

# Evolution of the Earth's Atmosphere and Climate

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Earth's climate prior to 2.5 Ga seems to have been, if anything, warmer than today (1,2), despite the faintness of the young Sun (3). The idea that the young Sun was 25-30 percent less bright has been bolstered by data on mass loss from young, solar-type stars (4). Sagan and Mullen (1) suggested many years ago that the warming required to offset low solar luminosity was provided by high concentrations of the reduced greenhouse gases, methane and ammonia. Ammonia, NH<sub>3</sub>, has since been shown to be photochemically unstable in low-O<sub>2</sub> atmospheres (5), but methane, CH<sub>4</sub>, is a viable candidate. Methane photolyzes only at wavelengths shorter than 145 nm, so it is long-lived in the absence of O<sub>2</sub> and O<sub>3</sub>. Furthermore, it is produced by anaerobic bacteria (methanogens) that are thought to have evolved early in Earth history (6). A biological methane flux comparable to today's flux, ca.500 Tg CH<sub>4</sub>/yr, could have been generated by methanogens living in an anaerobic early ocean and marine sediments (7). This flux should have increased once oxygenic photosynthesis evolved because of increased production and recycling of organic matter (8). An Archean methane flux equal to today's flux could have generated atmospheric CH<sub>4</sub> concentrations in excess of 1000 ppmv (9). This, in turn, could have provided 30 degrees or more of greenhouse warming (10) enough to have kept the early Earth warm even if atmospheric CO<sub>2</sub> concentrations were no higher than today.

All of this does not imply that atmospheric CO<sub>2</sub> concentrations must have been low throughout the Archean. Indeed, siderite-coated stream pebbles imply that pCO<sub>2</sub> was greater than 2.5X10<sup>-3</sup> bar, or ca.7 times present, at 3.2 Ga (11). Atmospheric CO<sub>2</sub> could have been much higher than this if the continents had formed slowly (12) and/or if subduction of carbonates into the mantle was inhibited (13). It is almost certainly a mistake to think of the Archean atmosphere as having a single composition and surface temperature. Rather, the atmosphere evolved from what may have been a CO<sub>2</sub>-rich mixture prior to ca.3.0 Ga to a CH<sub>4</sub>-rich mixture between 3.0 and 2.3 Ga. The rise in O<sub>2</sub> at ca.2.3 Ga (14,15) brought an end to the methane greenhouse and may have triggered the Huronian glaciation (10).

Although methane concentrations declined with the rise of O<sub>2</sub>, they may still have remained much higher than today throughout much of the Proterozoic. High methane production rates in marine sediments underlying a sulfidic Proterozoic deep ocean (16) could have generated methane fluxes several times higher than today (17). The response of atmospheric CH<sub>4</sub> to its input flux is nonlinear, so Proterozoic CH<sub>4</sub> concentrations of 50-100 ppmv are not implausible (ibid.) A rise in either atmospheric O<sub>2</sub> or oceanic sulfate near the end of the Proterozoic could have caused CH<sub>4</sub> concentrations to decrease a second time and may have triggered the Snowball Earth glaciations that took place at that time (18).

1. Sagan, C. and Mullen G. *Science* 177, 52-56 (1972). 2. Walker, J. C. G. et al. In Schopf, J. W., ed., *Earth's Earliest Biosphere* p. 260-290 (1983). 3. Gough, D.O. *Solar Phys.* 74, 21-34 (1981). 4. Wood, B.E., et al., *Ap. J.* 574, 412-425 (2002). 5. Kuhn, W.R. and Atreya, S.K. *Icarus* 37, 207-213 (1979). 6. Woese, C.R. and Fox, G.E. *Proc. Natl. Acad. Sci. USA* 74, 5088-5090 (1977). 7. Kharecha, P., Kasting, J.F., and Siefert, J.L. *Geobiology* (submitted).