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

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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 \sim 150 and 700 ppm for the latest Carboniferous and very low values of 100 \pm 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.

paleoclimate | Carboniferous | Permian | glaciation | coal

n 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 $CO_2 \sim 300$ 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 CO_2 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 (\sim 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 \sim 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 CO_2 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 ($e \leq 0.01$), 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 \sim 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.

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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 CO₂ concentrations of 150 and 700 ppm have been performed. These values are indicative of the full range of individual CO₂ 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 CO₂ concentration of 150 ppm CO₂ 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 ~ 10 °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 atmospheric CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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, wateruse 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 \sim 300 Ma (32). Furthermore, declining ⁸⁷Sr/⁸⁶Sr 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. 2. Annual mean temperature maps for latest-Carboniferous glacials and interglacials. Maps of annual mean near-surface temperatures for a CO_2 concentration of 700 ppm and a warm orbital configuration (*A*) and for 150 ppm of CO_2 and a cold orbital configuration (*B*). Reconstructed contours of continents (27) are drawn at the original resolution in both maps.

First, the minimum in atmospheric $CO_2 \sim 300$ Ma coincides with a maximum in atmospheric oxygen (34). Enhanced levels of oxygen have been shown to result in reduced surface air temperatures due to increased scattering of shortwave radiation (35). Second, the sporadic cooling effects of volcanic eruptions are not taken into account. Cold climate states are characterized by a low tropopause, making the injection of stratospheric aerosols from volcanic eruptions more likely (10). Both effects would raise the critical CO_2 concentration and would thus bring the glaciation threshold even closer to the reconstructed values.

Discussion

Today, the burning of fossil coal is responsible for 29% of the global primary energy production in 2015 (36) and 41% of anthropogenic CO₂ emissions from fossil fuels and industry in that year (37). Atmospheric CO₂ concentrations have recently surpassed 400 ppm, and the CO₂ emissions resulting from burning all coal reserves alone would exceed the allowed carbon budget for limiting global temperature increase to 2 °C above the preindustrial value (38). Ironically, the formation of the majority of these coal reserves during the late Palaeozoic (15) brought the Earth close to the threshold of global glaciation, a further illustration of the climatic relevance of the vast amounts of fossil carbon that still mostly drive our industrialized economies.

Materials and Methods

All simulations are performed with a coupled climate model (26) consisting of a modified version of the ocean general circulation model MOM3 (39, 40) run at a horizontal resolution of $3.75 \,^{\circ} \times 3.75^{\circ}$ with 24 vertical levels, a dynamic/thermodynamic sea-ice model (41), and a fast statistical–dynamical atmosphere model (42) with a coarse spatial resolution of 22.5° in longitude and 7.5° in latitude. The model has been successfully used in a number of paleoclimate studies, testing it, for example, against reconstructed temperatures over the last millennium (43). It compares well with other models in model intercomparison projects (44, 45); for cold climate states in particular, the simulated climate sensitivity and global glaciation threshold for the transition to Snowball Earth states during the Neoproterozoic (6) are in excellent agreement with results from a coupled atmosphere–ocean general circulation model (5). Land distribution and topography are based on a reconstruction (27) for 300 Ma, close to the boundary between the Carboniferous and the Permian; vegetation cover is prescribed following estimates



Fig. 3. Estimates of atmospheric CO_2 and the global glaciation threshold ~300 million years ago. Critical level of the CO_2 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 CO_2 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 CO_2 minimum at the beginning of the Permian are not resolved. The range of CO_2 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 W/m² based on the best estimate (47) for the present-day solar constant of 1,361 W/m² 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

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distribution unchanged). Finally, a set of simulations with fixed CO_2 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 author upon request. All data are archived at the Potsdam Institute for Climate Impact Research.

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