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Simulating Cambrian Climate: The Significance of Atmospheric CO2 Concentration and Continental Position

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Simulating Cambrian Climate: The Significance of Atmospheric CO_2 Concentration and Continental Position

Introduction & Significance

The goal of this study is to determine the most important factors influencing climate during the Cambrian Period, from 541 to 485 million years ago. We know from numerous geologic studies of that time period that the landscape was barren, with shallow waters covering some of the continents (Avigad et al., 2005; Frakes, 1979), and that climate was generally warm. (Hearing et al., 2018) The beginning of the period is also known for the "Cambrian Explosion," when multicellular life began to diversify rapidly. (Babcock, 2001) We can use the Earth's natural historic records, such as fossils, rock formations, and isotopes, to give us an idea about Cambrian atmospheric composition, ecosystems, and overall landscape. Hearing et al. (2018) suggests that the Cambrian may have had a greenhouse climate, based on temperature inferences from oxygen isotopes in Cambrian rocks, as there is evidence for ice near the Cambrian equator. This suggests that the Cambrian may have had periods of colder temperatures than previously thought. There is also evidence of a mass extinction associated with colder water temperature at about 500 Ma that approximately coincides with this cooler episode. (Runkel et al., 2010)

It is critical that we understand Earth's past climate for numerous reasons. Understanding past climate helps explain the ways vegetation and fauna were able to adapt to specific climate conditions. This is particularly important for the Cambrian since this is when multicellular life began to diversify. This is also significant for the present day, especially when we consider how the Earth system may respond to human activity. Understanding past natural variations helps us quantify the importance of natural feedback in climate change. Past climate is also used as a framework for current computational models and having more information about Earth's past can help improve the models for predicting future changes. This research using a global climate model will be the first to examine Cambrian climate sensitivity to atmospheric composition and continental position, and aims to address the following specific questions:

- How sensitive was the Cambrian climate to atmospheric CO_2?
- How sensitive was the Cambrian climate to continental arrangement?
- Is it possible that the generally warm Cambrian climate could have been punctuated by cooler episodes, given what we understand about Cambrian climate sensitivity to CO_2 and continental configuration?

Discussion of Previous Paleoclimate Studies

The Cambrian Explosion occurred well after some major physical and chemical changes in the Earth system during the Neoproterozoic, such as the breakup of the supercontinent Rodinia 750 million years ago and the early formation of the continent of Gondwana, both of which were accompanied by large fluctuations in climate. (Babcock, 2001) Most of the development of life preserved in the fossil record occurred during a short period of time in the Early Cambrian, between 521 and 509. Ma (Babcock, 2001) According to Babcock (2001), this coincided with increased mid-ocean ridge activity and the expansion of ocean. Flooding of low-lying continents allowed for increased erosion and changed the chemical composition of the ocean (through increased oxygen), which assisted with the evolution of multicellular life and led to very well-preserved fossil records. The Chenjiang Biota, from Yunnan, China, contains the most diverse Cambrian life from Gondwana (Figure 1). This biota contains members of Precambrian and post-Cambrian life (blue and green bacteria, prokaryotes, and evidence of evolution). Large predators such as arthropods dominated all types of life during the Cambrian. The Cambrian was also, however, punctuated by extinctions. For example, the record of trilobites suggests there was a mass extinction at the end of the Early Cambrian. (Babcock, 2001) In regions such as Laurentia and Gondwana, there was a lack of mineralized skeletons found in most taxa at this time. The Burgess Shale, from British Columbia, Canada, is representative of life with no skeletons in the Middle Cambrian. (Babcock, 2001)

Oxygen isotopes in calcium carbonate and calcium phosphate shells are one of the most common proxies used to infer past temperature. Hearing et al. (2018) proposed that shelly fossils from limestone in the United Kingdom could provide a new source of oxygen isotope data representative of the Cambrian. Their oxygen isotope data from the Early Cambrian showed evidence of a greenhouse climate, with 20 to 25 degrees Celsius sea-surface temperatures at high latitudes. This correlates with a lack of evidence for ice sheets near the poles and the presence of limestone units that span across a large latitudinal range.

Another clue used in determining ancient climatic conditions is the presence of evaporites. Evaporites indicate the climate of particularly dry locations with low precipitation and low relative humidity. (Markwick, 2007) Evaporites form from salty solutions when the rate of evaporation is greater than the rate of water from precipitation or other sources, such as groundwater and playa lakes. There must be a source of water already present in order for evaporites to form, and today they occur in regions that are semi-arid and arid that have a shortened or infrequent wet season where the rate of precipitation is not greater than that of evaporation. However, net evaporation and relative humidity is not even included in modern climate records, and numerous methods of numerically representing these gaps in climate data have been created. Annual average precipitation must be less than 50 cm/year. For desert regions, precipitation would have to be less than 25 cm/year. According to Hearing et al. (2018), there are evaporites from the Cambrian that span a wide range of latitudes. This corroborates with their isotope data from the Early Cambrian, around 541 - 509 Ma, that suggests a greenhouse climate. Utilizing atmospheric CO_2 estimates made by Berner and Kothavala (2001) for the Cambrian in the GEOCARB III model, (~2800 ppm to 8960 ppm, up to 32 times pre-industrial concentrations) and the Fast Ocean Atmosphere Model (FOAM), from the Mathematics and Computer Science Division of Argonne National Laboratory and the Space Science and Engineering Center at the University of Wisconsin-Madison, Hearing et al. (2018) simulated a Cambrian climate scenario for ~510 Ma, over a span of 2000 years. They found that they could reproduce the high temperatures from the oxygen isotope record if atmospheric CO_2 in the model was set to 8960 ppm. These results lend support to the idea that any evidence of ice development at high latitudes was likely from the Early Cambrian, or during very brief periods of cooling.

In the Late Cambrian, there is evidence for large-scale environmental change. According to Elrick et al. (2011), in the Furongian Epoch (Late Cambrian,~497 to 485 Ma), there was a 3 to 5‰ positive shift in $\delta^{13}C$ that lasted approximately four million years. (Elrick et al., 2011) This event was known as the Steptoean Positive Carbon-Isotope Excursion, or SPICE. SPICE was associated with an oceanic anoxic event that led to well-preserved organic materials. Seawater temperatures at the beginning and end of the SPICE event were unusually warm, but there was a cool period in between. According to Elrick et al. (2011), ocean temperatures during the warmest part of the event rose by ~9 to 12 degrees Celsius, while, during its coolest, ocean temperatures dropped by ~6 degrees Celsius. Lower $\delta^{18}O$ concentrations were associated with the unusually warm ocean waters. The higher $\delta^{18}O$ was attributed to seawater cooling and a mass extinction event with upwelling of cooler ocean waters onto continental shelves, and an increase of $\delta^{13}C$. Generally, $\delta^{13}C$ spikes occur in cool climates. However, as suggested by Elrick et al.

(2011), SPICE is significant due to the fact that SPICE lasted longer than any of the other $\delta^{13}C$ excursions during the Paleozoic Era. It is also significant in that it provides evidence for cooler conditions during the Cambrian. Evidence of environmental fluctuations during SPICE coincides with a global extinction event. The unusual warming during SPICE has been attributed to an additional atmospheric CO_2 source, such as volcanic activity, and reduced amount of weathering of the land.

Runkel et al. (2010) provide additional evidence for cooling in the middle of SPICE. They theorized that sandstone intraclasts within the Jordan Formation (which was near the equator during the Cambrian) indicate that ice bonded the sand together, and that there may have been local freezing and thawing cycles. Runkel et al. (2010) also suggested that there was a large mass extinction during the Mid-Late Cambrian, as well as periodic cooling, where cold water moves upwards over continental shelves and freezing shorelines. These freezing and thawing events, however, were not similar to the Cryogenian Period during the Neoproterozoic, when ice covered much of the earth, but, rather, were episodic, local, and unstable.

According to Babcock et al. (2015), higher sea level at times during the Cambrian could be due to glacial melting which provides implicit support for periodic cooling. This corresponds with the shale and limestone deposits that occur in British Columbia, Canada, and the United Kingdom. (Hearing et al., 2018) Collectively, this evidence suggests that the Cambrian may have had an overall greenhouse climate, but it may have been an unstable environment with abrupt changes leading to the periodic cooling and mass extinction events that followed.

Investigating past climate relies mostly on historic geologic records, such as fossils and sediments, which provide little understanding of the dynamics of ancient climates. For this, we must use a global climate model to try to reconcile conflicting climate proxies from the Late Cambrian, specifically during the SPICE event.

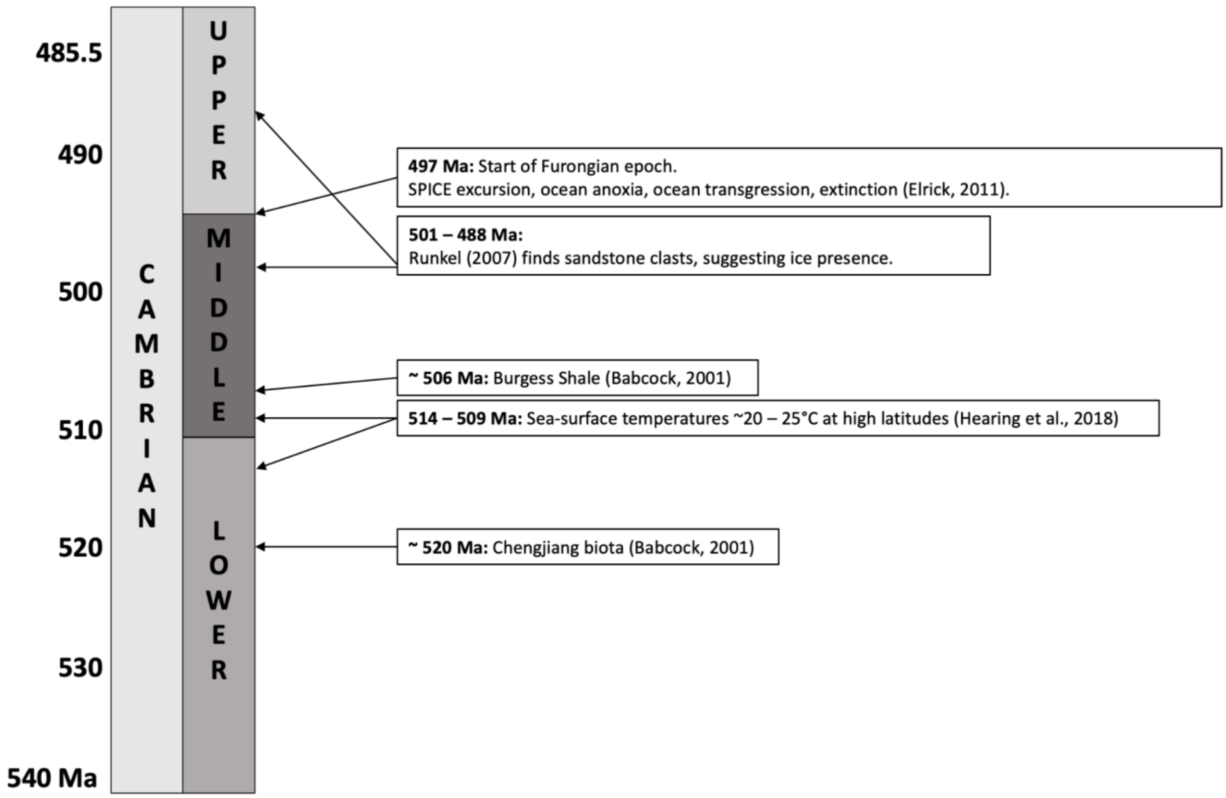
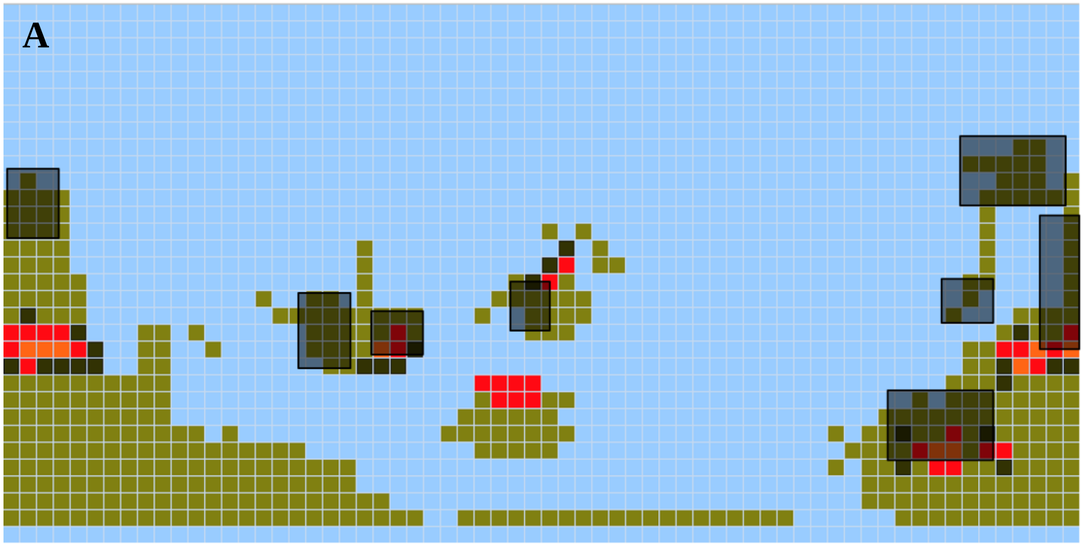
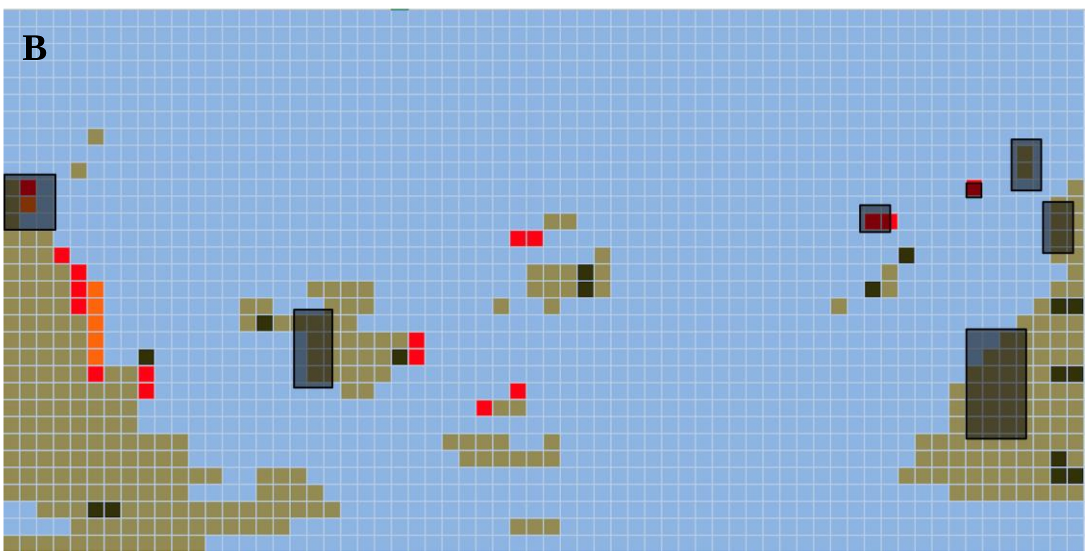


Figure 1. Chronostratigraphic chart of events that occurred during the Cambrian based on a review of previous work. (Babcock, 2001)

Methodology

Using a climate model, we attempt to simulate conditions that would support or reject evidence of ice near the equator in the Late Cambrian, as suggested by Runkel et al. (2010). We also test conditions that would have produced a greenhouse climate, as is suggested by the work of Hearing et al. (2018). We use a low-resolution Global Climate Model, the Planetary Simulator (PlaSim), developed at the University of Hamburg in Germany. (Haberkorn et al., 2009) The model has a T21 spectral resolution (this corresponds to a Gaussian grid size of about 5.6 deg longitude by 5.6 deg latitude) and simulates the climate system with a simplified 50 m deep "slab" ocean that approximates ocean heat transport through diffusion. (Lunkeit et al., 2012) The model includes 10 levels that extend upward in the vertical domain, and four levels that extend into the soil. The first experiment was run on a high-performance computer (HPC) with modern continental configuration and was designed to confirm that the current version of PlaSim would generate similar results as the climate report created by the developers of PlaSim, included with the model. We tested the model with similar parameters included in the climate report, such as near-modern-day CO_2 concentration (348 ppm at the time of the report), for a span of 50 years. After testing and validating the model, we ran several Cambrian experiments that used varying CO_2 concentrations, two different land-surface albedo, and two different continental configurations (provided by Deep Time Maps, as seen in Figures 2A and 2B). The CO_2 concentrations were chosen based on estimates made by Berner and Kothavala (2001) with GEOCARB III, as mentioned in the previous section. The solar constant used for all experiments was 1309 W/m^2, approximately 4% less than modern-day. (Hearing et al., 2018) We ran each experiment for a span of a hundred years on a Linux machine. To determine the climate sensitivity to CO_2 and continental configuration, we examined climatic variables, such as temperature, sea ice cover (and thickness), and precipitation. Table 1 provides details of the seven experiments, including the continental configuration used for each experiment. In the discussion of our results below, we focus on a comparison of the experiments using the 540 Ma continental configuration (CAMB2, CAMB3, and CAMB4), with their equivalent experiments using the 500 Ma continental configuration (CAMB7, CAMB6, and CAMB5, respectively).





Figures 2A & 2B. Continental configurations used for the Cambrian simulations. Both are adapted from Deep Time Maps. Figure 1A shows the continental configuration from 540 Ma, and Figure 1B is from 500 Ma. Dark brown colors represent regions where the elevation is ~500 m, while red notes regions of ~800 m, and orange is ~1000 m. Black boxes note locations where evaporites may have been present, as suggested by Scotese (2000).

EXPERIMENTS	Land- Surface Albedo	CO_2 Concentration (ppm)	Continental Configuration	Description
CAMB1	0.37	400	540 Ma	Low CO_2 (Present Day)
CAMB2	0.37	2800	540 Ma	High Albedo (540 Ma)
CAMB3	0.24	2800	540 Ma	Low Albedo (540 Ma)
CAMB4	0.24	8960	540 Ma	High CO_2 (540 Ma)
CAMB5	0.24	8960	500 Ma	High CO_2 (500 Ma)
CAMB6	0.24	2800	500 Ma	Low Albedo (500 Ma)
CAMB7	0.37	2800	500 Ma	High Albedo (500 Ma)

Table 1. Details of the seven Cambrian experiments run using PlaSim.

Results

Surface Temperature

Due to the high concentration of atmospheric CO_2 (8960 ppm), experiments CAMB4 and CAMB5 produced the warmest mean annual surface temperatures (Figure 3), while CAMB2 and CAMB7, with high land-surface albedo and lower CO_2, provided the coolest scenarios, with the exception of CAMB1. CAMB1 was run with modern-day CO_2 concentration of 400 ppm, and the planet became covered with ice and snow. This is what is known as a 'Snowball Earth' and represents conditions that were probably more likely in the Neoproterozoic, at 650 Ma, not the Cambrian. With a somewhat reduced continental surface area at 500 Ma, CAMB5, overall, had the warmest mean annual surface temperatures, with the exception of some smaller regions within the low-to mid-latitudes, where CAMB4 produced temperatures that exceed 35℃. CAMB4 and CAMB5 (Figure 4C) had much larger variations where there were changes in land cover in CAMB5, exceeding a 14℃ temperature difference in quite a few regions near 30 degrees N, as well as in the low to mid southern latitudes. CAMB3 and CAMB6, with low land-surface albedo and low CO_2, produced similar annual average surface temperatures at low latitudes and at the equator. However, due to the differing continental configuration, CAMB6 had slightly warmer surface temperatures, near 20 degrees Celsius at mid to high latitudes, with greater differences (and warmer conditions) in the Northern Hemisphere. CAMB3 and CAMB6 (Figure 4B) have the smallest differences in surface temperatures overall, compared to the rest of the simulations, varying from 4 to 8℃ at mid to low latitudes, especially near regions where there would have been more land cover in CAMB3. CAMB2, the coolest scenario that did not produce a global freeze, had a mean annual surface temperature that varies considerably from the other high-albedo, low-CO_2 scenario, CAMB7, by ~2℃ in the low-latitudes, and up to 12-14℃ in the high latitudes of the Northern Hemisphere (Figure 4A). Near the equator, the annual average surface temperature is near 20℃ for both experiments, which, notably, is not conducive to ice formation in low latitudes.

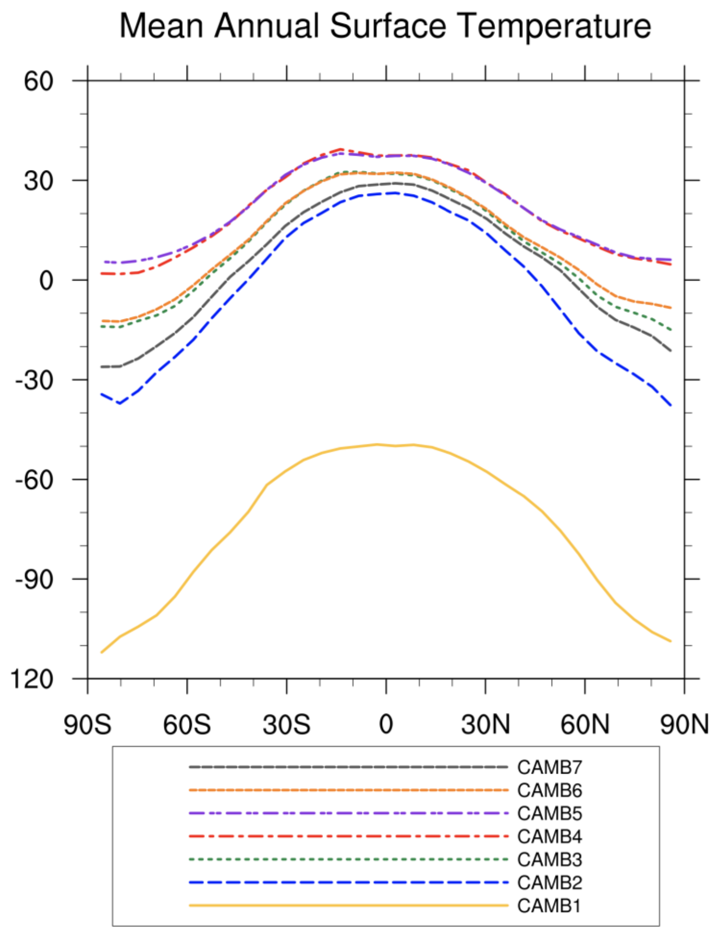
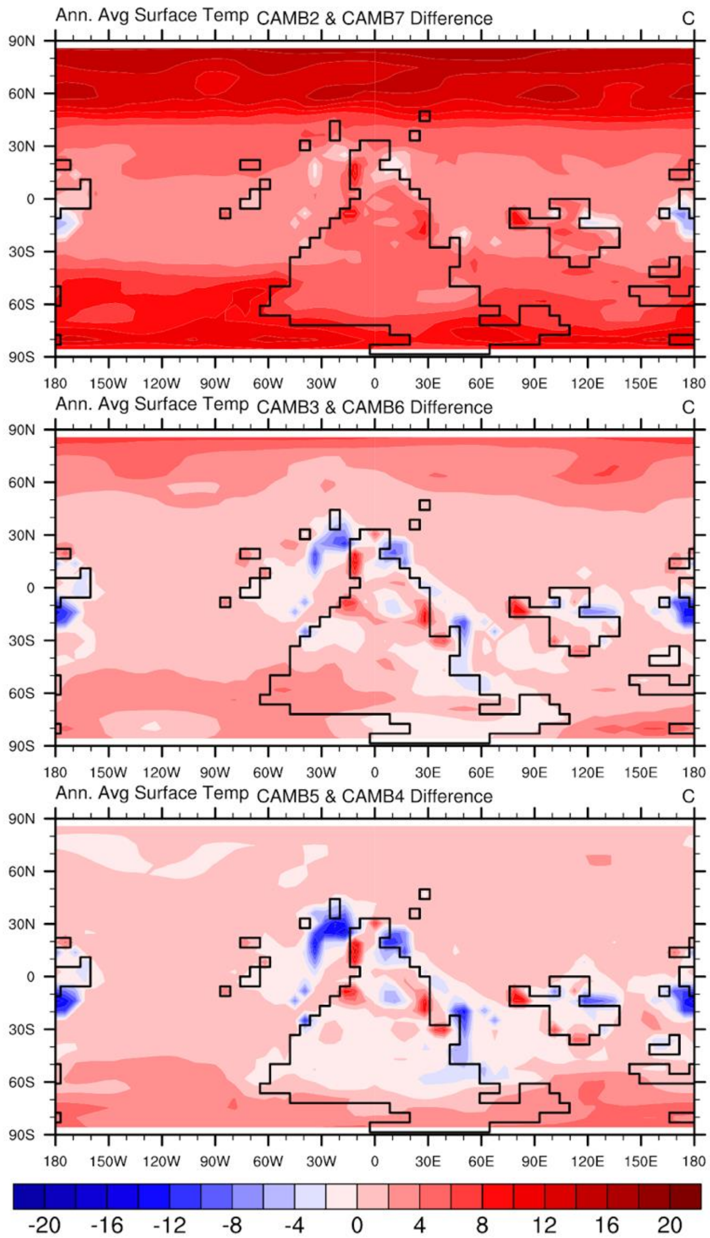


Figure 3. Latitudinally averaged mean annual surface temperature for all seven Cambrian Experiments (℃)



Figures 4A, 4B, & 4C. Temperature differences between (A) CAMB2 & CAMB7, (B) CAMB3 & CAMB6, as well as (C) CAMB4 & CAMB5 experiments. The most significant differences in annual average surface temperature are noted to be in regions that were originally covered by land in CAMB4, where the surface temperatures were significantly warmer due to the land surface.

We compare the annual average surface temperatures from CAMB5 (Figure 5) with that of Hearing et al. (2018), which used an equivalent atmospheric CO_2 concentration. While the annual average surface temperatures in CAMB5 on land are extremely warm, and temperatures exceed 52 degrees Celsius over land and near the shores in some regions, surface temperatures over the ocean were much cooler than the experiment from Hearing et al. (2018), especially near the poles, where there is a difference of at least several degrees Celsius. Near the equator, sea surface temperatures are very similar between the two simulations. While experiments CAMB4 and CAMB5 used the same parameters as the experiment from Hearing et al. (2018), different models and continental configurations were used across all three experiments. More specifically, Hearing et al. (2018) are able to examine the impacts of warming on ocean circulation, which is not possible in PlaSim, with a slab ocean.

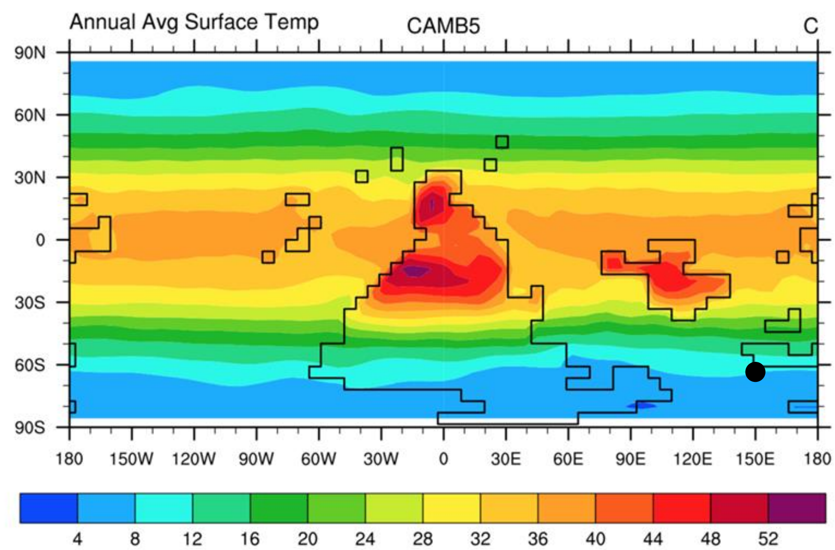
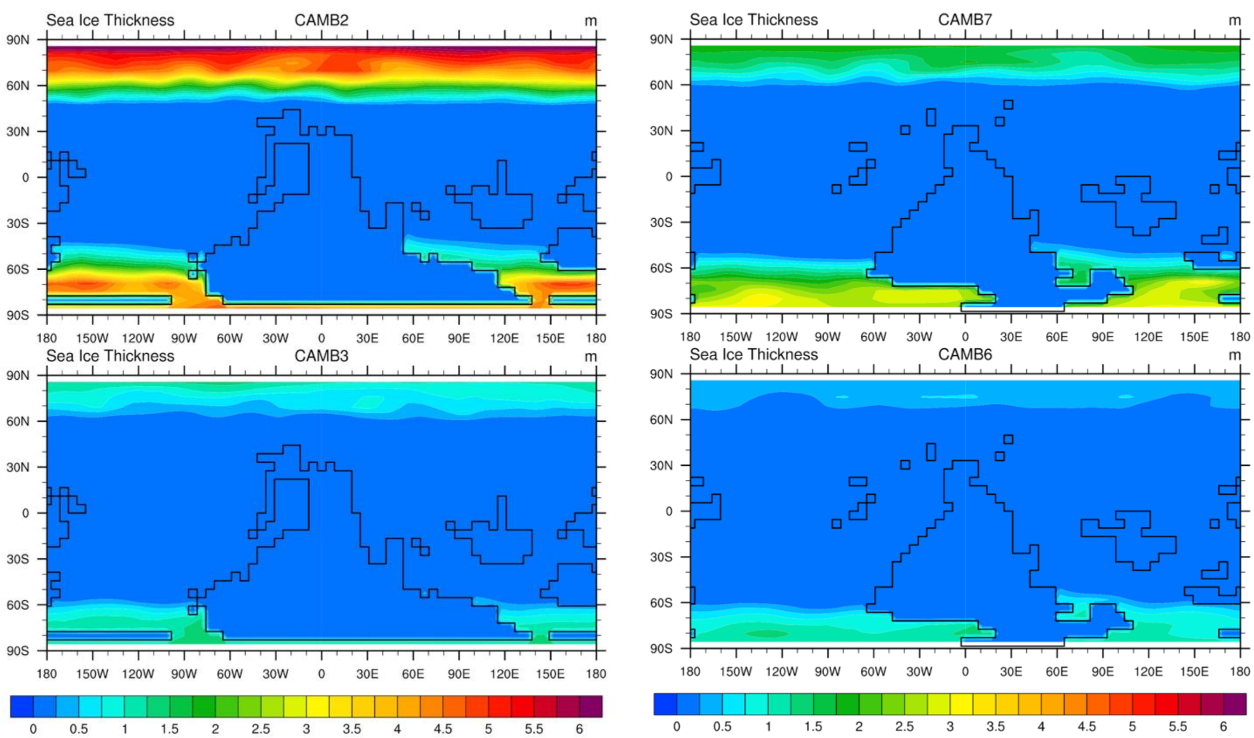


Figure 5. Annual average surface temperature run in PlaSim for CAMB5. The black dot represents where phosphate $\delta^{18}O$ data was taken in Hearing et al. (2018). Their simulations suggested sea surface temperature was ~20°C at this location.

Sea Ice Cover

No Cambrian experiment, apart from CAMB1 (where the model produced a "Snowball Earth" by using modern CO_2) produced conditions that would allow for ice to form near or at the equator, as suggested by Runkel et al. (2010). In the CAMB4 and CAMB5 simulations, little to no sea ice was produced anywhere on the planet (Figure 6), even though snowfall was still present during the winter season, as seen in Figure 7. When comparing the annual average sea ice cover across all seven experiments, CAMB2 and CAMB3 notably produced the largest amount of ice cover, in some regions, exceeding ~6 m in depth. However, this was only present poleward of 50° in CAMB2, while the largest concentration of sea ice in CAMB3 is mostly prevalent in the most southern latitudes, south of 60°.



Figures 6A, 6B, 6C, and 6D. Sea ice cover, as well as thickness for CAMB2, CAMB7, CAMB3, and CAMB6.

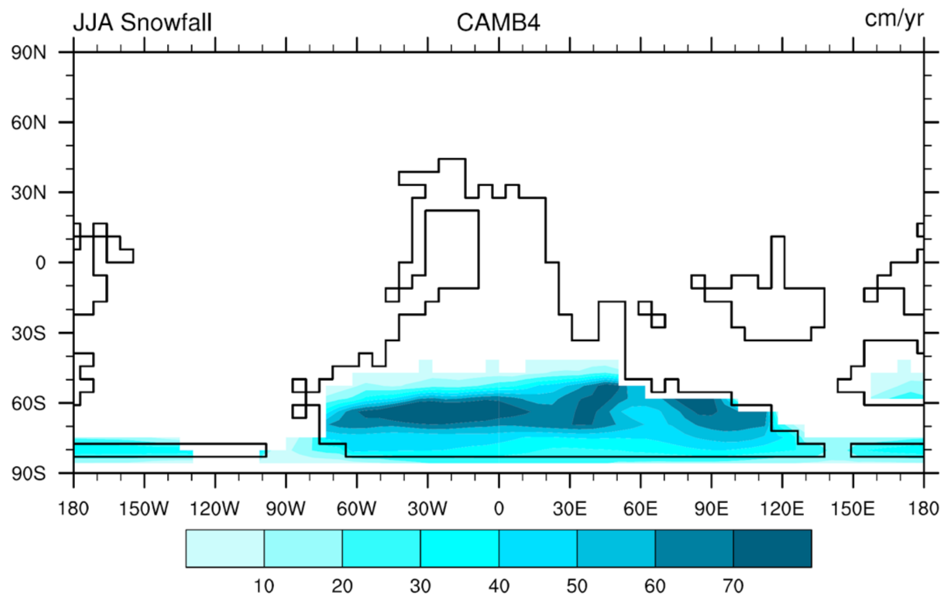


Figure 7. Snowfall amount for the winter season in the Southern Hemisphere in CAMB4.

Both CAMB6 and CAMB7, which are comparable to CAMB3 and CAMB2, respectively, produced significantly less sea ice with respect to ocean cover and depth. While CAMB6 and CAMB7 exhibit similar characteristics to CAMB2 and CAMB3 respectively, the maximum sea ice depth observed between the two simulations does not exceed ~ 2 m and exists only poleward of 60°. This also implies that the Cambrian configuration from 500 Ma produces significantly warmer conditions than 540 Ma, since there is, overall, significantly less land surface area, (more energy is absorbed by the ocean) and a higher sea level.

Precipitation

CAMB4 and CAMB5, the warmest scenarios, produced the highest annual average precipitation. Figure 8 shows the mean annual latitudinally averaged precipitation (cm/yr) for all seven Cambrian simulations. It is notable that both CAMB4 and CAMB5 had mid-latitude peaks in mean annual precipitation that were shifted poleward in both hemispheres in comparison to the remaining five experiments. CAMB2 experienced the driest conditions overall, where mean annual precipitation was as little as ~20 to 30 cm/yr at low latitudes, and only peaked at ~340 cm/yr at the equator, in comparison to ~380 cm/yr in CAMB4 and CAMB5. Although CAMB4 is slightly drier than CAMB5 in the subtropics due to greater land-surface area, the total amount of precipitation varies by ~2 cm/year between CAMB4 and CAMB5.

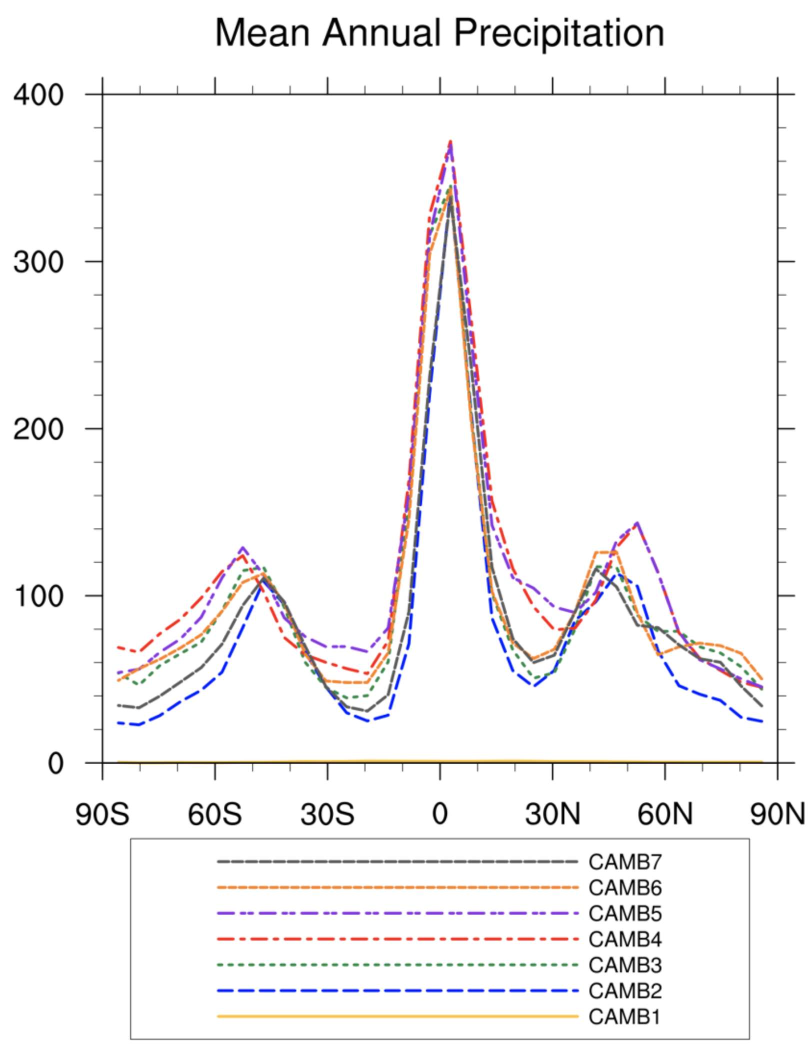
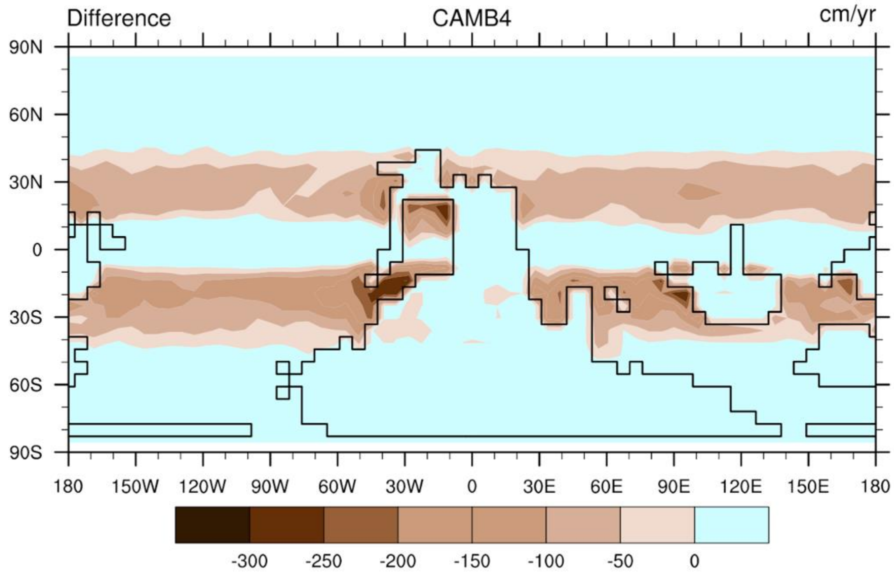
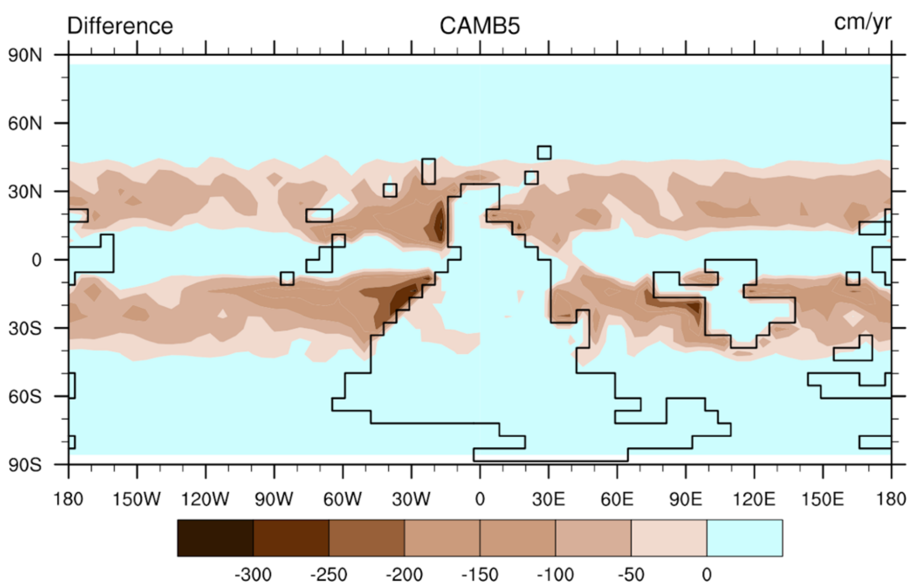


Figure 8. Mean annual precipitation for all seven Cambrian experiments.

Although experiments CAMB4 and CAMB5 used the same albedo, solar constant, and CO_2 concentration, the continental configuration (from 540 Ma) used in CAMB4 had slightly smaller oceans (lower sea level) and larger continents than that of 500 Ma, which would assist in favoring slightly drier conditions overall. CAMB3 also utilized the same continental configuration, solar constant and albedo as CAMB4, but CO_2 concentration was only 2800 ppm, and global average precipitation was lower, by 8 cm/yr (Table 2). In CAMB2, which used a higher land surface albedo, but was otherwise comparable to CAMB3, global average precipitation was reduced by an additional ~19 cm/yr. Thus, we can infer that Cambrian precipitation is more sensitive to CO_2 concentration and albedo than it is to the differences in continental configuration.

The very warm annual average temperatures and low mean annual precipitation at low latitudes present in experiments such as CAMB4 and CAMB5 can be linked to Cambrian climate proxies such as the presence of evaporites at low latitudes, as suggested by Markwick (2007). If a particular region receives less than 50 cm/yr of precipitation, and if the evaporation rate is larger than the rate of precipitation for one season, evaporites can form. Based on the Mean Annual Precipitation, experiments CAMB4 and CAMB5 receive significantly less precipitation than 50 cm/yr, suggesting very dry conditions that are favorable for evaporite formation. Figure 9 below shows the difference between the annual average precipitation and evaporation for CAMB4 and CAMB5. The driest regions, specifically, are near midlatitude coastal regions in both the Northern and Southern Hemispheres. Regions where evaporation is greater than precipitation also align with maximum surface temperature values over land. Since the rate of evaporation in those particular regions during the Cambrian is much larger than the average yearly precipitation rate, it can be inferred that evaporites might have existed due to the very warm, dry conditions allowed by the high CO_2 concentration, and low albedo.





Figures 9A & 9B. Difference between annual average precipitation and evaporation in CAMB4 and CAMB5, specifically, regions where evaporation is greater than precipitation (less than -50 cm/year). Differences greater than zero are not included.

Global average surface temperatures and total precipitation (Table 2) are very similar to the annual averages discussed above. For example, in experiments such as CAMB2 and CAMB3, where we tested climate sensitivity to albedo and CO_2 concentration with the same continental configuration, the global average surface temperature is approximately 10°C warmer in CAMB3, while annual precipitation is higher. This implies that the Cambrian climate is highly sensitive to the concentration of CO_2 and albedo. When comparing the two different continental arrangements, the Cambrian configuration at 500 Ma (used in CAMB5, CAMB6, and CAMB7) yielded slightly warmer temperatures and higher annual precipitation, as there was a slightly larger area of ocean cover in comparison to the continental configuration at 540 Ma, used in CAMB1, CAMB2, CAMB3, and CAMB4. This suggests that Cambrian climate is somewhat sensitive to continental arrangement and total land surface area but is more sensitive to CO_2 concentration and albedo.

Global Averages

GLOBAL AVERAGE	Surface Albedo	Total Precip (cm/yr)	TOA Net LW Flux (W/m^2)	Surface Net SW Flux (W/m^2)	TOA Net SW Flux (W/m^2)	Surface Temp (K)	Atm. Temp (K)	GH Forcing (W/m^2)
CAMB1	0.7071792	0.7820928	-106.7903	90.5853	106.7025	208.6036	190.762	0.968
CAMB2	0.2612015	90.50832	-209.30	146.7743	208.7305	280.3732	204.5885	7.531
CAMB3	0.1639057	109.11456	-223.2012	155.9018	222.8289	290.5005	209.9033	8.812
CAMB4	0.1159035	127.7208	-230.6229	158.1265	230.1519	299.6702	217.6699	9.899
CAMB5	0.10354	129.613	-229.9812	157.3279	229.6788	299.7886	217.5503	9.929
CAMB6	0.14307	111.3221	-223.439	155.5947	223.1177	291.2778	210.0614	8.932
CAMB7	0.2052201	100.915	-216.3201	149.8959	214.7234	285.9585	206.623	8.274

Table 2 describes the global average surface albedo, total precipitation, surface temperature, atmospheric temperature, as well as radiation parameters and greenhouse forcing for all seven Cambrian experiments.

Conclusion

Based on the simulations that were run using PlaSim, Cambrian climate is primarily sensitive to CO_2 concentration. At both 540 and 500 Ma, annual average surface temperatures significantly increased as the amount of CO_2 increased, and temperature differences between the two continental configurations were the largest when atmospheric CO_2 was at its highest. Annual average precipitation was also highest in CAMB4 and CAMB5, where CO_2 concentration was at 8960 ppm. Lower precipitation was observed in cases with the lower concentration of CO_2 (2800 ppm). In general, experiments CAMB4 and CAMB5 showed the most similarities with the experiment of Hearing et al. (2018), except for a few regional discrepancies, such as the cool ocean temperatures near the poles, and very warm continental temperature in the mid-latitudes.

The difference in continental configuration can be considered a less significant factor in determining the climate of the Cambrian. The 500 Ma continental configuration, with reduced land surface area compared to that of 540 Ma, allowed for a larger temperature difference between experiments with higher CO_2 concentration. Also, at 500 Ma, changes in land surface albedo produced a larger difference in total sea ice than at 540 Ma. Finally, the difference in continental configuration did not produce a major difference in annual average precipitation nor in the general locations of maximum precipitation or evaporation.

We were not able to simulate a long-term or short-term cooling event that would produce ice formation near, or at the equator, including during the winter season, as suggested by Runkel (2010). However, the possibility for local, short-term cooling periods is still likely, without the presence of ice near the equator, particularly in a scenario in which there were to be a lower concentration of atmospheric CO_2, as well as a larger amount of land coverage, such as the continental configuration at 540 Ma rather than at 500 Ma. This would still coincide with the mass extinction events observed during SPICE, as mentioned by Elrick et al., (2011). CAMB4 was able to produce snowfall of up to ~70 cm/yr at mid-high latitudes, even with a high concentration of CO2, so episodic freezing and thawing cycles could have still occurred. In order for ice to form at low latitudes, the concentration of CO_2 would have to be significantly reduced (as demonstrated in CAMB1, the "Snowball Earth" simulation that resulted from using modern-day CO_2 values).

It is important to point out that the modeling scenarios presented in this study represent a range of possible conditions in the Cambrian. Uncertainty in setting up the boundary conditions for these scenarios, can propagate uncertainty in the results. For example, the topographic height values used in PlaSim are estimates, as the exact elevation of these continents are not known. The range of values for CO_2 concentration (Berner and Kothavala, 2001) with GEOCARB III, solar constant, and land surface albedo are also, necessarily, estimates. While Hearing et al. (2018) and experiments CAMB4 and CAMB5 used a similar solar constant, atmospheric CO_2 concentration, and land surface albedo, these experiments utilize different numerical models and continental configurations. PlaSim has a simplified "slab" ocean model, where the diffusion of heat within the ocean is the only approximation of ocean heat transport. FOAM is more complex and utilizes a higher resolution, and allows for dynamical ocean heat transport, including, advection, and vertical mixing. To allow for the least amount of discrepancies, further work should include running the same set of experiments using the FOAM model, as it has the advantage of a complex ocean model, that can better capture the impact of ocean heat transport on such processes as the formation of sea ice.

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References

Avigad, D., Sandler, A., Kolodner, K., Stern, R., McWilliams, M., Miller, N., & Beyth, M. (2005). Mass-production of Cambro–Ordovician quartz-rich sandstone as a consequence of chemical weathering of Pan-African terranes: Environmental implications. *Earth and Planetary Science Letters*, 240(3-4), 818–826. https://doi.org/10.1016/j.epsl.2005.09.021.

Babcock, L. E., Peng, S.-C., Brett, C. E., Zhu, M.-Y., Ahlberg, P., Bevis, M., & Robison, R. A. (2015). Global climate, sea level cycles, and biotic events in the Cambrian Period. *Palaeoworld*, 24(1-2), 5–15. https://doi.org/10.1016/j.palwor.2015.03.005

Babcock, L. E., W. Zhang, & Leslie, S. A. (2001). The Chengjiang Biota: Record of the Early Cambrian Diversification of Life and Clues to Exceptional Preservation of Fossils. *GSA Today*, 11(2), 4. https://doi.org/10.1130/1052-5173(2001)0112.0.co;2

Berner, R. A. & Kothavala, Z. (2001). GEOCARB III: A revised model of atmospheric CO2 over Phanerozoic time. *American Journal of Science*, 301(2), 182–204. https://doi.org/10.2475/ajs.301.2.182

Frakes, L. A. (1979). *Climates Throughout Geologic Time*. Elsevier Inc., New York. 322.

Deep Time Maps, (2020). *Global Paleogeography and Tectonics in Deep Time Series*. http://deeptimemaps.com/global-paleogeography-and-tectonics-in-deep-time-series/. Accessed May 2020

Elrick, M., Rieboldt, S., Saltzman, M., & Mckay, R. M. (2011). Oxygen-isotope trends and seawater temperature changes across the Late Cambrian Steptoean positive carbon-isotope excursion (SPICE event). *Geology*, 39(10), 987–990. https://doi.org/10.1130/g32109.1

Haberkorn, K., Sielmann, F., Lunkeit, F., Kirk, E., Schneidereit, A., & Fraedrich, K. (2009). *Planet Simulator Climate*, 90.

Hearing, T., Harvey, T., Williams, M., Leng, M., Lamb, A., Wilby, P., … Donnadieu, Y. (2018). An early Cambrian greenhouse climate: *Science Advances*, 4(5). https://doi.org/10.1126/sciadv.aar5690.

Lunkeit, F., Borth, H., Fraedrich, K., Kirk, E., Kleidon, A., Luksch, U., … Seilmann, S. (2011). *Planet Simulator Reference Manual Version 16*, 85.

Markwick, P.J. (2007). The palaeogeographic and palaeoclimatic significance of climate proxies for data-model comparisons, in Williams, M., Haywood, A.M., Gregory, F.J., and Schmidt, D.N. eds. *Deep-Time Perspectives on Climate Change: Marrying the Signal from Computer Models and Biological Proxies*, 251–312. https://doi.org/10.1144/tms002.13

Runkel, A. C., Mackey, T.J., Cowan, C.A., & Fox, D. L. (2010). Tropical shoreline ice in the late Cambrian: Implications for earth's climate between the Cambrian Explosion and the Great Ordovician Biodiversification Event. *GSA Today*, 20(11), 4–10. https://doi.org/10.1130/GSATG84A.1

Scotese, C. R. (2000). *Early Cambrian Climate*. http://www.scotese.com/ecambcli.htm. Accessed January 2021