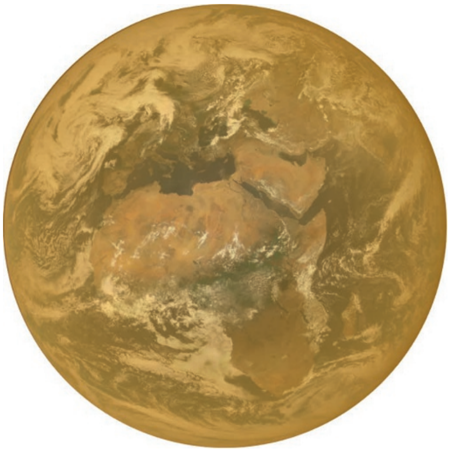
Earth's changeable atmosphere

Billions of years ago, high atmospheric greenhouse gas concentrations were vital to life's tenuous foothold on Earth. Despite new constraints, the composition and evolution of Earth's early atmosphere remains hazy.

The Sun has grown in luminosity throughout its lifetime: 2.7 billion years ago it was only about 70% as luminous as today. As Carl Sagan and George Mullen[1] pointed out in 1972, with today's concentrations of greenhouse gases, average temperatures would have been well below the freezing point of sea water until 2.3 billion years ago. Yet, evidence for liquid water dates back to 4.4 billion years ago[2], and open marine conditions have persisted almost without interruption since at least 3.8 billion years ago. That Earth's climate was at least temperate — possibly with the exception of a few relatively short-lived Snowball Earth glaciations — is fairly well documented. However, a wide variety of atmospheric conditions have been invoked to explain this warmth, each heavily debated. Two papers, on pages 448 and 452 in this issue of *Nature Geoscience*, reassess the potential role for nitrogen in solving the faint young Sun problem.

The evidence for high atmospheric carbon dioxide concentrations immediately following Snowball Earth deglaciations is strong. High levels of CO_2 at other times in Earth's history are, however, equivocal. Prior to the rise in atmospheric oxygen 2.5 billion years ago, methane could also reach high concentrations in the atmosphere. There are indications that between 2.7 and 2.5 billion years ago, high levels of atmospheric methane led to the episodic formation of atmospheric hazes composed of hydrocarbons[3]. However, the conditions that would allow high production and persistence of methane only occurred over a fairly limited time period during the Archaean. It is thus unlikely that methane is the whole story.

Nitrogen species — namely ammonia[1] and nitrous oxide[4] — have been invoked to fill the gap in radiative forcing. The high solubility of ammonia makes it difficult to identify conditions that would allow large quantities to build in the atmosphere without quickly raining out. There is no reason to rule out the potent greenhouse gas nitrous oxide, but a lack of clear proxies for its presence in the atmosphere has often relegated this idea to the sidelines. Molecular nitrogen itself has also been invoked. In one model[5], high partial pressures of molecular nitrogen — two to three times present-day levels — would broaden the spectrum of radiation absorbed by greenhouse gases such as carbon dioxide and methane. Interactions between H_2 and N_2 under high N_2 concentrations could also have a substantial greenhouse effect[6].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However, on page 448, Som and colleagues suggest that air pressure 2.7 billion years ago is unlikely to have been high enough for either mechanism to occur. Having looked at the characteristics of vesicles in basalts from this time period, they suggest that air pressure was no more than half today's levels. This finding implies that N_2 had little or no role in warming the Earth over this time period. Thus the atmosphere must have been rich in other greenhouse gases.

Nevertheless, for warming earlier in Earth's history — around four billion years ago — nitrogen isn't off the hook. Specifically, on page 452, Airapetian and colleagues suggest that the early Sun was prone to large and frequent coronal mass ejection events; interactions between these superflares and the Earth's magnetic field allowed energetic particles to enter the atmosphere where they interacted with molecular nitrogen, carbon dioxide and methane to form nitrous oxide in sufficient quantities to warm the Earth. This effect would have faded as the Sun became less stormy with age.

In any case, there is no reason to assume that the combination of greenhouse gases that warmed the Earth during one era is the same as the greenhouse gas cocktail that heated the Earth in the next. Atmospheric greenhouse gas concentrations can vary rapidly over just thousands of years, and the evolution of the Earth's atmosphere over the Precambrian occurred against a backdrop of dramatic upheavals in biological activity, styles of volcanism and surface redox chemistry. As Lee and colleagues report on page 417, even the emergence of continental crust some 2.7 billion years ago had repercussions on atmospheric chemistry, in part by reducing the efficiency of oxidative weathering. Thus although conditions may have been rife for, for example, H_2–N_2 collisions during one part of the Archaean, the rise of methanogens or a drop in the N_2 pressure would reduce this effect, and require another mechanism to maintain temperature stability.

Untangling these various processes will not be easy given the relatively sparse Precambrian rock record and a lack of simple proxies for many greenhouse gases. Investigating the few known incidences of greenhouse warming breakdown may be one way forward: the Huronian glaciation, which started about 2.4 billion years ago and may well have extended to low latitudes, occurred after the Great Oxidation Event, when atmospheric oxygen concentrations first rose to detectable levels. The presence of free oxygen reduces the lifetime of atmospheric methane and inhibits biogenic methane production. This fact has led to speculations that methane was a key greenhouse gas in the time period preceding the Great Oxidation Event[7].

Despite the low luminosity of the Sun during life's early days, widespread glaciations were few and far between, allowing biological systems to quickly — and permanently — colonize the oceans and land. That early life owes its survival to the abundance of greenhouse gases is clear. Just what those greenhouse gases were — and how much early metabolisms might have contributed to them — provides a rich field of study for the future. ❐

References

1. Sagan, C. & Mullen, G. *Science* **177,** 52–56 (1972).
2. Wilde, S. A., Valley, J. W., Peck, W. H. & Graham, C. M. *Nature* **409,** 175–178 (2001).
3. Izon, G. *et al. Earth Planet. Sci. Lett.* **431,** 264–273 (2015).
4. Buick, R. *Geobiology* **5,** 97–100 (2007).
5. Goldblatt, C. *et al. Nature Geosci.* **2,** 891–896 (2009).
6. Wordsworth, R. & Pierrehumbert, R. *Science* **339,** 64–67 (2013).
7. Kopp, R. E., Kirschvink, J. L., Hilburn, I. A. & Nash, C. Z. *Proc. Natl Acad. Sci. USA* **102,** 11131–11136 (2005).