Climate control: Is CO_2 really in charge?

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CROCODILES in the Arctic? You better believe it. There was a time, about 90 million years ago, when the Earth was so warm that crocodile-like creatures lived and bred inside the Arctic Circle. At other times, ice has spread over large parts of the planet.

Cold, hot, cold, hot - what causes the dramatic swings in Earth's climate? (Image: Macduff Everton/Radius Images/Corbis)

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The prime suspect for these dramatic swings in Earth's climate is carbon dioxide: hot periods over the past half a billion years generally coincided with high levels of CO_2 in the atmosphere and vice versa. A few studies, however, suggest that there may been periods when it was cold when CO_2 levels were high, or hot when CO_2 levels were low. So what was going on at these times? Are we missing part of the climate puzzle?

Explaining these anomalies matters, because researchers are increasingly looking at past changes in our climate to help find out what's in store for future generations as CO_2 levels shoot up. Such studies provide "real-world" guides to the future that do not rely on computer models alone.

The tricky part about studying the climate of the past is working out what happened millions or even billions of years ago. Luckily, there are all kinds of clues to look at. Rocks reveal much about conditions at the time they formed; many rocks form only when there is liquid water, for instance. Ice sheets also leave numerous signs of their presence, from distinctive patterns of erosion to the mud and boulders they deposit.

Combine all the different indicators, and a consistent picture of past temperature emerges. While there have been ice ages from time to time, there is evidence of liquid water stretching back more than 3 billion years. Indeed, for much of Earth's history the planet has been warmer than it is now.

This is surprising, because the sun has been getting steadily hotter and emits one-third more energy now than it did 4 billion years ago. If Earth's climate was all down to the sun, the planet ought to have grown steadily hotter.

In 1981, Jim Kasting of Pennsylvania State University in University Park suggested that this relative stability in climate is all down to a CO_2 "thermostat". It has to do with the long-term carbon cycle: some CO_2, in the form of organic matter or carbonate rocks, gets buried deep in the Earth's crust for a time, and is eventually released back into the atmosphere by volcanoes.

The first step in the formation of carbonate rocks occurs when CO_2 reacts with silicate rocks. This process is called weathering - and the rate of weathering, Kasting pointed out, depends on the temperature. When the planet warms, weathering speeds up, removing more CO_2 from the atmosphere and thus causing the temperature to fall. When the planet cools, weathering slows but volcanoes keep on pumping out CO_2, so levels eventually rise.

You would not want this kind of thermostat controlling your fridge: it can take millions of years to have a major effect, so there can still be wild swings in the climate. However, it might help explain why Earth's temperature has remained in the vital liquid water range.

Bubble trouble

The implication is that although any number of factors can affect the climate - from orbital variations to changes in the position of continents - the level of greenhouse gases, and CO_2 in particular, is the most important. To find out if this is true, we have to look at how CO_2 levels have changed in the past.

The best way to do this is to measure CO_2 levels in the tiny bubbles of air trapped in the ice sheets of Greenland and Antarctica - but this does not take us back very far. "The oldest ice on the planet is about a million years old, maybe a little older," says Aradhna Tripati of the University of California, Los Angeles.

To get an idea of CO_2 levels in the more distant past, researchers have to rely on less-direct methods. One is to model the long-term processes affecting CO_2 levels, such as the amount of volcanism and the rate of fossil-fuel formation. Geochemists have been refining such models for decades, which provide a broad-brush picture of average CO_2 levels over tens of millions of years but cannot tell us much about shorter-term swings.

Another method is to look at the density of the pores, or stomata, in fossilised leaves. Plants need stomata to let CO_2 in, but they also lose water through them, so they usually have no more than necessary. "It has been observed in many plants that the density of the pores goes down as CO_2 goes up, and it tends to be a species-specific response," says Dana Royer of Wesleyan University in Middletown, Connecticut. Royer and others have estimated past CO_2 levels by looking at the changes in stomatal density in plant lineages that have otherwise not changed much over time, such as *Ginkgo biloba*.

Measuring the ratio of isotopes of carbon in fossil soils and shells in marine sediments can also give an idea of changes in CO_2 over the past half billion years or so. There are issues with all of these approaches, but in general they all support the idea that global temperature and CO_2 levels are linked. Over the past 400 million years of Earth's history, CO_2 levels have been relatively low when the planet had extensive ice sheets, from about 330 to 290 million years ago and from 35 million years ago to today. For the rest of the time, they have been much higher (see graph).

Nevertheless, hidden in these broad sweeps of time are some niggling inconsistencies. Take the Miocene, from 23 to 5 million years ago, the time that saw the growth of ice sheets in Antarctica. In the middle of the Miocene, about 15 million years ago, there was a period of relative warmth. However, reconstructions suggest CO_2 levels over this period remained low, below 300 parts per million (ppm).

The existence of such inconsistencies no more disproves the idea that CO_2 causes warming than your house warming up on a sunny day proves it does not get warm when you turn the heating on - rather, it suggests that some other factor caused the warming. In theory the mid-Miocene anomaly could be due to the sun warming, for instance, except that as far as we know the sun's output, while gradually increasing, otherwise varies very little.

So Wolfram Kürschner of Utrecht University in the Netherlands and colleagues decided to check the results of earlier studies using a method based on stomatal density. After examining fossilised leaves from three plant groups, Kürschner's team reported in 2008 that while CO_2 levels fell from 600 ppm to below 300 ppm at the start of the Miocene, they rose to 500 ppm during the mid-Miocene warmth before falling again (*Proceedings of the National Academy of Sciences*, vol 105, p 449).

Meanwhile, Tripati and her colleagues were developing their own method for revealing past CO_2 levels. Their technique involves studying the ratio of boron to calcium in the fossil shells of creatures that lived in surface waters. This ratio is related to the ocean's acidity at the time the shells grew, which in turn is linked to atmospheric CO_2 levels.

The team used fossils in deep-sea sediment cores from two sites in the western tropical Pacific Ocean to reconstruct the CO_2 history of the last 20 million years. First, Tripati's team showed that CO_2 levels for the past 800,000 years calculated using their method match those measured in the ice cores, strong evidence that their technique is accurate. Looking further back, they too found that CO_2 levels were high in the mid-Miocene, ranging from 350 ppm to 500 ppm - comparable to today's level of 380 ppm (*Science*, vol 326, p 1394).

The story is similar for other apparent inconsistencies. Towards the end of the Ordovician period, 440 million years ago, the planet entered a deep ice age that caused a major extinction, even though CO_2 levels appeared to have been high. However, more detailed studies by Seth Young of the University of Indiana in Bloomington show levels did fall at the start of the ice age. They rose later as weathering slowed, eventually bringing about the end of the ice age.

Rather than some unknown factor being behind these inconsistencies, it now appears they were simply due to problems with the earlier studies. "The more we look at the past, the more evidence we seem to find for this idea that CO_2 is very important for controlling Earth's climate," says Tripati.

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So what is going to happen next? How do findings based on studies of past climate compare with the predictions made by computer models? "None of these are a perfect representation of the Earth," says Tripati. "Can we use the past response of climate to better understand how sensitive Earth's temperature is to greenhouse gas levels?"

Climate sensitivity refers to how much global temperature rises when the level of CO_2 in the atmosphere doubles. Just about everything hinges on this number. The higher Earth's climate sensitivity, the more temperature and sea level will rise as we pump CO_2 into the atmosphere, and the greater the disruption to our civilisation and ecosystems. "If somebody wants to argue intelligently against some kind of CO_2 effect on climate, they tend to focus on very low climate sensitivities, say 1 °C per CO_2 doubling," says Mark Pagani of Yale University.

True sensitivity

Sensitivity is defined as the effect of doubling the level of CO_2 in the atmosphere because CO_2 has less effect as levels rise. If an increase from 280 to 560 ppm warms the planet by 1 °C, an increase from 280 to 1120 ppm should warm it by 2 °C. Indeed, physics tells us that for every doubling of CO_2 the Earth's temperature should rise by 1 °C - if nothing else changes.

In reality, all kinds of things change when the planet heats up. When the atmosphere warms, for instance, it holds more water vapour, a potent greenhouse gas, which leads to further warming. Warming also reduces the area covered by snow and sea ice, meaning less energy is reflected back into space, again leading to further warming. Plugging such feedbacks into computer models gives a climate sensitivity of between 2 °C and 4.5 °C, with a best estimate of 3 °C, the last report of the Intergovernmental Panel on Climate Change concluded.

Unfortunately, in some ways this figure is misleading, and not just because of the uncertainties in the models. The deeper problem is that current climate models include only feedbacks that kick in rapidly in response to warming. Feedbacks that kick in only after decades or centuries, such as changes in the extent of ice sheets on land (as opposed to snow and sea ice), are left out.

So the true climate sensitivity, or Earth system sensitivity, could be larger than the short-term sensitivity. And because existing climate models are not yet sophisticated enough to include slow feedbacks, the only way to work out the Earth system sensitivity is to look at the effect of past CO_2 rises.

Royer and colleagues recently made a rough estimate of the average Earth system sensitivity over the past 400 million years based on all the past CO_2 reconstructions. Their calculations suggest that it is around 3 °C per CO_2 doubling (*Nature*, vol 446, p 530).

"The deep time [data] cuts the tails off of the uncertainties," says Richard Alley of Pennsylvania State University. "The really low value of just 1 °C for doubling of CO_2 just doesn't work. And the really high values, 10 to 11 °C for doubling of CO_2, don't work either. A number of 3 °C or somewhat higher works pretty well."

The trouble with Royer's approach is that climate sensitivity is not constant. There appear to be times - when ice sheets have grown bloated towards the end of ice ages, for instance - when just a little "nudge" can lead to dramatic warming. In the absence of large ice sheets, sensitivity might be lower.

To get a more accurate picture, researchers have to look at periods similar to the present. One such time is the early Pliocene about 4.5 million years ago, when CO_2 levels were around 400 ppm - only slightly higher than they are now - yet the Earth was more than 3 °C warmer, with smaller permanent ice sheets and sea level up to 25 metres higher.

One recent study of the Pliocene concluded that the Earth system sensitivity at this time was 4.5 °C per CO_2 doubling (*Nature Geoscience*, vol 3, p 60). Another study, by Pagani and colleagues, using a different methodology, found that it could have been as high as 7 °C per CO_2 doubling (*Nature Geoscience*, vol 3, p 27).

Other studies also point to the Earth system sensitivity being significantly higher than model predictions. This does not necessarily mean that we can expect more warming than predicted by 2100, as studies of past climate reveal the response to CO_2 rises after many centuries. What it does suggest is that the planet will keep warming long after reaching the "maximum" predicted by current models if CO_2 levels remain high. "If the Earth actually has a very high sensitivity, it puts more pressure, if you will, on trying to find solutions for what's going on now," says Royer.

So while many of the details have yet to be settled, the big picture emerging from studies of past climate couldn't be clearer. Carbon dioxide is the most important of the many factors affecting the planet's climate. And if we double the level of CO_2 in the atmosphere, we can expect the temperature to rise around 3 °C in the short term and keep climbing over the following centuries.

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