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3d-simulations of the Archean climate: Solutions to the 'faint young Sun problem' demand higher greenhouse gas concentrations than previously thought

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During the Archean eon (3.8–2.5 billion years ago), the Sun was up to 25% less luminous than today, yet there is convincing evidence that the Earth's ocean surface was not completely frozen during this time period. As the Earth's rotation rate was higher and the continental fraction smaller than today, the climate system and, particularly, its response to changes in radiation were different from the present-day climate state. This has significant implications for the effect of higher greenhouse gas concentrations which are expected to play a crucial role in solving this 'faint young Sun problem'. Here, we present the first comprehensive 3-dimensional simulations of the Archean climate using a fully coupled ocean-atmosphere-sea-ice model. Our simulations thus include processes as the sea-ice albedo feedback and the higher rotation rate of the Earth. We find that a CO_2 partial pressure of 0.4 bar is needed to prevent the early Archean Earth from falling into a 'snowball state'. This value is significantly higher than estimates of about 0.06 bar based on previous studies with 1-dimensional radiative-convective models. Our results also suggest that currently favoured CO_2/CH_4 greenhouse solutions could be in conflict with geochemical constraints emerging for the middle and late Archean. In order to gain a deeper understanding of the underlying mechanisms determining the critical partial pressure for the early Archean, we further present the key characteristics of three simulated climate states which differ in their atmospheric CO_2 content: one of them is ice-free, one has about the same mean surface air temperature of 288 K as today's Earth and the third one is the coldest stable state in which there is still an area with liquid surface water (i.e., the critical state at the transition to a 'snowball Earth'). We find that the most important aspects leading to the higher critical CO_2 amount are albedo changes due to growing sea-ice as well as a reduction of meridional heat transport which results in a steeper latitudinal temperature profile. The dependence of the surface albedo on global mean temperature under early Archean boundary conditions is found to be approximately linear for partially frozen ocean surfaces. We suggest to use this relation derived from our set of simulations as a simple parameterisation of the ice-albedo feedback in 1-dimensional models in which the effect has so far been neglected.