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What ancient climates tell us about high carbon dioxide concentrations in Earth's atmosphere

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Headlines

- Earth's climate has always closely followed the concentration of carbon dioxide (CO_2), and other greenhouse gases in the atmosphere. The concentration was as low as 180ppm in the coldest part of the last ice age, 20,000 years ago. Around 10,000 years later, when the concentration increased to 280ppm, that ice age came to an end.
- Over the last 800,000 years, the concentration of atmospheric CO_2 naturally varied between 180-280ppm, but never rose significantly above 280ppm.
- In the 170 years since 1850, the concentration of CO_2 has risen from 280ppm to more than 410ppm, primarily due to fossil fuel burning and changes in how humans use the land. Left unchallenged, the increasing rate of change could see the CO_2 concentration increase to about 1000ppm by 2100.
- Earth last experienced 400ppm of CO_2 around 4 million years ago, during the Pliocene era. At this time, the average temperature was 2-4°C warmer than today, and the sea level was 10-25m higher.
- The concentration of CO_2 was last at over 1000ppm around 50 million years ago, when the average temperature was about 13°C warmer and sea level would have been around 70m higher than today because there was no (or very little) ice on the planet.
- Crucially, today's rate of change of CO_2 concentration, which is 200 times greater than it was after the last ice age, may prevent living organisms from adapting to new conditions.
- The lesson from the past is clear: sustained concentrations of CO_2 in the atmosphere above 400ppm will lead to very different conditions to those we experience on Earth today. To avoid the most adverse consequences, and allow humanity to adapt to changes that are already happening, we need to step up action to curtail greenhouse gas emissions to zero by 2050 at the latest.

Introduction

Ancient air bubbles frozen deep in the polar ice sheets act as miniature time-capsules of the last 800,000 years[1], recording how the concentration of carbon dioxide (CO_2) in the atmosphere has varied over this time. Multiple studies analysing data collected from these air bubbles show clearly that when the concentration of CO_2 changed, so did Earth's climate[2].

During ice ages, when the sea level was around 120m lower than now and global temperature was about 4°C cooler, the CO_2 concentration was as little as 180 parts per million (ppm). Between ice ages, CO_2 concentration increased to around 280ppm and the world warmed to something like our familiar modern climate. The last time Earth had an ice age was 20,000 years ago. It then took 10,000 years for CO_2 to rise from 180ppm to 280ppm, and for most of the ice to melt. In other words, the world experienced significant global warming of 4°C because of an increase in CO_2 concentration of 100ppm over about 10,000 years.

Around 1850, at the start of the Industrial Revolution, the CO_2 concentration in the atmosphere was still 280ppm. Since then, it has increased at a higher and higher rate, and now stands at well over 410ppm[3]. Scientists have expressed concern that upsetting the delicate balance of our planet's atmosphere is leading to the global warming crisis we are currently experiencing. Left unchallenged, a continuation of this trend, which is now 200 times faster than after the last ice age, could lead to concentrations of around 1000ppm by 2100.

This is due primarily to the greenhouse gas emissions, mainly CO_2, from burning fossil fuels and the turning over of untouched land for human activities such as agriculture and urbanisation. Computer simulations predict a range of outcomes for the climate, but useful data can also be derived by looking into the geological past when Earth's atmosphere was similar to the one humans have created now. Geological records show the environmental consequences of high levels of atmospheric CO_2, and what can be avoided if we curtail greenhouse gas emissions to zero by 2050, at the latest.

The 'greenhouse' worlds of the Pliocene and Eocene

Geological history has much to teach about the future fate of the planet as our climate changes. By combining decades of detailed geological study and data from core samples (cylindrical sections of rock obtained by drilling) from the sea-floor and exposed sedimentary rocks on land, and integrating these records with climate models, scientists have been able to reconstruct a picture of what climates and environments were like millions of years ago.

The concentration of CO_2 in the atmosphere has varied greatly over the hundreds of millions of years that Earth has supported life. However, in 2013, the concentration of CO_2 in the atmosphere passed 400ppm for the first time in human history. The last time atmospheric CO_2 was this high was during an era called the Pliocene (5.3-2.6 million years ago), before modern humans had evolved.

If we keep burning fossil fuels at the present increasing rate, by the end of this century it will be around 1000ppm. The last time Earth experienced this was during the Eocene era (56-33.9 million years ago).

This briefing note explains what the 'greenhouse' worlds of the Pliocene and Eocene were like, and how they are relevant to climate change happening today, as well as to forecasts for the next 80 years – to the year 2100.

Pliocene conditions

During the Pliocene, the concentration of CO_2 varied but was regularly above 400ppm[4,5]. At these times, the world was on average 2-4°C warmer than today, and even warmer, possibly double that, in the polar regions.

Eocene conditions

The Eocene had a concentration of CO_2 of up to 1400ppm[6]. This was so high because of a combined increase in volcanoes issuing large volumes of greenhouse gases into the atmosphere, and a reduction in rock weathering that otherwise captures CO_2 from the atmosphere. As a consequence, the global average temperature was 13°C higher than today[7].

What was the environment like in these greenhouse worlds?

In addition to being warmer, there was also more intense precipitation[8]. Prevailing westerly winds circulated close to the poles and precipitation was high in high latitudes. The global monsoon system was probably also more intense than it is now. There was less sea-ice in the Arctic than today, and indeed it may have been totally free of sea-ice every summer. In the northern hemisphere, forests extended to the Arctic coastline, where today there is only scant vegetation, and arid deserts, such as the Gobi Desert, were smaller. Tropical cyclones were more intense and probably more frequent[9].

What kind of life was there on Earth?

Pliocene: Many species of plants and animals that are alive today were around during the Pliocene. However, there were many species of giant animals that are now extinct, known as mega-fauna, such as the giant ground sloth and large sabre-toothed cats. The so-called 'terror of the deep', a species of giant shark growing up to 15m long, called *Megalodon*, lived in the ocean. These species thrived in the warm temperatures.

Eocene: The world was very different to today: Antarctica and Greenland had no ice sheets[10] but were covered in forests[11,12], the fossilised remains of which are preserved in Eocene rocks.

What was the sea level like?

Pliocene: Global sea level may have been 10-25m higher than today, which suggests that the Greenland and West Antarctic ice sheets did not exist and the East Antarctic ice sheet was much smaller than today[13].

Eocene: There were no major ice sheets on the planet during the Eocene, hence sea levels were likely to have been around 70m higher than today. This is calculated based on today's volume of ice, as the Eocene rock record does not allow scientists to measure the sea level of this time[14].

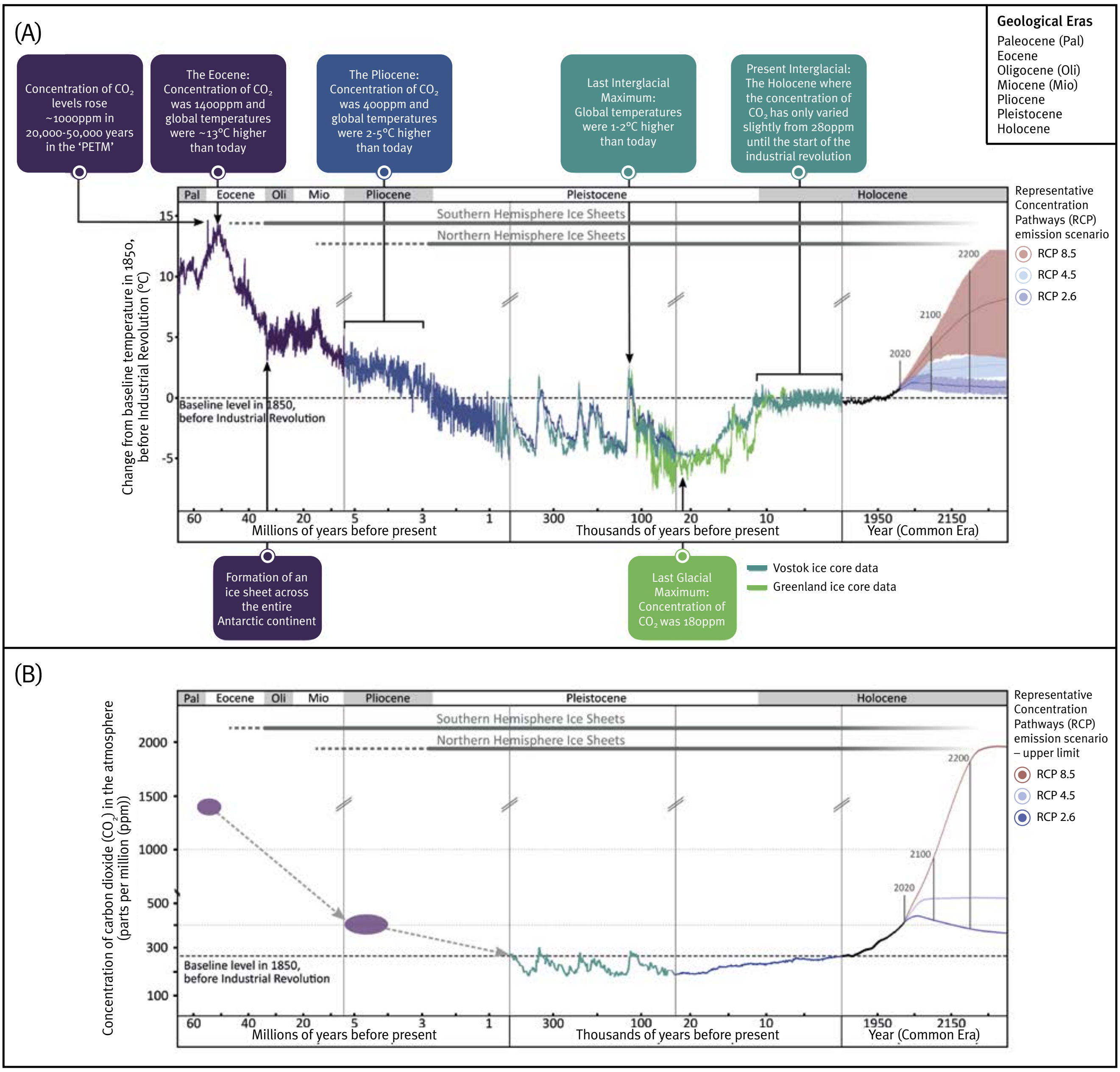
How do scientists know about the climates of greenhouse worlds?

The chemical composition of all living organisms is influenced by the levels of atmospheric gases. When creatures die, their remains can accumulate within sediments, such as at the bottom of the ocean, which turn to rock over millions of years. By examining the chemical composition of these sedimentary rocks, scientists can calculate the proportions of atmospheric gases, including CO_2, that were present as far back as 400 million years ago (see Figure 1)[15,16,17].

More recent changes in greenhouse gases, over the last 800,000 years, can be directly sampled from air bubbles trapped within ancient ice recovered by drilling deep ice cores in Antarctica and, for the last 100,000 years, in Greenland (see Figure 1A).

Figure 1: How the Earth's climate and CO_2 levels have changed over time

These graphs show (A) the change in average annual temperature over time and (B) the concentration of CO_2 in the atmosphere over time. There is some level of uncertainty over the ancient CO_2 values but they are presented here without error bars to aid clarity.



a. Past climate and CO_2 data are from Burke et al. (2018) and references therein. The graphs also include an extended modern temperature anomaly record from the United States' National Oceanic and Atmospheric Administration (NOAA) which can be found at https://www.ncdc.noaa.gov/cag/global/time-series/globe/land_ocean/ytd/12/1880-2019. CO_2 data are from the Antarctic Ice Cores Revised 800 ka dataset from NOAA (Bereiter et al., 2015). Mauna Loa observational record https://www.esrl.noaa.gov/gmd/ccgg/trends/data.html, is courtesy of Dr. Pieter Tans NOAA/ESRL and Dr. Ralph Keeling, Scripps Institution of Oceanography. RCP projections are from the IPCC 5th Assessment Report.

b. Burke, K. D., Williams, J. W., Chandler, M. A., Haywood, A. M., Lunt, D. J., & Otto-Bliesner, B. L. 2018. Pliocene and Eocene provide best analogs for near-future climates. Proceedings of the National Academy of Sciences, 115(52), 13288–13293. https://doi.org/10.1073/pnas.1809600115.

c. NOAA National Centers for Environmental information, Climate at a Glance: Global Time Series, published April 2020, retrieved on April 14, 2020 from https://www.ncdc.noaa.gov/cag/.

d. Bernhard Bereiter, Sarah Eggleston, Jochen Schmitt, Christoph Nehrbass-Ahles, Thomas F. Stocker, Hubertus Fischer, Sepp Kipfstuhl and Jerome Chappellaz. 2015. Revision of the EPICA Dome C CO_2 record from 800 to 600 kyr before present. Geophysical Research Letters, 42, 542-549. doi: 10.1002/2014GL061957. https://www.ncdc.noaa.gov/paleo-search/study/17975.

e. IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

f. Bereiter, B., S. Eggleston, J. Schmitt,C. Nehrbass-Ahles, T. F. Stocker, H. Fischer,S. Kipfstuhl, and J. Chappellaz. 2015. Revision of the EPICA Dome C CO_2 recordfrom 800 to 600 kyr before present, Geophys. Res. Lett., 42, 542–549, https://doi.org/10.1002/2014GL061957.

Why is the temperature today not as high as in the Pliocene?

Simple physics confirms that higher concentration of CO_2 in the atmosphere leads to global warming. The prevailing explanation why temperatures in the Pliocene were higher than today's temperatures is because the CO_2 concentration had been 400ppm for a long time. Pliocene temperatures were in, what scientists call, 'equilibrium' with a climate system that has that concentration of CO_2 in the atmosphere. Although today's CO_2 concentration has risen sharply since the Industrial Revolution, this change is yet to have its full impact on temperature – one analogy is that our situation is like turning up the dial on the oven then having to wait some time before it heats up to that temperature. In this way, the Pliocene tells us what our future temperature might be. There are also 'feedback' cycles that amplify the warming that is caused directly by higher CO_2 concentrations, and have not played out fully yet in today's climate. For example, as ice melts, its white reflective surface is replaced by a dark surface that absorbs solar radiation, leading to further warming, especially locally[18].

Why did CO_2 concentration in the atmosphere decline after the Pliocene and Eocene?

Scientists suspect that long-term geological processes changed the delicate balance between CO_2 released into the atmosphere by tectonic and volcanic processes, and CO_2 removed from the atmosphere through processes such as rock weathering.

As plants and marine organisms captured and stored CO_2, the lower concentration in the atmosphere led to cooler conditions, and especially colder waters. This led to nutrient-rich water rising from the ocean depths, nourishing marine microplankton that then capture CO_2 in larger quantities before sinking to the ocean bed. This feedback cycle led to further reduction in the atmospheric concentration of CO_2 as well as laying the foundation of carbon-rich coal and gas in rock sequences.

What can we learn from the greenhouse worlds about future climate change?

The Pliocene is the most easily understood geological example of a world in equilibrium with a CO_2 concentration of around 400ppm – similar to today's atmosphere. Geological evidence about this era informs scientists about the relationships between greenhouse gases, temperatures, ice sheets and sea-levels. The Eocene provides a window into our possible, yet avoidable, future in 2100.

How quickly did the greenhouse world changes occur?

This is perhaps the most critical issue. During the Eocene, one period at around 55 million years ago (referred to in the scientific literature as the Paleocene-Eocene Thermal Maximum (PETM) – See Figure 1A) saw CO_2 concentration rising naturally from low-100s-ppm to over 1000ppm in around 20,000-50,000 years, which was a phenomenal and rapid change. Between the Eocene and Pliocene, CO_2 concentration gradually reduced and Earth cooled, although with some fluctuations. Coming out of the last ice age, Earth warmed by 4°C over 10,000 years, during which time CO_2 concentration rose from 180 to 280ppm.

Humans have caused the concentration of CO_2 to increase from 280 to 410ppm in just 170 years, and the bulk of this increase (around 100ppm) has occurred in the last 50 years; a change that was 200 times faster than the end of the last ice age. Furthermore, continuing the trajectory that greenhouse gas emissions are on today will lead to around 1000ppm in 80 years' time, also around 200 times faster than the most rapid warming during the Eocene. Hence, these rates of change have no precedent geologically or climatically.

So what?

When Earth's climate changed naturally over thousands of years, generations of animals and plants were able to adapt to the changing conditions over similar periods. For example, gradual warming after the last ice age allowed trees in northern Europe to migrate northwards toward the Arctic. That smooth geographic transition was possible because the myriad of symbiotic relationships between plants, soil and animals were able to be maintained over the long time-period. The rate of change now is so great that it is not at all clear that plants will be able to easily migrate to more conducive climates as they have in the past[19], leading to a loss of biodiversity and restrictions in our ability to grow the food we need.

The Pliocene and Eocene eras provide examples of where our world is heading with the accelerated rise in the concentration of atmospheric CO_2. A greenhouse world is likely to be habitable for humans, but it would be very different from today's. Human civilisations have developed under a stable climate in the last 10,000 years, however pushing the climate to an extreme level not seen for millions of years will cause substantial problems for the way we live on this planet. The best solution to this problem is not to do it.

To avoid the most adverse consequences and allow humanity to adapt to those changes that are already happening, it is imperative to step up action to curtail greenhouse gas emissions to zero by 2050, at the latest.

References

1. Lüthi, D., M. Le Floch, B. Bereiter, T. Blunier, J.-M. Barnola, et al. 2008. High-resolution carbon dioxide concentration record 650,000-800,000 years before present. *Nature* 453: 379-382.
2. Foster, G., Royer, D. & Lunt, D. Future climate forcing potentially without precedent in the last 420 million years. *Nat Commun* 8, 14845 (2017).
3. IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.
4. Martínez-Botí, M. A., Foster, G. L., Chalk, T. B., Rohling, E. J., Sexton, P. F., Lunt, D. J., Pancost, R. D., Badger, M. P. S., and Schmidt, D. N.: Plio-Pleistocene climate sensitivity evaluated using high-resolution CO_2 records, *Nature,* 518, 49–54.
5. Haywood, A.M., Dowsett, H.J., Dolan, A.M., 2016. Integrating geological archives and 456 climate models for the mid-Pliocene warm period. *Nature Communications* 7, 457 10.1038/ncomms10646.
6. Anagnostou, E., John, E.H., Edgar, K.M., Foster, G.L., Ridgwell, A., Inglis, G.N., Pancost, R.D., Lunt, D.J., Pearson, P.N. Changing atmospheric CO_2 concentration was the primary driver of early Cenozoic climate, *Nature.*
7. Inglis, G.N. et al. Global mean surface temperature and climate sensitivity of the EECO, PETM and latest Paleocene, *Clim.* Past Discuss.
8. Sniderman, J.M.K., Woodhead, J.D., Hellstrom, J., Jordan, G.J., Drysdale, R.N., Tyler, J.J., Porch, N. Pliocene reversal of late Neogene aridification. *Proceedings of the National Academy of Sciences,* 113, 1999-2004.
9. Yan, Q., Wei, T., Korty, R.L., Kossin, J.P., Zhang, Z., Wang, H. Enhanced intensity of global tropical cyclones during the mid-Pliocene warm period. *Proceedings of the National Academy of Sciences,* 113, 12963-12967.
10. DeConto, R.M. and Pollard, D. Rapid Cenozoic glaciation of Antarctica induced by declining atmospheric CO_2 *Nature* 421, 245-9 (2003).
11. Pross, J., Contreras, L., Bijl, P.K., Greenwood, D.R., Bohaty, S.M., Bendle, J.A., Röhl, U., Tauxe, L., Raine, J.I., Huck, C.E., van de Flierdt, T., Jamieson, S.S.R., Stickley, C.E., van de Schootbrugge, B., Schouten, S., Escutia, C., Brinkhuis, H., and IODP Expedition 318 Scientists (2012), Persistent near-tropical warmth on the Antarctic continent during the early Eocene epoch. *Nature,* 488, 7409, 73-77.
12. Francis, J. and Poole, I. Cretaceous and early Tertiary climates of Antarctica: evidence from fossil wood, *Palaeogeogr. Palaeocl. Paleoecol.,* 182, 47–64, 2002.
13. Cook, C.P., van de Flierdt, T., Williams, T., Hemming, S.R., Iwai, M., Kobayashi, M., Jimenez-Espejo, F.J., Escutia, C., Gonzales, J.J., Khim, B.-K., McKay, R.M., Passchier, S., Tauxe, L., Sugisaki, S., Lopez Galindo, A., Patterson, M.O., Bohaty, S.M., Riesselman, C.R., Sangiorgi, F., Pierce, E.L., Brinkhuis, H., and IODP Expedition 318 Scientists (2013), Dynamic Behaviour of the East Antarctic Ice Sheet during Pliocene Warmth. *Nature Geoscience,* 6, 765-769.
14. Lear, C., Elderfield, H. & Wilson, P.A. Cenozoic deep-Sea temperatures and global ice volumes from Mg/Ca in benthic foraminiferal calcite. *Science* 287, 269-72. (2000).
15. Beerling, D. J., Fox, A., Stevenson, D. S., and Valdes, P. J.: Enhanced chemistry-climate feedbacks in past greenhouse worlds, *P. Natl. Acad. Sci.,* 108, 9770–9775, 2011.
16. Raymo, M. E. & Ruddiman, W. F. Tectonic forcing of late Cenozoic climate. *Nature* 359, 117–122 (1992).
17. Zachos, J. C., Dickens, G. R. & Zeebe, R. E. An early Cenozoic perspective on greenhouse warming and carbon-cycle dynamics. *Nature* 451, 279_283 (2008).
18. Hodgkins, R. 2018. Polar feedbacks in a changing climate. In *Routledge Handbook of the Polar Regions.* Nuttall, M., Christensen, T.R. and Siegert, M.J. eds. p251-262. Routledge, Abingdon, UK.
19. Renton, M., Childs, S., Standish, R., Shackelford, N. 2013. Plant migration and persistence under climate change in fragmented landscapes: Does it depend on the key point of vulnerability within the lifecycle? *Ecological Modelling,* 249, 50-58.

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