increased sunlight there triggers deglaciation. (For more on orbitally driven ice ages, see the article by Mark Maslin, Physics Today, May 2020, page 48, and Physics Today, September 2016, page 13.)

"This record that we've all been looking at and interpreting," says Shackleton, "can be interpreted in a completely different way." With their new approach to measuring Earth's energy imbalance, she and her colleagues plan to better study millennial-scale perturbations of the climate system and whether they instigate a large restructuring of atmospheric and oceanic circulation patterns.

Alex Lopatka

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