Fossil soils constrain ancient climate sensitivity

Dana L. Royer[1]

Department of Earth and Environmental Sciences, Wesleyan University, Middletown, CT 06459

carbon dioxide | paleoclimate | paleosol

Global temperatures have covaried with atmospheric carbon dioxide (CO_2) over the last 450 million years of Earth's history (1). Critically, ancient greenhouse periods provide some of the most pertinent information for anticipating how the Earth will respond to the current anthropogenic loading of greenhouse gases. Paleo-CO_2 can be inferred either by proxy or by the modeling of the long-term carbon cycle. For much of the geologic past, estimates of CO_2 are consistent across methods (1). One exception is the paleosol carbonate proxy, whose CO_2 estimates are often more than twice as high as coeval estimates from other methods (1). This discrepancy has led some to question the validity of the other methods and has hindered attempts to understand the linkages between paleo-CO_2 and other parts of the Earth system. In this issue of PNAS, Breecker and colleagues (2) break important new ground for resolving this conflict.

The paleosol carbonate proxy for atmospheric CO_2 is based on the analysis of carbonate nodules that precipitate in soils in seasonally dry to dry climates. These nodules incorporate carbon from two sources: atmospheric CO_2 that diffuses directly into the soil and in situ CO_2 from biological respiration. Because the stable carbon isotopic composition of these two sources is distinct, the concentration of atmospheric CO_2 can be inferred if the concentration of soil CO_2 and the isotopic compositions of the two sources are known (3). Atmospheric CO_2 estimates scale directly with soil CO_2 concentration: If the soil term is wrong by a factor of two, the inferred atmospheric CO_2 will be off by a factor of two. Estimates of soil CO_2 concentration for fossil soils have been based on measurements taken during the growing season in equivalent living soils. However, Breecker et al. (2, 4) demonstrate convincingly that the window of active carbonate formation is restricted to the warmer and dryer parts of the growing season. Carbonate formation is simply not thermodynamically favorable during cooler and wetter seasons. Critically, biological productivity and respiration are low during these dry periods. As a result, soil CO_2 concentration during the critical window of active carbonate formation has been overestimated in most soils by a factor of two or more (2).

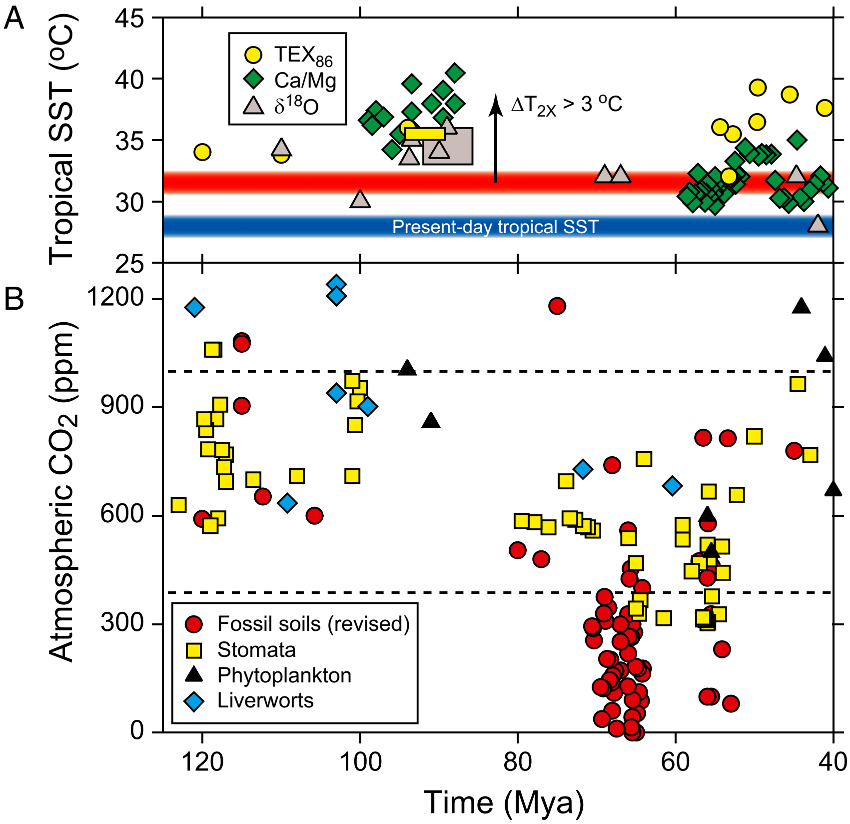

Fig. 1. Constraints on climate sensitivity for the globally warm Cretaceous and early Paleogene (125–40 Mya). (*A*) Tropical sea surface temperature (SST) records (15–29). Boxes represent studies with high sampling density. The red band corresponds to estimated tropical SST under an atmospheric CO_2 concentration of 1,000 ppm and a climate sensitivity ($\Delta T_{2\times}$) of 3°C per CO_2 doubling. Temperatures above this band probably represent times when climate sensitivity exceeded 3°C (see text). (*B*) Atmospheric CO_2 records (compilation from ref. 2). Dashed lines correspond to present-day CO_2 (387 ppm; A.D. 2009) and 1,000 ppm CO_2. Records from the boron proxy are excluded because they are likely unreliable (30); records from the goethite and nahcolite proxies are excluded because they are not yet widely applied.

What does this mean? CO_2 estimates from the paleosol carbonate proxy can be cut in half (or more). Doing so snaps the paleosol-based estimates in line with most other approaches (2) (Fig. 1*B*) and produces the most precise view to date of Earth's CO_2 history. We are now better equipped to answer some important, basic questions. For example, what is the quantitative relationship between CO_2 and temperature? That is, for every doubling of CO_2, what is the long-term (10^3–10^4 years) equilibrium response of global temperature (termed here climate sensitivity)? Most assessments of climate sensitivity for the present day hover around 3°C per CO_2 doubling (5), although if the long-term waxing and waning of continental ice sheets are considered it is probably closer to 6°C (6). Less is known about climate sensitivity during ancient greenhouse periods, simply because having poles draped in forest instead of ice represents a profound rearrangement of climate feedbacks.

Records of CO_2 and temperature are now sufficiently robust for placing firm

---

D.L.R. designed research, performed research, and wrote the paper.

The author declares no conflict of interest.

See companion article on page 576.

[1] E-mail: droyer@wesleyan.edu.

minimum constraints on climate sensitivity during parts of the Cretaceous and early Paleogene (125–40 Mya), a well-known globally warm interval. Indeed, owing to the logarithmic relationship between CO_2 and temperature, the geologic record is ideally suited for establishing minimum thresholds. This is because, to accommodate a declining sensitivity, other boundary conditions of the Earth system need to shift exponentially, for example, unreasonable oscillations in atmospheric CO_2. Policywise, establishing a basement value for climate sensitivity is a critical step for addressing our current climate crisis (5).

With few exceptions, CO_2 during the Cretaceous and early Paleogene was <1,000 ppm (2) (Fig. 1*B*). Global mean surface temperature is very difficult to establish for these ancient periods. However, temperature change in the tropics today scales at roughly two-thirds the global change (5, 6). If we assume a similar relationship in the past and a climate sensitivity of 3°C per CO_2 doubling, a rise in atmospheric CO_2 to 1,000 ppm results in a 3.6°C warming in the tropics (relative to a 280-ppm baseline). Given that tropical sea surface temperatures range from 27° to 29°C today, tropical temperatures exceeding 30.6°–32.6°C (red band in Fig. 1*A*) during the Cretaceous and early Paleogene likely correspond to a climate sensitivity >3°C.

This threshold was commonly surpassed during the Cretaceous and early Paleogene (Fig. 1*A*). For times when CO_2 was <1,000 ppm, the tropical temperature threshold for a 3°C climate sensitivity would shift to correspondingly cooler values. Further, there is abundant evidence for flatter latitudinal temperature gradients during greenhouse periods (7, 8), meaning, again, that the tropical temperature threshold used here is probably a maximum. Together, it is clear that during the Cretaceous and Paleogene climate sensitivity commonly exceeded 3°C per CO_2 doubling.

Breecker et al. have contributed significantly toward improving one of the more popular paleo-CO_2 proxies.

Although further work is needed, the geologic evidence (2) (Fig. 1) is most consistent with long-term, future climate change being more severe than presently anticipated (5). Also, global climate models tuned to ancient greenhouse periods commonly have emergent climate sensitivities of <3°C and they fail to simulate the shallow latitudinal temperature gradients (9). Thus even for times with little ice, there are important positive feedbacks that are presently not captured adequately in climate models. Processes for warming the high latitudes without a change in CO_2 include more vigorous heat transport (10, 11), more widespread stratospheric clouds in the high latitudes (12), and climate feedbacks from polar forests (13).

and their study highlights the value of a clearly resolved paleo-CO_2 record. However, a limitation is that they uniformly apply a "best guess" value of 2,500 ppm for soil CO_2 concentration. They recognize this as an oversimplification and is an area for future work. Better modeling of the term, perhaps through independent proxy (14), may result in a further tightening of the paleo-CO_2 record.

1. Royer DL (2006) CO_2-forced climate thresholds during the Phanerozoic. *Geochim Cosmochim Acta* 70:5665–5675.
2. Breecker DO, Sharp ZD, McFadden LD (2010) Atmospheric CO_2 concentrations during ancient greenhouse climates were similar to those predicted for 2100 A.D. *Proc Natl Acad Sci USA* 107:576–580.
3. Cerling TE (1991) Carbon dioxide in the atmosphere: Evidence from Cenozoic and Mesozoic paleosols. *Am J Sci* 291:377–400.
4. Breecker DO, Sharp ZD, McFadden LD (2009) Seasonal bias in the formation and stable isotopic composition of pedogenic carbonate in modern soils from central New Mexico, USA. *Geol Soc Am Bull* 121:630–640.
5. IPCC (2007) *Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge Univ Press, Cambridge, UK).
6. Hansen J, et al. (2008) Target atmospheric CO_2: Where should humanity aim? *Open Atmospheric Sci J* 2: 217–231.
7. Bice KL, Huber BT, Norris RD (2003) Extreme polar warmth during the Cretaceous greenhouse? Paradox of the late Turonian $\delta^{18}O$ record at Deep Sea Drilling Project Site 511. *Paleoceanography* 18:1031.
8. Bijl PK, et al. (2009) Early Palaeogene temperature evolution of the southwest Pacific Ocean. *Nature* 461: 776–779.
9. Shellito CJ, Sloan LC, Huber M (2003) Climate model sensitivity to atmospheric CO_2 levels in the Early-Middle Paleogene. *Palaeogeogr Palaeoclimatol Palaeoecol* 193: 113–123.
10. Korty RL, Emanuel KA, Scott JR (2008) Tropical cyclone-induced upper-ocean mixing and climate: Application to equable climates. *J Clim* 21:638–654.
11. Ufnar DF, González LA, Ludvigson GA, Brenner RL, Witzke BJ (2004) Evidence for increased latent heat transport during the Cretaceous (Albian) greenhouse warming. *Geology* 32:1049–1052.
12. Abbot DS, Tziperman E (2008) Sea ice, high-latitude convection, and equable climates. *Geophys Res Lett* 35:L03702.
13. Beerling DJ, Nicholas Hewitt C, Pyle JA, Raven JA (2007) Critical issues in trace gas biogeochemistry and global change. *Philos Trans R Soc Lond A* 365:1629–1642.
14. Retallack GJ (2009) Refining a pedogenic-carbonate CO_2 paleobarometer to quantify a middle Miocene greenhouse spike. *Palaeogeogr Palaeoclimatol Palaeoecol* 281:57–65.
15. Bice KL, et al. (2006) A multiple proxy and model study of Cretaceous upper ocean temperatures and atmospheric CO_2 concentration. *Paleoceanography* 21: PA2002.
16. Bornemann A, et al. (2008) Isotopic evidence for glaciation during the Cretaceous supergreenhouse. *Science* 319:189–192.
17. Forster A, Schouten S, Baas M, Sinninghe Damsté JS (2007) Mid-Cretaceous (Albian Santonian) sea surface temperature record of the tropical Atlantic Ocean. *Geology* 35:919–922.
18. Forster A, Schouten S, Moriya K, Wilson PA, Sinninghe Damsté JS (2007) Tropical warming and intermittent cooling during the Cenomanian/Turonian oceanic anoxic event 2: Sea surface temperature records from the equatorial Atlantic. *Paleoceanography* 22:PA1219.
19. Moriya K, Wilson PA, Friedrich O, Erbacher J, Kawahata H (2007) Testing for ice sheets during the mid-Cretaceous greenhouse using glassy foraminiferal calcite from the mid-Cenomanian tropics on Demerara Rise. *Geology* 35:615–618.
20. Norris RD, Bice KL, Magno EA, Wilson PA (2002) Jiggling the tropical thermostat in the Cretaceous hothouse. *Geology* 30:299–302.
21. Pearson PN, et al. (2001) Warm tropical sea surface temperatures in the Late Cretaceous and Eocene epochs. *Nature* 413:481–487.
22. Pearson PN, et al. (2007) Stable warm tropical climate through the Eocene Epoch. *Geology* 35:211–214.
23. Schouten S, et al. (2003) Extremely high sea-surface temperatures at low latitudes during the middle Cretaceous as revealed by archaeal membrane lipids. *Geology* 31:1069–1072.
24. Tripati A, et al. (2003) Tropical sea-surface temperature reconstruction for the early Paleogene using Mg/Ca ratios of planktonic foraminifera. *Paleoceanography* 18:1101.
25. Wagner T, et al. (2008) Rapid warming and salinity changes of Cretaceous surface waters in the subtropical North Atlantic. *Geology* 36:203–206.
26. Wilson PA, Norris RD (2001) Warm tropical ocean surface and global anoxia during the mid-Cretaceous period. *Nature* 412:425–429.
27. Wilson PA, Norris RD, Cooper MJ (2002) Testing the Cretaceous greenhouse hypothesis using glassy foraminiferal calcite from the core of the Turonian tropics on Demerara Rise. *Geology* 30:607–610.
28. Wilson PA, Opdyke BN (1996) Equatorial sea-surface temperatures for the Maastrichtian revealed through remarkable preservation of metastable carbonate. *Geology* 24:555–558.
29. Sexton PF, Wilson PA, Pearson PN (2006) Microstructural and geochemical perspectives on planktic foraminiferal preservation: "glassy" versus "frosty". *Geochem Geophys Geosyst* 7:Q12P19.
30. Pagani M, Lemarchand D, Spivack A, Gaillardet J (2005) A critical evaluation of the boron isotope-*p*H proxy: The accuracy of ancient ocean *p*H estimates. *Geochim Cosmochim Acta* 69:953–961.