



POTSDAM-INSTITUT FÜR
KLIMAFOLGENFORSCHUNG

Originally published as:

Feulner, G. (2017): Formation of most of our coal brought Earth close to global glaciation. - Proceedings of the National Academy of Sciences of the United States of America (PNAS), 114, 43, 11333-11337

DOI: [10.1073/pnas.1712062114](https://doi.org/10.1073/pnas.1712062114)



Formation of most of our coal brought Earth close to global glaciation

Georg Feulner^{a,1}

^aPotsdam Institute for Climate Impact Research, Leibniz Association, D-14473 Potsdam, Germany

Edited by Mark H. Thiemens, University of California, San Diego, La Jolla, CA, and approved September 5, 2017 (received for review July 7, 2017)

The bulk of Earth's coal deposits used as fossil fuel today was formed from plant debris during the late Carboniferous and early Permian periods. The high burial rate of organic carbon correlates with a significant drawdown of atmospheric carbon dioxide (CO₂) at that time. A recent analysis of a high-resolution record reveals large orbitally driven variations in atmospheric CO₂ concentration between ~150 and 700 ppm for the latest Carboniferous and very low values of 100 ± 80 ppm for the earliest Permian. Here, I explore the sensitivity of the climate around the Carboniferous/Permian boundary to changes in Earth's orbital parameters and in atmospheric CO₂ using a coupled climate model. The coldest orbital configurations are characterized by large axial tilt and small eccentricities of Earth's elliptical orbit, whereas the warmest configuration occurs at minimum tilt, maximum eccentricity, and a perihelion passage during Northern hemisphere spring. Global glaciation occurs at CO₂ concentrations <40 ppm, suggesting a rather narrow escape from a fully glaciated Snowball Earth state given the low levels and large fluctuations of atmospheric CO₂. These findings highlight the importance of orbital cycles for the climate and carbon cycle during the late Paleozoic ice age and the climatic significance of the fossil carbon stored in Earth's coal deposits.

palaeoclimate | Carboniferous | Permian | glaciation | coal

In the climate system, global glaciation is a result of the positive ice-albedo feedback causing runaway cooling initiated, for example, by a reduction in incoming solar radiation or a decrease in greenhouse gases (1). In its long history, Earth experienced several episodes of planetary glaciation. The most recent of these “Snowball Earth” events (2) occurred during the Neoproterozoic era [1,000–541 million years ago (Ma)] about 717–662 and 639–635 Ma (3, 4). Climate-modeling studies demonstrate that atmospheric concentrations of carbon dioxide (CO₂) below ~100 ppm were required to initiate these events (5, 6). The required drawdown of CO₂ has been suggested to be linked to increased weathering of tropical landmasses (7) or volcanic flood basalts (8). In addition, biologically induced changes in cloud cover (9) and stratospheric aerosols from volcanic eruptions (10) could have contributed to the cooling.

The only other epoch with similarly low values of atmospheric CO₂ since these global glaciations occurred in the Palaeozoic era (541–252 Ma)—except for the most recent past, for which the steadily increasing solar luminosity (11) makes global glaciation ever more difficult. Proxy records (12) reveal a minimum in atmospheric CO₂ ~300 Ma close to the boundary between the Carboniferous (359–299 Ma) and Permian (299–252 Ma) periods. In addition to tectonic factors, the high burial rate of organic carbon (13) was the major process for the observed drawdown of atmospheric CO₂ during this late Palaeozoic ice age (14). Indeed, the major part of Earth's coal deposits was formed in this time period (15, 16). Atmospheric CO₂ concentrations in the latest Carboniferous period (~300–310 Ma) have recently been empirically estimated (17) to fluctuate wildly between ~150 and 700 ppm in response to variations of Earth's orbital parameters. For comparison, Quaternary CO₂ values vary over glacial cycles between ~180 and 300 ppm (18). During the earliest Permian

period (297–298 Ma), even lower values (19) of 100 ± 80 ppm are reached, coinciding with a maximum of the late-Palaeozoic glaciations (14). Despite this evidence for orbital variations and very low CO₂ concentrations, the sensitivity of the climate during the latest Carboniferous and earliest Permian to changes in orbital parameters and atmospheric CO₂ has never been systematically investigated. Earlier modeling efforts for the late-Palaeozoic have primarily focused on ice-sheet growth (20–23) or precipitation patterns (24, 25).

Here, I use a coupled climate model (26)—consisting of an ocean general circulation model, a fast atmosphere, and a dynamic/thermodynamic sea-ice model—and boundary conditions for the time ~300 Ma (*Materials and Methods*) to explore the climate system around the Carboniferous/Permian boundary for different orbital configurations and, in particular, with respect to the threshold of global glaciation at this time.

Orbital Parameters and Late-Carboniferous Climate

Simulated annual global mean temperatures for the latest Carboniferous and earliest Permian vary considerably with Earth's orbital parameters (Fig. 1). Keeping atmospheric CO₂ at 100 ppm and all other boundary conditions fixed, global mean temperatures range from –1.4 °C to +0.45 °C. In general, Earth's climate during this time period gets warmer with decreasing tilt of its rotational axis (obliquity) and with increasing eccentricity of its elliptical orbit. The warmest orbital configuration is reached for minimum obliquity ($\omega = 22.0^\circ$), maximum eccentricity ($e = 0.069$), and a perihelion passage during Northern hemisphere spring. The coldest configurations, on the other hand, are characterized by maximum obliquity ($\omega = 24.5^\circ$), small orbital eccentricities ($e \lesssim 0.01$), and perihelion during boreal autumn. The warming with increasing eccentricity can be attributed to the higher annual mean solar radiation for more eccentric orbits. Climate states with lower obliquity are warmer because of larger absorption of solar radiation in Southern hemisphere midlatitudes during early Northern summer (and Northern hemisphere

Significance

The bulk of the coal driving the Industrial Revolution and contributing to global warming today has been deposited during the Carboniferous period (359–299 million years ago), resulting in a significant drawdown of atmospheric carbon dioxide at that time. In this work, a combination of climate model simulations and recent estimates for carbon dioxide levels in the atmosphere is used to demonstrate that the cooling due to the diminished greenhouse effect brought our planet close to the limit of global glaciation ~300 million years ago. These findings highlight the climatic importance of the fossil carbon stored in Earth's coal deposits and thus have implications for climate policy.

Author contributions: G.F. designed research, performed research, analyzed data, and wrote the paper.

The author declares no conflict of interest.

This article is a PNAS Direct Submission.

¹Email: feulner@pik-potsdam.de.

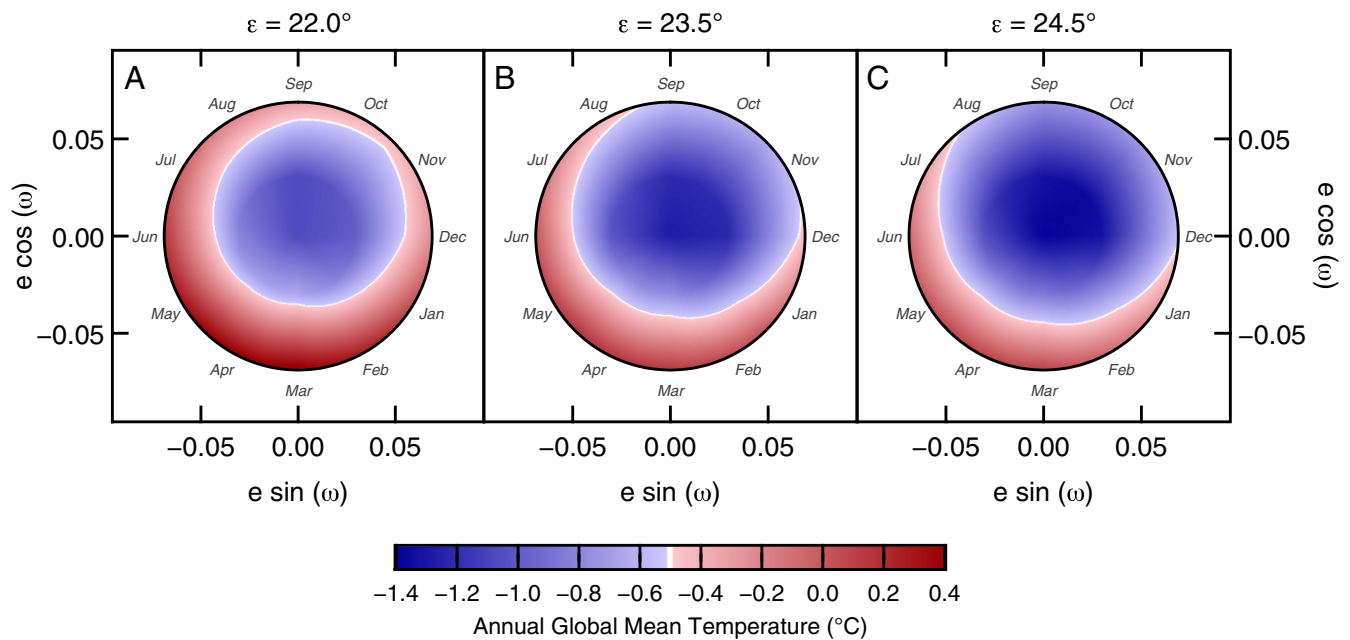


Fig. 1. Annual global mean temperature for different orbital parameters. Average near-surface temperatures are shown in polar coordinates as a function of orbital eccentricity e and precession angle ω for obliquity $\varepsilon = 22.0^\circ$ (A), $\varepsilon = 23.5^\circ$ (B), and $\varepsilon = 24.5^\circ$ (C). The month of perihelion passage is indicated in each diagram.

midlatitudes during early Northern winter) caused by the surplus of incident solar radiation for smaller axial tilts in the winter hemisphere together with the delayed melting of sea ice and snow in the summer hemisphere.

Late-Carboniferous Glacials and Interglacials

To describe typical glacial and interglacial climate states during the latest Carboniferous, simulations with the coldest and warmest orbital configurations and more realistic CO_2 concentrations of 150 and 700 ppm have been performed. These values are indicative of the full range of individual CO_2 estimates for late-Carboniferous glacials and interglacials (17). Even for a late-Carboniferous interglacial characterized by a relatively high atmospheric CO_2 concentration of 700 ppm and the warmest orbital configuration, Earth's climate is relatively cool with an annual global mean temperature of 12°C . In reality, however, the interglacial climate state is likely somewhat warmer than in the simulation because I do not take the partial melting of the ice sheet and the increase in vegetation cover into account. Both effects would lower the albedo as compared with the glacial state and lead to further warming. For a low CO_2 concentration of 150 ppm CO_2 and the coldest orbital configuration, global mean temperatures are down to 1.4°C . Regionally, the coldest temperatures are found over the Southern polar continent and its ice sheet (Fig. 2). In the western highlands of tropical Pangaea, annual mean temperatures are below the freezing point in the glacial simulation, in line with evidence for upland glaciation in this region (28, 29). For comparison, global temperatures over the most recent glacial cycles are estimated (30) to have varied between $\sim 10^\circ\text{C}$ and 15°C . The differences between glacial/interglacial temperature variations between the late Carboniferous and the Quaternary are largely due to the higher solar constant today and the smaller range of changes in atmospheric CO_2 over the recent glacial cycles.

Threshold for Global Glaciation

Finally, the sensitivity of the late-Palaeozoic climate system with respect to global glaciation is explored by lowering the atmo-

spheric CO_2 concentration in the model for a cold orbital configuration with obliquity $\omega = 24.5^\circ$ and orbital eccentricity $e = 0$. The coldest climate state without global ice cover is reached for a CO_2 concentration of 40 ppm at a very low annual global mean temperature of -8.9°C . Global glaciation occurs at 35 ppm, the next lowest CO_2 value tested in the simulations. Because of the increased solar luminosity, this threshold for global glaciation during the late Palaeozoic is considerably lower than during the Neoproterozoic (5, 6). In addition, continental configuration and vegetation cover influence the glaciation threshold.

It is interesting to compare this simulated value for the critical CO_2 concentration with the empirical estimates for that time (17); Fig. 3. Estimated CO_2 levels during the latest Carboniferous are well above the glaciation threshold despite considerable fluctuations on orbital time scales. During the earliest Permian, however, the threshold for Snowball Earth glaciation of 37.5 ± 2.5 ppm is within the uncertainty range of the estimates of 100 ± 80 ppm. Note that the time resolution of the empirical estimates is insufficient to resolve orbital variations during this time. It is likely that the atmospheric CO_2 concentration in the earliest Permian underwent orbitally driven fluctuations similar to the latest Carboniferous—where we have records with a sufficiently high temporal resolution (17)—or the past million years—where we can measure the variations from ice cores (18). In this sense, Earth's escape from global glaciation during the earliest Permian can certainly be regarded as surprisingly narrow. Further CO_2 drawdown (and thus a Snowball Earth state) was most likely prevented by negative feedbacks limiting vegetation growth and weathering under the very cold and dry climatic conditions close to the global glaciation threshold. Indeed, water-use efficiency of typical coal forest taxa has been shown to be significantly reduced at low CO_2 values (31), which could have contributed to the observed dieback of coal forests ~ 300 Ma (32). Furthermore, declining $^{87}\text{Sr}/^{86}\text{Sr}$ strontium isotope ratios of seawater suggest a marked decrease in global weathering at that time (33).

The glaciation threshold derived here is most likely conservative because of two effects not considered in the simulations.

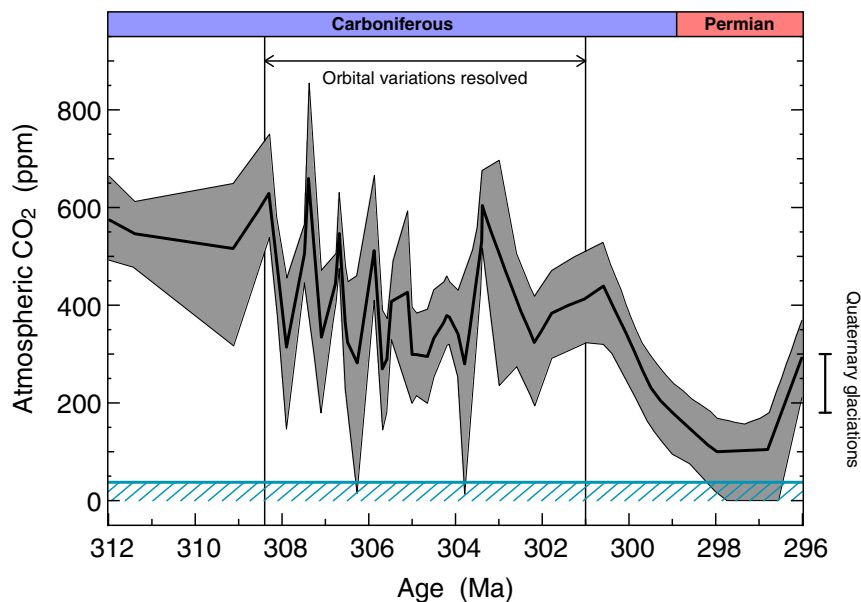


Fig. 3. Estimates of atmospheric CO₂ and the global glaciation threshold ~ 300 million years ago. Critical level of the CO₂ concentration of 37.5 ± 2.5 ppm, below which Earth enters a fully glaciated state (cyan; this work), is compared with empirical estimates of the atmospheric CO₂ level during the latest Carboniferous and earliest Permian (17) (black and gray shading indicates 2.5%/97.5% uncertainty ranges). Note that the temporal resolution of the empirical estimates is considerably lower before 308 Ma and after 301 Ma; in particular, orbital-scale fluctuations during the CO₂ minimum at the beginning of the Permian are not resolved. The range of CO₂ variations during the Quaternary (18) is indicated on the right-hand side.

(46) for climate zones at the time. An idealized elliptical ice sheet with a maximum height of $h_0 = 2000$ m is placed on the polar continent in the South, centered at longitude $\lambda_0 = 240^\circ$ and latitude $\varphi_0 = -71.25^\circ$ and with an elevation distribution following $h_0 \times (1 - [((\lambda - \lambda_0)/122.5^\circ)^6 + ((\varphi - \varphi_0)/20.0^\circ)^6])$. The solar constant is set to $1,327 \text{ W/m}^2$ based on the best estimate (47) for the present-day solar constant of $1,361 \text{ W/m}^2$ and standard solar evolution (48). Sensitivity to orbital parameters is investigated at a fixed atmospheric CO₂ concentration of 100 ppm and for obliquity values ε of 22.0° , 23.5° , 24.5° , eccentricity values e of 0, 0.03, 0.069, and perihelion angles ω (defined relative to vernal equinox) ranging from 0° to 315° in intervals of 45° for nonzero eccentricity. Two additional simulations characterize the extremes of climate variations through glacial cycles by using 700 ppm CO₂ at the warmest orbital configuration and 150 ppm CO₂ at the coldest orbital configuration (leaving sea-level, ice-sheet, and vegetation

distribution unchanged). Finally, a set of simulations with fixed CO₂ concentrations < 100 ppm and the coldest orbital configuration tests the limit of global glaciation. All simulations are integrated for at least 2,000 model years until climate equilibrium is approached. The source code for the model used in this study, the data and input files necessary to reproduce the experiments, and model output data are available from the authors upon request. All data are archived at the Potsdam Institute for Climate Impact Research.

ACKNOWLEDGMENTS. I thank Christopher Scotese for providing his paleocontinental reconstruction in electronic form and Julia Brugger, as well as two anonymous reviewers for helpful comments. The European Regional Development Fund, the German Federal Ministry of Education and Research, and the Land Brandenburg supported this project by providing resources on the high-performance computer system at the Potsdam Institute for Climate Impact Research.

- Öpik EJ (1965) Climatic change in cosmic perspective. *Icarus* 4:289–307.
- Kirschvink JL (1992) Late proterozoic low-latitude global glaciation: The snowball Earth. *The Proterozoic Biosphere: A Multidisciplinary Study*, eds Schopf JW, Klein C (Cambridge Univ Press, Cambridge, UK), pp 51–52.
- Prave AR, Condon DJ, Hoffmann KH, Tapster S, Fallick AE (2016) Duration and nature of the end-Cryogenian (Marinoan) glaciation. *Geology* 44:631–634.
- Rooney AD, et al. (2014) Re-Os geochronology and coupled Os-Sr isotope constraints on the Sturtian snowball Earth. *Proc Natl Acad Sci USA* 111:51–56.
- Liu Y, Peltier WR, Yang J, Vettoretti G (2013) The initiation of Neoproterozoic “snowball” climates in CCSM3: The influence of paleocontinental configuration. *Clim Past* 9:2555–2577.
- Feulner G, Kienert H (2014) Climate simulations of Neoproterozoic snowball Earth events: Similar critical carbon dioxide levels for the Sturtian and Marinoan glaciations. *Earth Planet Sci Lett* 404:200–205.
- Hoffman PF, Schrag DP (2002) The snowball earth hypothesis: Testing the limits of global change. *Terra Nova* 14:129–155.
- Goddéris Y, et al. (2003) The Sturtian ‘snowball’ glaciation: Fire and ice. *Earth Planet Sci Lett* 211:1–12.
- Feulner G, Hallmann C, Kienert H (2015) Snowball cooling after algal rise. *Nat Geosci* 8:659–662.
- Macdonald FA, Wordsworth R (2017) Initiation of snowball Earth with volcanic sulfur aerosol emissions. *Geophys Res Lett* 44:1938–1946.
- Feulner G (2012) The faint young sun problem. *Rev Geophys* 50:RG2006.
- Royer DL (2006) CO₂-forced climate thresholds during the Phanerozoic. *Geochim Cosmochim Acta* 70:5665–5675.
- Berner RA (2003) The long-term carbon cycle, fossil fuels and atmospheric composition. *Nature* 426:323–326.
- Montañez IP, Poulsen CJ (2013) The late Paleozoic ice age: An evolving paradigm. *Annu Rev Earth Planet Sci* 41:629–656.
- Thomas LJ (2012) *Coal Geology* (John Wiley & Sons, New York).
- Nelsen MP, DiMichele WA, Peters SE, Boyce CK (2016) Delayed fungal evolution did not cause the Paleozoic peak in coal production. *Proc Natl Acad Sci USA* 113:2442–2447.
- Montañez IP, et al. (2016) Climate, pCO₂ and terrestrial carbon cycle linkages during late Palaeozoic glacial-interglacial cycles. *Nat Geosci* 9:824–828.
- Siegenthaler U, et al. (2005) Stable carbon cycle-climate relationship during the late Pleistocene. *Science* 310:1313–1317.
- Montañez IP, et al. (2007) CO₂-forced climate and vegetation instability during late Paleozoic deglaciation. *Science* 315:87–91.
- Crowley TJ, Baum SK, Hyde WT (1991) Climate model comparison of Gondwanan and Laurentide glaciations. *J Geophys Res* 96:9217–9226.
- Hyde WT, Crowley TJ, Tarasov L, Peltier WR (1999) The Pangean ice age: Studies with a coupled climate-ice sheet model. *Clim Dyn* 15:619–629.
- Horton DE, Poulsen CJ, Pollard D (2007) Orbital and CO₂ forcing of late Paleozoic continental ice sheets. *Geophys Res Lett* 34:L19708.
- Horton DE, Poulsen CJ, Pollard D (2010) Influence of high-latitude vegetation feedbacks on late Paleozoic glacial cycles. *Nat Geosci* 3:572–577.
- Otto-Bliessner BL (1993) Tropical mountains and coal formation—a climate model study of the Westphalian (306 MA). *Geophys Res Lett* 20:1947–1950.
- Peysér CE, Poulsen CJ (2008) Controls on Permo-Carboniferous precipitation over tropical Pangaea: A GCM sensitivity study. *Palaeogeogr Palaeoclimatol Palaeoecol* 268:181–192.
- Montoya M, et al. (2005) The earth system model of intermediate complexity CLIMBER-3 α . Part I: Description and performance for present-day conditions. *Clim Dyn* 25:237–263.
- Scotese CR (2014) *Atlas of Permo-Carboniferous Paleogeographic Maps* (Mollweide Projection), Maps 53–64, Volumes 4, the Late Paleozoic, PALEOMAP Atlas for ArcGIS (PALEOMAP Project, Evanston, IL).

