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Hot and cold Earth through time

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What was Earth's temperature tens to hundreds of millions of years ago? Our planet has gone through different periods, some with extensive polar ice caps and others being completely ice-free. Estimating past global temperature is important for understanding the history of life on Earth, for predicting future climate, and more broadly, to inform the search for other habitable planets. However, there have been major disagreements about how hot or cold the ancient Earth was and whether there has been an overall decline in temperature over time. On page xxxx of this issue, Judd et al. (1) report a new reconstruction of Earth's temperature over the last 485 million years by combining climate models with geological data. In contrast to some estimates, they conclude that global warm periods were maintained in similar temperature ranges. This corroborates recent pre-dictions by Isson and Rauzi (2) from a large data compilation of different geological samples, establishing a wider agreement.

Polar ice caps leave distinctive geological evidence that geologists can recover (3), which has allowed mapping of how extensive these frozen regions were over the Phanerozoic Eon—the last 540 million years during which animals and plants evolved. This record shows a cycle between 'icehouse' periods with large permanent ice caps and 'greenhouse' periods without them. The present-day Earth is an icehouse, and it has been for the last 34 million years. The current average surface temperature is around 15 ^{0}C. But were previous icehouse periods also at this temperature? and how hot were the green-house periods? Knowing the past temperature of the Earth helps us better under-stand future climate changes, but measuring it is difficult. Ice cap locations depend on the positioning of the continents, which has changed substantially over time. The sparce geological record causes frequent revision of timing and extent of past glaciation.

One method to precisely measure temperature over geological time is using the ratio of two different isotopes of oxygen, which is the most common element in the Earth's crust. Most oxygen atoms have 8 protons and 8 neutrons. But a small number of oxygen atoms have different numbers of neutrons. One of the naturally occurring oxygen isotopes has 10 neutrons, thus having a heavier weight than its most abundant form. Many marine organisms in-corporate oxygen into their shells or other body parts . The isotope ratio—the ratio of heavier atoms to lighter atoms—in their shells depends on the temperature of the local seawater (higher temperature favors a greater proportion of the lighter iso-tope) and has been used to reconstruct the change in global temperature over geological time (4).

Isson and Rauzi compared the oxygen isotope ratio in different geo-logical samples to predict Earth's past temperature. Although previous measurements in samples covering the last 65 million years are consistent with planetary cooling of Earth and the transition into its current icehouse period (5), wider use of these values has been contentious. Previous analysis of oxygen isotope ratios found lighter values and predicted increasingly hotter global temperatures further back in time. Taken at face value, the findings suggested that primordial Earth—more than 2 billion years ago—had water masses at temperatures exceeding 70 ^{0}C (6). This raises questions about the survival of microbes and formation of ice caps that occasionally appeared on ancient Earth.

A popular answer to this question is that oxygen isotope ratios in seawater have not stayed the same over time. Because the oxygen in shells comes from seawater, a change in the composition of the water would bias the temperature estimates. Thus, Earth's temperature may have been cooler than predicted. However, proving this bias re-quires oxygen-containing minerals that record the seawater isotope ratios directly without the effect of temperature, which have been difficult to find. Fortunately, iron oxides contain oxygen which originates from seawater (7), and the ratios of oxygen isotopes in iron oxides are roughly the same as that of the seawater, without a strong dependence on temperature . Analyzing iron oxides have indeed shown that the seawater iso-tope composition has changed over time (7).

On the basis of this observation, Isson and Rauzi removed the bias imparted by the changing seawater composition and produced a new estimate of Earth's temperature over time. The authors found that seawater temperatures 2 billion years ago were likely similar to those recorded in the more recent period of history. Thus, the models showing extreme temperatures of around 70 ^{0}C on the early Earth appear unlikely, and the evolution of complex life on Earth does not appear to have been the result of a long-term cooling of the planet.

Although these revelations are exciting, reconstructing the long-term average temperature of Earth from oxygen isotope ratios still has uncertainties. The method only records the local seawater temperature. For example, shells from long-deceased organisms that lived in a polar region would record a different temperature to an organism that lived at the same time in a warm tropical region. Neither of the estimates would accurately match the global average temperature at the time. Previous studies have often plotted isotope ratios from tropical locations only to try to avoid this bias (8).

Judd et al. have brought a powerful new tool to this task: data assimilation. They combined a large set of climate model simulations at different global temperatures across the last 485 million years with the oxygen isotope dataset as well as with other less frequently sampled temperature indicators such as temperature-sensitive organic molecules. Joining the model and the geological data enabled the authors to account for regional variations in predicted temperature. For example, a sample from a polar region was compared to climate model predictions in the same region. This produces a more accurate estimate of the global average temperature of Earth over time.

The new Phanerozoic temperature record by Judd et al. shows a sequence of cool and warm climates that is broadly consistent with the known ice cap expansion and retreat. It also reveals some key differences compared to previous temperature estimates. Earlier studies using only tropical oxygen isotope ratios predicted a long-term decline in temperature over the last 500 million years, proposing that earlier greenhouse periods were warmer than more recent ones (8). The new reconstruction of Judd et al. disagrees and instead predicts that greenhouse periods had simi-lar temperature ranges. Given a similar temperature prediction for primordial Earth by Isson and Rauzi, the finding suggests that Earth possesses a global climate regulation system that causes temperature to stay within a particular range. One wide-ly accepted assumption is that the reaction of igneous rocks with water and atmospheric carbon dioxide (CO2) helps to limit the extent of long-term climate change. This process slowly removes CO2 from the atmosphere and is amplified when climate warms. It is also being employed as a geoengineering method to try to counter anthropogenic emissions (9) Thus, further confirmation of a climate regulation system is welcome.

However, the new Phanerozoic temperature record of Judd et al. opens up some potential problems. The model predicts generally hotter temperatures for the greenhouse periods than those achieved in models of Earth's long-term carbon cycle (10). Thus, reassessment of Earth's carbon-climate system over long timescale may be needed to close this gap. Further, the issue of seawater oxygen iso-tope variation has not been entirely re-solved. The iron oxide dataset used to correct against this is sparse (7). Although it has sufficient datapoints to conclude that the isotope ratio has most likely changed over the past billions of years, the amount of change over the last 500 million years is not clear. Even small variations in seawater oxygen isotopes have a large effect on temperature predictions made through the data assimilation methods used by the authors. More data to constrain this effect is needed, and alternative reconstructions of Earth's temperature that do not rely on oxygen isotopes must continue to be developed.

Direct comparison of a possible future greenhouse climate to the past ones remains difficult because those warm periods were established gradually over millions of years. However, they are the only evidence available for what greenhouse climates look like, and they are vital for testing the accuracy of climate models (11). More fundamental scientific questions about the thermal limits of Earth's biosphere and the role of temperature change in the evolution of more com-plex life forms also arise, and improved understanding of past temperatures will help answer them. This will also help assess the driving processes behind long-term temperature changes and the natural mechanisms of stabilizing or destabilizing Earth's climate.

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