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Sensitivity of Neoproterozoic Snowball-Earth Inceptions to Continental Configuration, Orbital Geometry, and Volcanism

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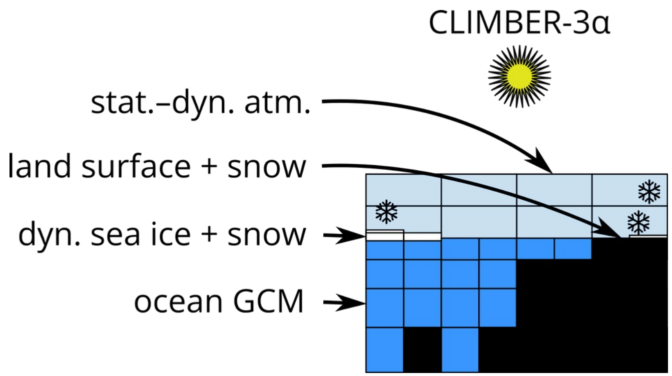
Stefan Petri, Jeroen van Hunen, James U.L. Baldini

Vienna

28 April 2023

Sturtian “Snowball Earth” (720 Ma)



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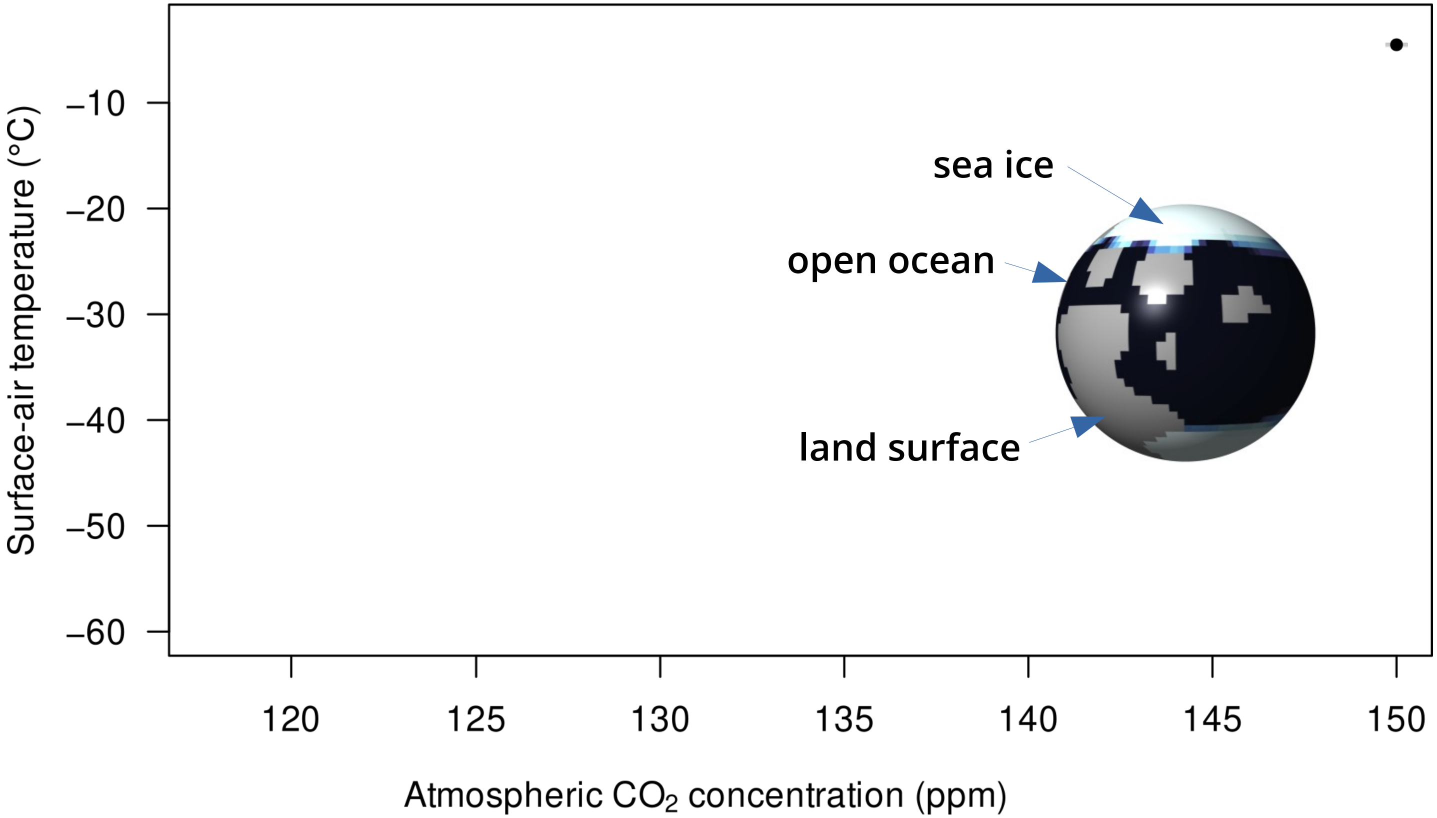

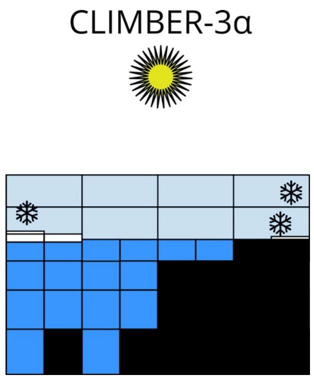

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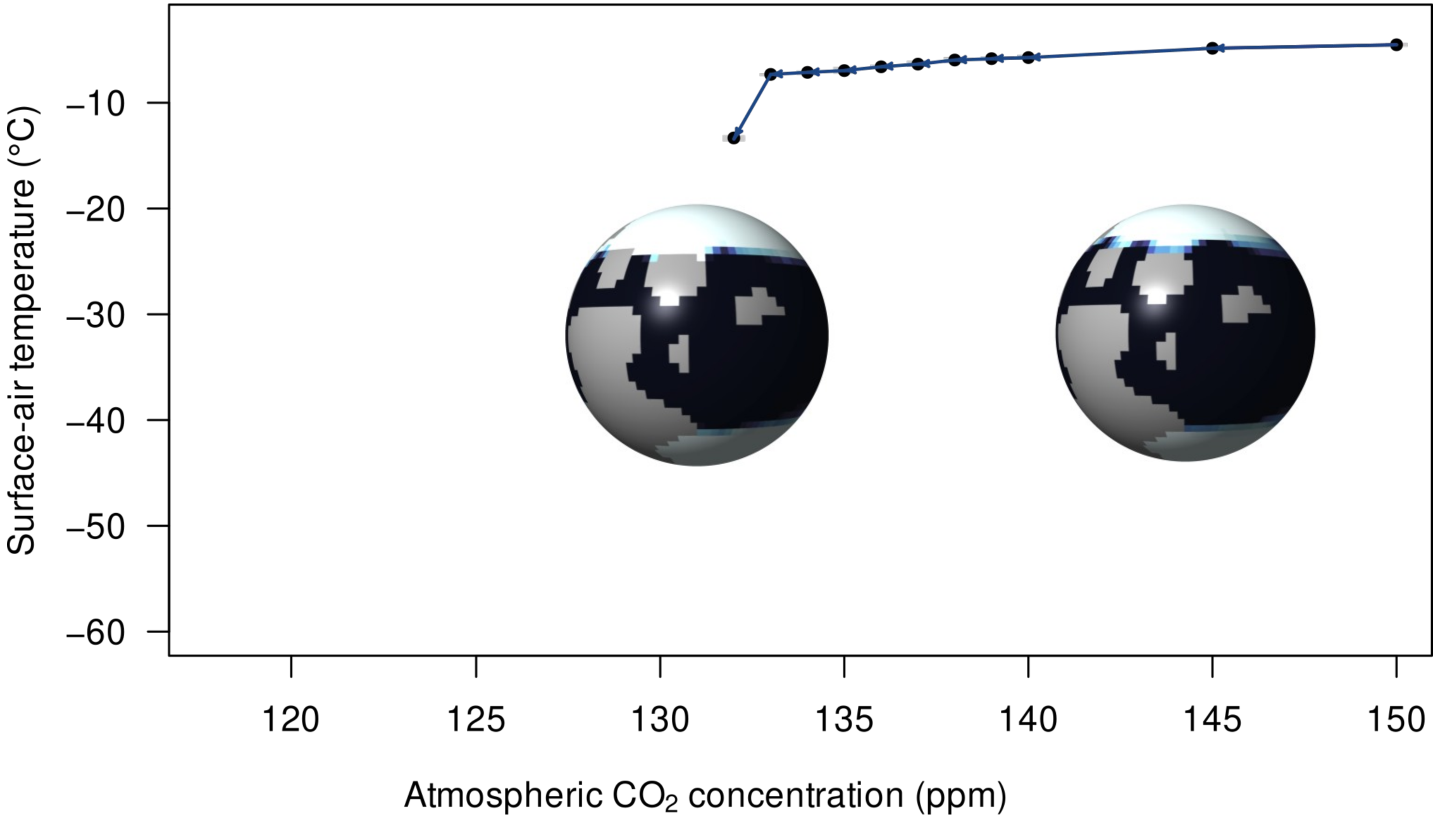

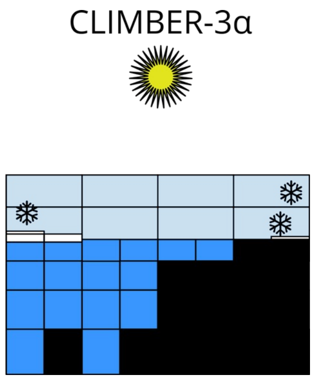

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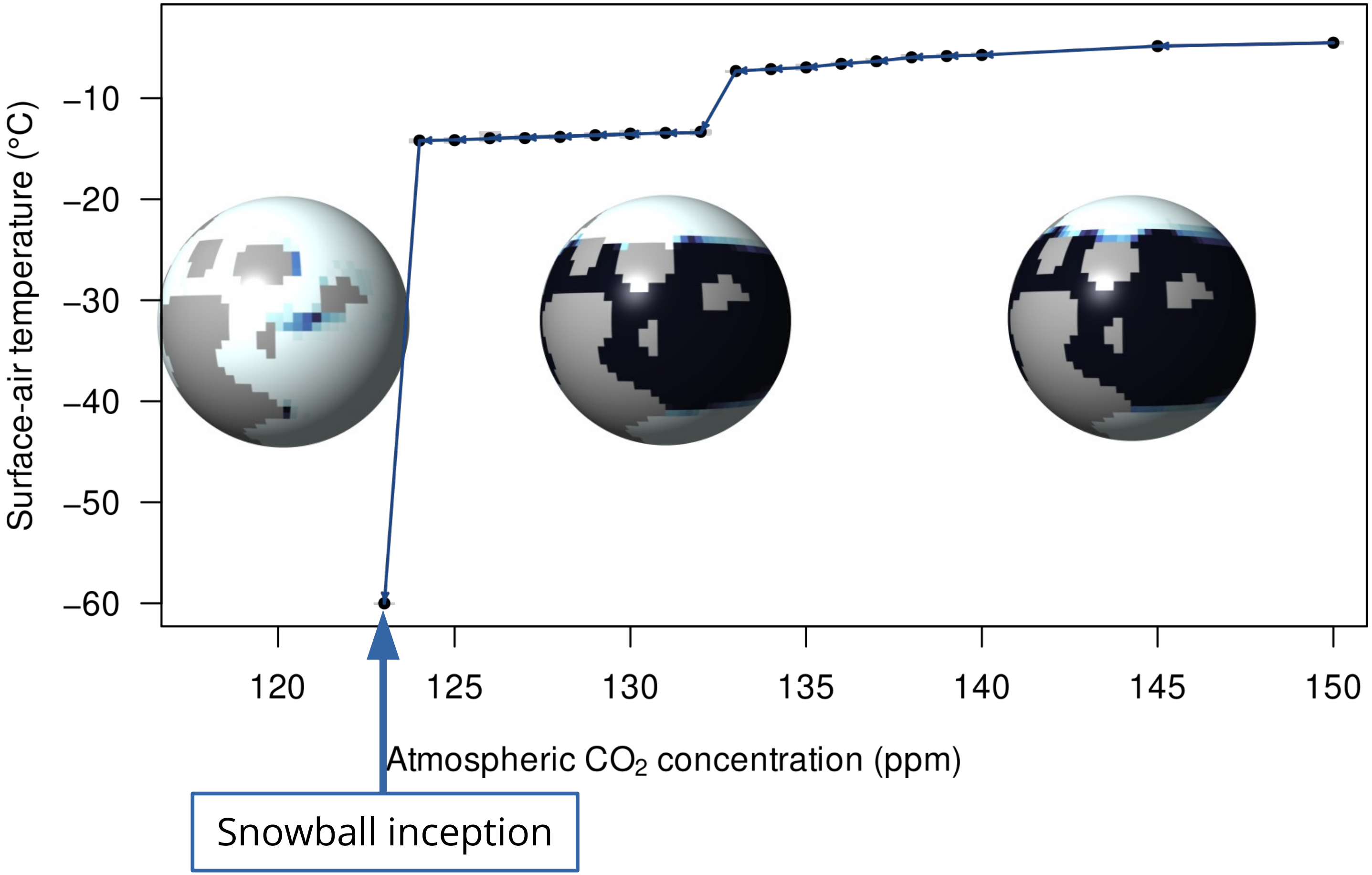
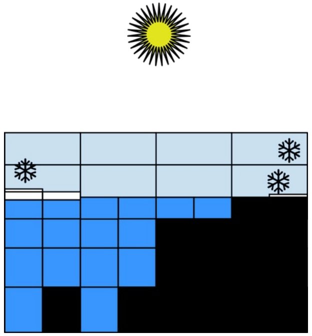
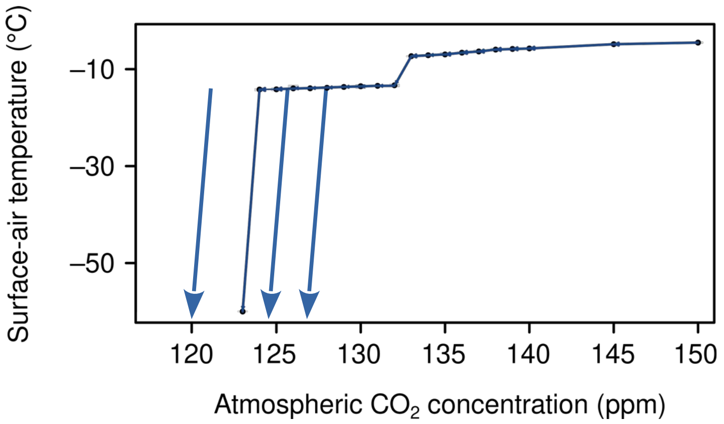
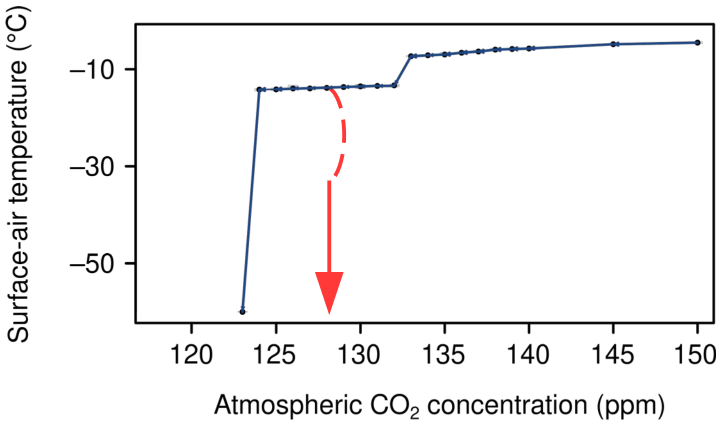


CLIMBER-3α

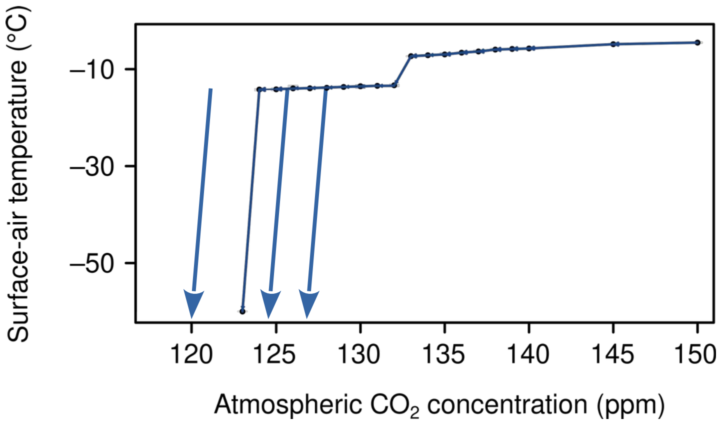


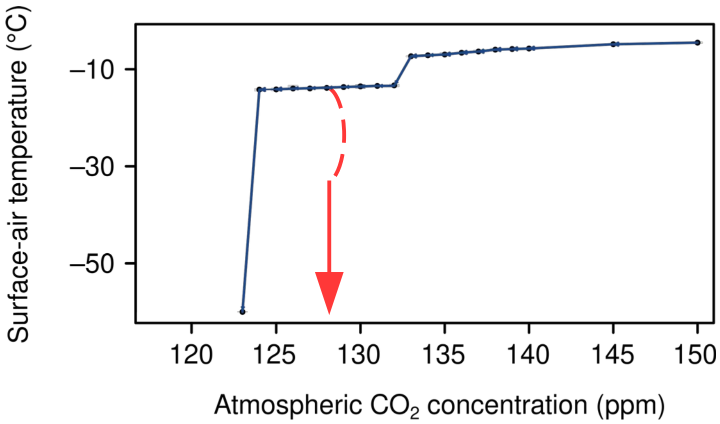
Experiments



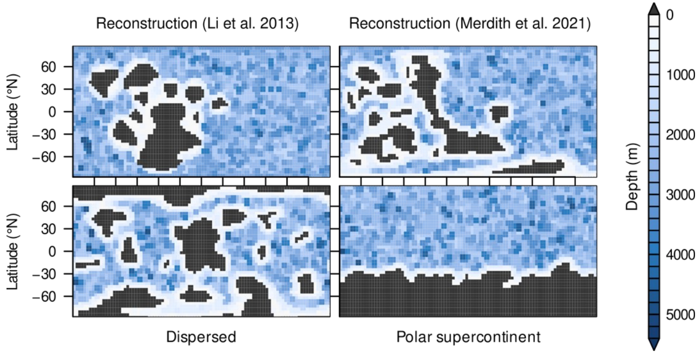


Experiments

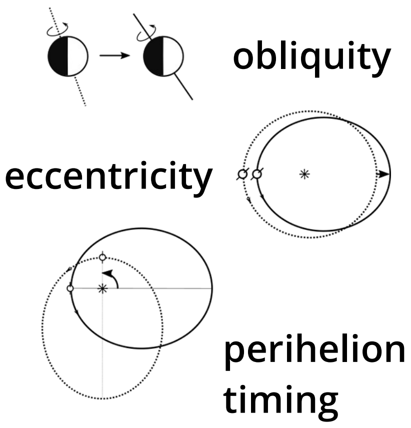




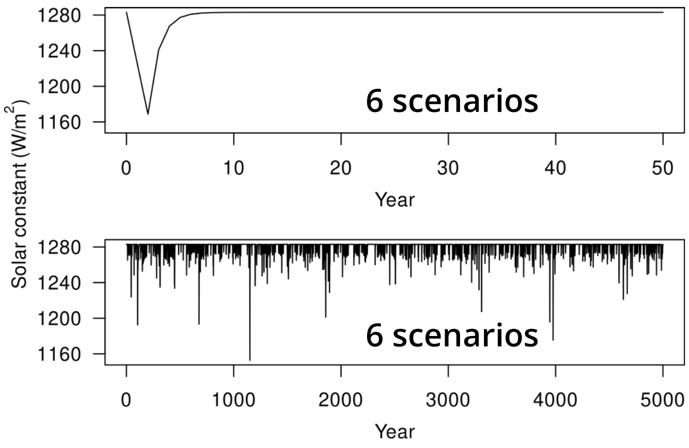
Shifting continents (720 Ma)



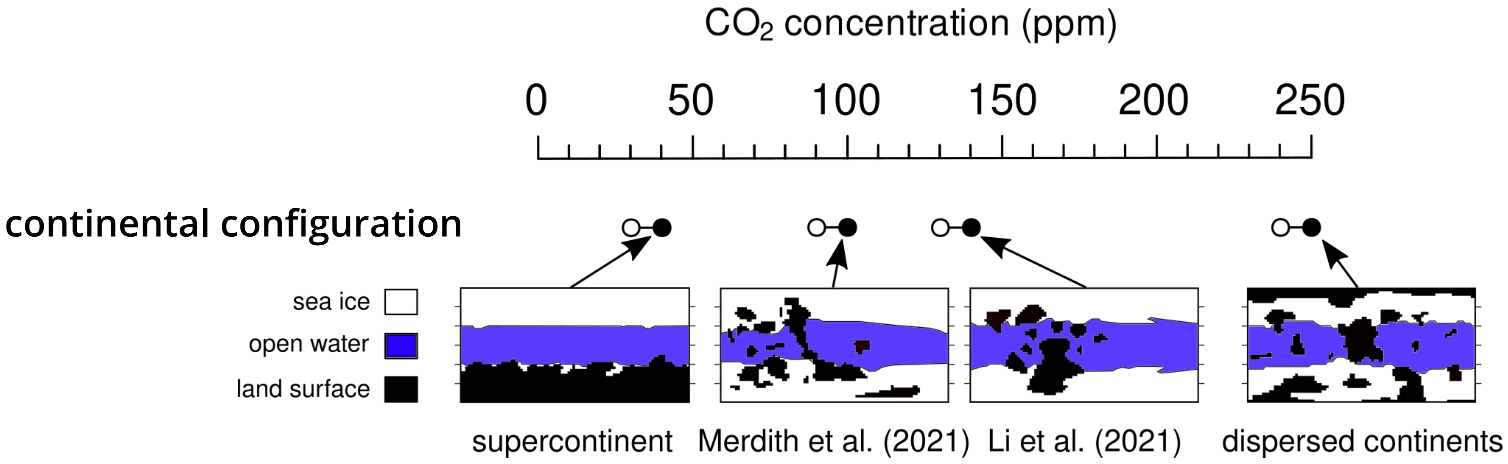
Changing the orbit



Adding volcanism



Thresholds for Snowball Inception



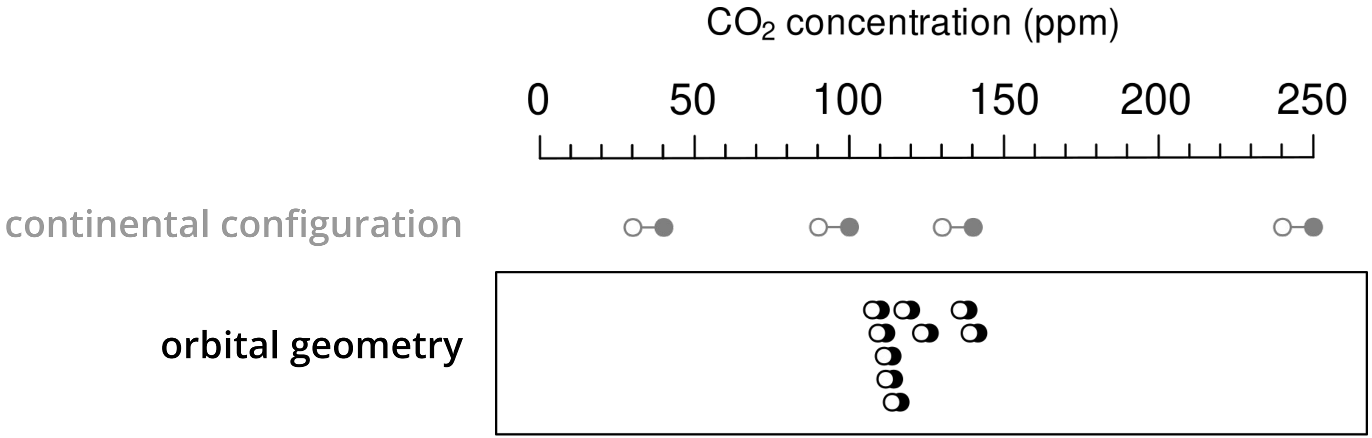
warmest

intermediate stable sea-ice extent

NO intermediate stable sea-ice extent

coldest

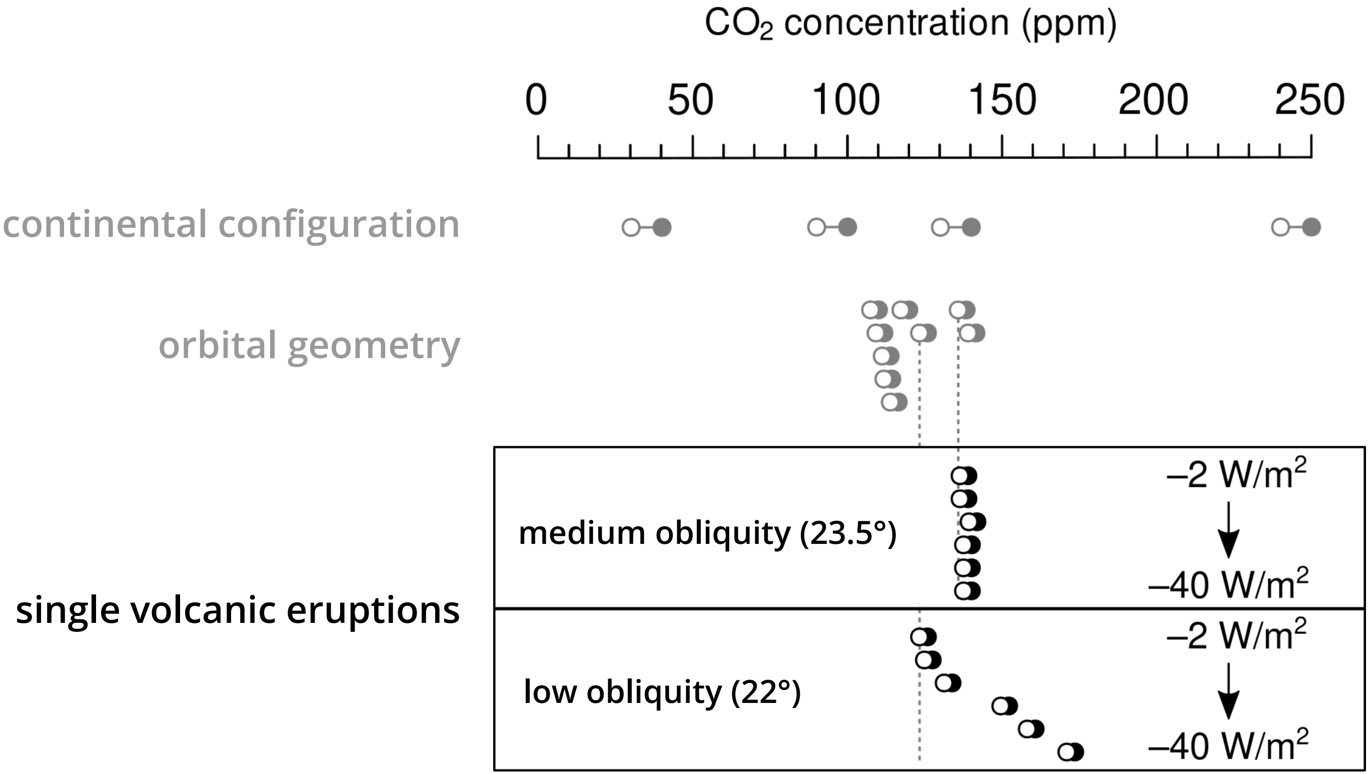
Thresholds for Snowball Inception



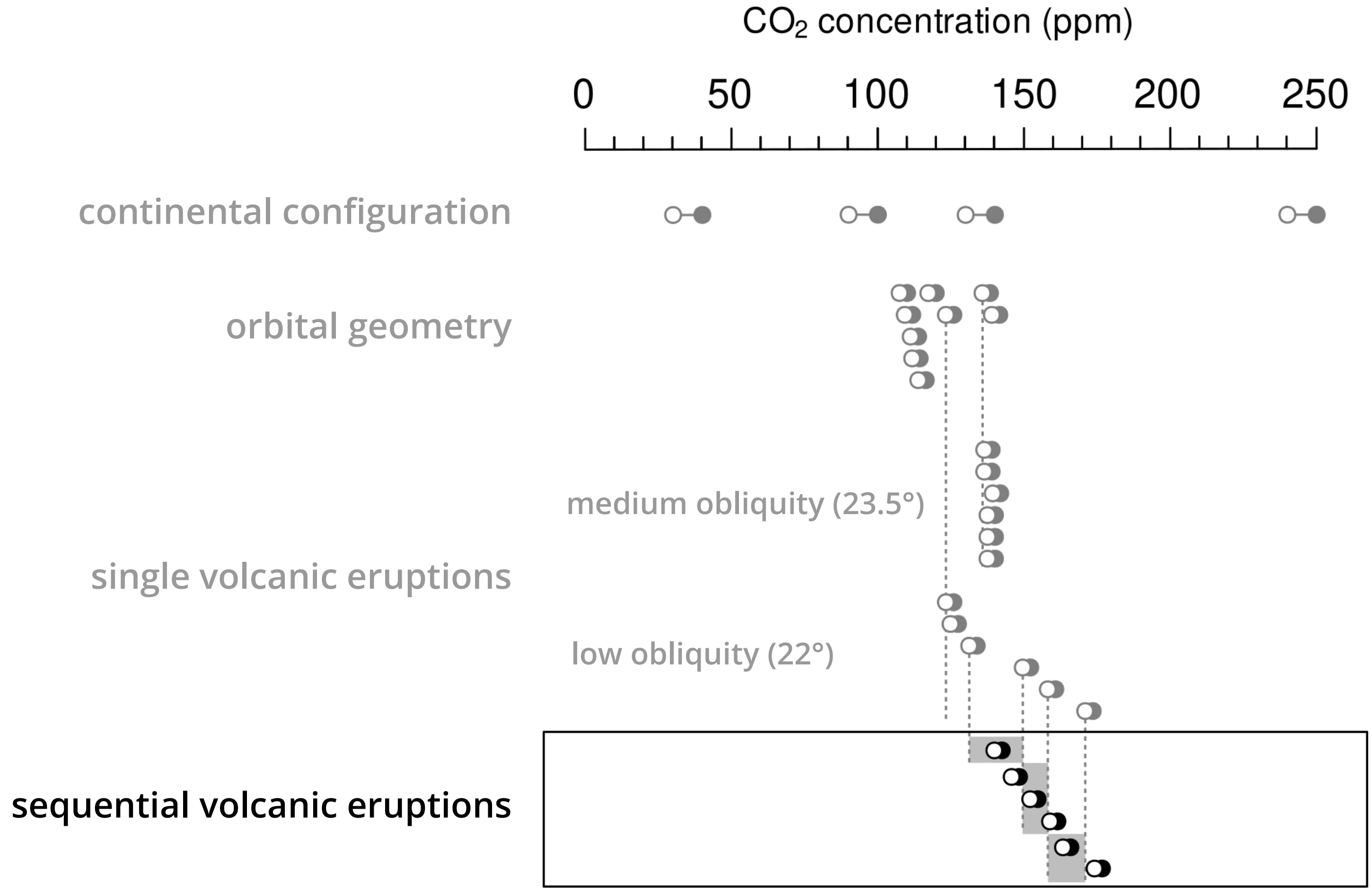
warmest → coldest

(low obliquity + high eccentricity) (high obliquity + low eccentricity)

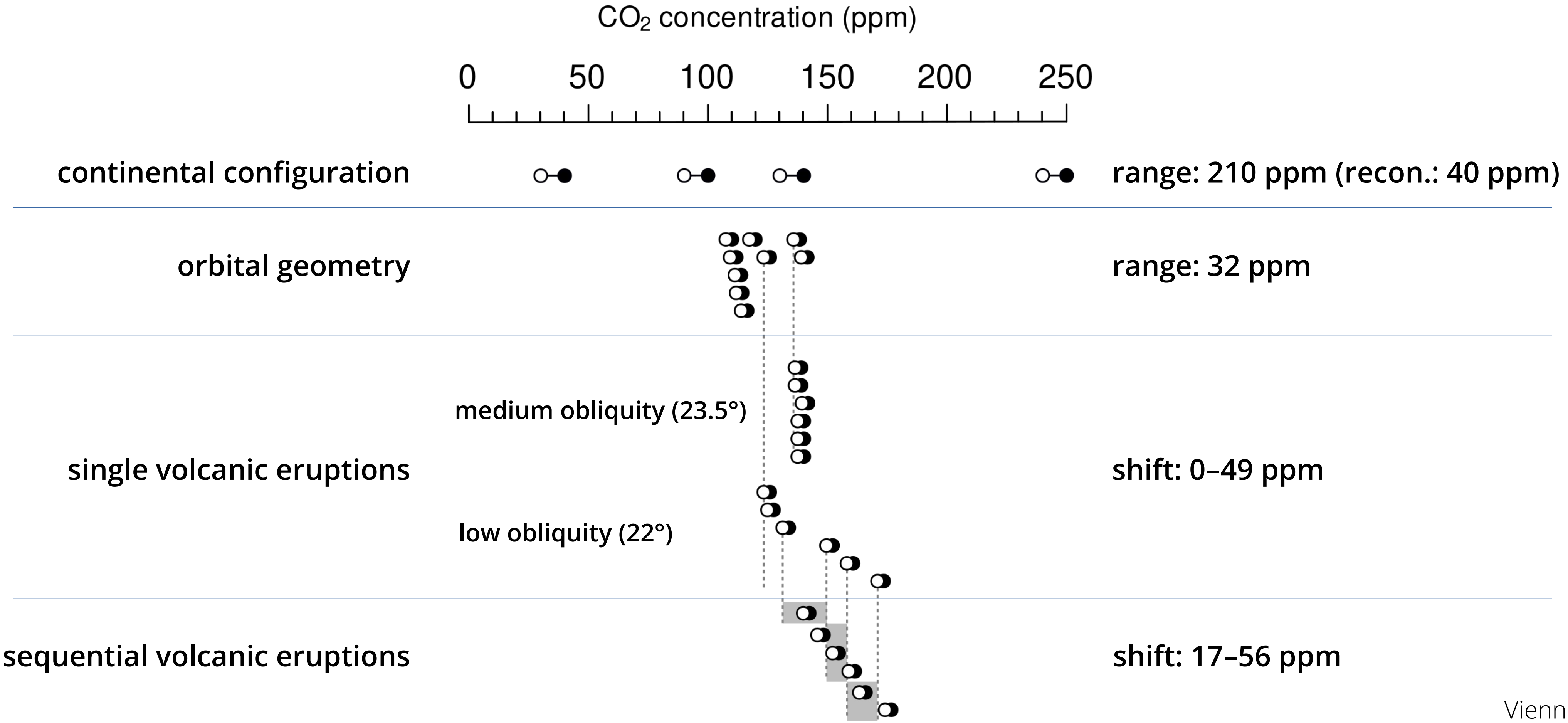
Thresholds for Snowball Inception



Thresholds for Snowball Inception



Thresholds for Snowball Inception



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Vienna
28 April 2023

Prepared transcript of the talk

(Please note that this is not a verbatim transcript but was used in preparation of the talk. It includes minor details which were skipped in the actual talk.)

Slide 1: Title

- Good morning to everyone in the room and online.
- My name is Julius Eberhard, I am working at the Potsdam Institute for Climate Impact Research, and I am very happy to present the work of mine and colleagues from the Potsdam Institute and Durham University.
- Please note that sharing is encouraged and you can find the QR code of our abstract on this slide.
- The work is about the "Sensitivity of Neoproterozoic Snowball-Earth inceptions to continental configuration, orbital geometry, and volcanism".
- In this talk, I am going to focus on the Sturtian Snowball Earth, which started around 720 million years ago.

Slide 2: Sturtian "Snowball Earth" (720 Ma)

- You see a schematic of our climate model CLIMBER-3 alpha.
- It is a model of intermediate complexity and consists of a statistical–dynamical atmosphere, a simple land-surface module allowing for snow cover, thermodynamic–dynamic sea ice with potential snow cover, and an ocean general circulation model, here abbreviated as GCM.
- We do not include dynamic ice sheets.

Slide 3: Sturtian "Snowball Earth" (720 Ma)

- Let me show a simple experiment.
- The diagram shows mean global surface-air temperatures for different CO2 concentrations.
- Starting at a CO2 concentration of 150 ppm, we let the model approach equilibrium and cool it down by carefully reducing the CO2 concentration step by step.
- Additionally, I show the mean sea ice cover in white, open ocean in blue and continents in gray.
- Upon reducing the CO2, the model undergoes a gradual cooling but shows an intermediate tipping toward a somewhat colder state.

- Eventually, we observe a tipping to a fully ice-covered ocean at 123 ppm, which we call the threshold for Snowball inception.
- It is known from a multitude of previous studies that this threshold can vary in a wide range depending on the boundary conditions and the model choice.
- Therefore, we did a large number of experiments in order to quantify this sensitivity to various relevant boundary conditions and perturbations with a single model.

Slide 4: Experiments

- We consider two types of Snowball inceptions:
- To the left, I show the same experiment as before but with varying thresholds under equilibrium conditions.
- To the right, you see a Snowball inception due to a large perturbation of the model, in which case the Snowball inception happens at a higher CO2 concentration than for equilibrium conditions.
- The left type of simulations is realized by either changing the continental configuration, shown at the bottom left, or varying the orbital parameters obliquity, eccentricity, and perihelion timing, shown in the middle.
- For the continental configurations, we have two actual reconstructions for the Sturtian by Li and colleagues and Merdith and colleagues, and we have two idealized distributions, namely an evenly dispersed configuration and a supercontinent at the South Pole.
- For the orbital geometry, we vary the parameters within plausible ranges for the past 200 million years.
- The right type of simulations emulates volcanic eruptions as transient, annually resolved reductions of the incoming solar radiation.
- Here, we distinguish different single events, shown at the top, and sequential eruptions over 5000 years, shown at the bottom.
- For each type of perturbation, we take 6 different scenarios regarding the magnitude or statistical parameters of the forcing.

Slide 5: Thresholds for Snowball Inception

- Let me now go through the thresholds we found.
- The black dots indicate the last non-Snowball state, the white dots the first Snowball state in the CO2 reduction experiments.
- For the different continental distributions, we find the lowest theshold for the supercontinent configuration, which has the warmest surface.
- The dispersed configuration, the coldest one, has the highest threshold, 210 ppm above the supercontinent.

- The thresholds for the two reconstructions, however, are not ordered by their surface temperature but by the existence of an intermediate stable sea-ice extent, which makes the climate more stable in colder states.
- Remember that you saw one such state in the experiment before.
- Here, the reconstruction of Merdith and colleagues supports one such state, while the other reconstruction does not.

Slide 6: Thresholds for Snowball Inception

- The simulations with differing orbital geometry span a range of 32 ppm, which is a bit less than the continental reconstructions.
- The thresholds correlate with the surface temperatures at a fixed CO2 concentration, where we have the warmest configurations at low obliquity and high eccentricity, while the coldest configurations have high obliquity and low eccentricity.

Slide 7: Thresholds for Snowball Inception

- The thresholds for the single volcanic eruptions are shown in comparison to the thresholds without perturbation.
- From top to bottom, the eruptions increase in magnitude, between minus 2 and minus 40 watts per square meter peak net solar forcing.
- We were surprised by the difference between simulations with medium obliquity at 23.5 degrees and low obliquity at 22 degrees.
- The former configuration is very resistant against perturbations, while the latter shows shifts in the threshold of up to 49 ppm for extremely large eruptions of minus 40 watts per square meter.

Slide 8: Thresholds for Snowball Inception

- Finally, for the sequential eruptions, we compare the largest event in the time series with the single eruptions and obtain the ranges shown in gray.
- If the superposition of sequential eruptions has no other effect than single events, the thresholds will be expected to fall in these ranges.
- In 2 scenarios, the thresholds exceed those expected from the single eruptions, which means that the consideration of superimposed eruptions has a crucial effect.
- These two cases are characterized by particularly strong background forcing from small eruptions.

Slide 9: Thresholds for Snowball Inception

- On my last slide, you find a summary of the threshold, their ranges and the shifts from volcanism.
- Please feel free to contact me via e-mail in case of questions.
- Have a good day and I thank you for your attention!

Supplementary material for "Sensitivity of Neoproterozoic Snowball-Earth inceptions to continental configuration, orbital geometry, and volcanism", EGU General Assembly 2023

This is a collection of additional figures on the results presented in the talk at the General Assembly on 28 April 2023 in Vienna.

Thresholds for Snowball-Earth inception and mean surface-air temperatures for different continental configurations (Figure 1)

L+13 indicates the continental configuration according to the reconstruction by Li et al. (2013), Sediment. Geol. 294. Similarly, M+21 refers to the reconstruction by Merdith et al. (2021), Earth-Sci. Rev. 214.

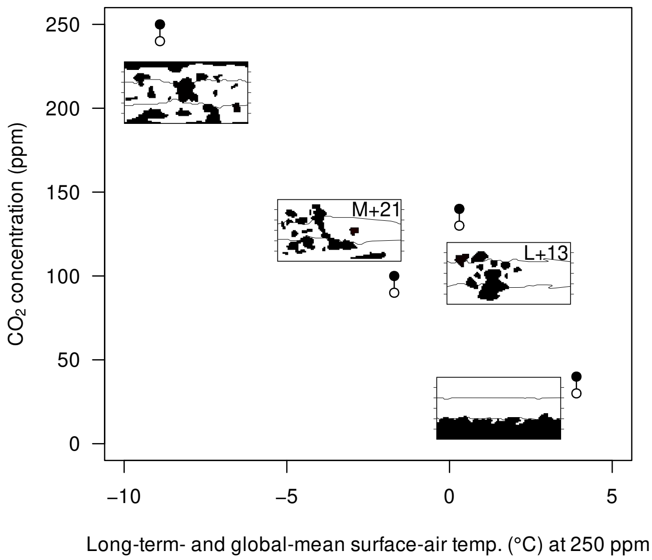

Figure 1: Long-term- and global-mean surface-air temperature at 250 ppm and CO_2 concentration just above (black dots) and below (white dots) the Snowball-inception threshold for different Sturtian boundary conditions (right). Insets show the continental configurations used in the simulations and the sea-ice margins (sea-ice concentration of 0.5) in the black-dotted cases, i.e. just above the threshold.

Thresholds for Snowball-Earth inception and mean surface-air temperatures for different orbital geometries (Figure 2)

The varied orbital parameters are obliquity (ε), eccentricity (e), and argument of perihelion (ω), where ω = 0° corresponds to perihelion in September and ω = 90° to perihelion in December.

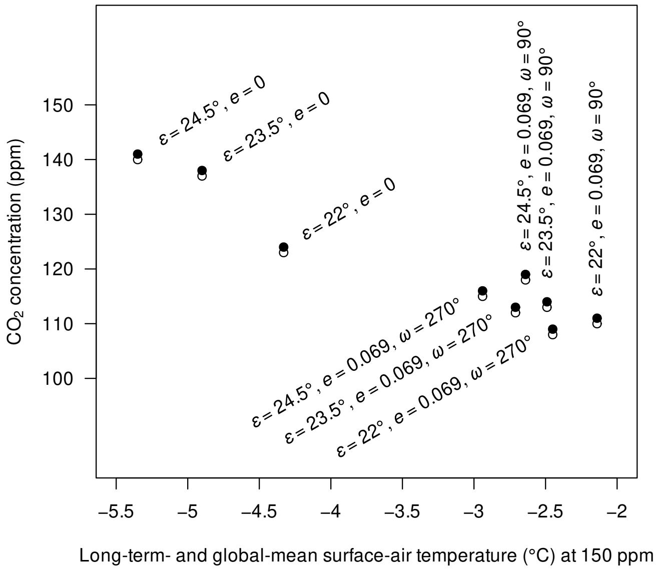

Figure 2: Long-term- and global-mean surface-air temperatures at 150 ppm and CO_2 concentrations just above (black dots) and below (white dots) Snowball inceptions under unperturbed conditions, shown for nine different orbital geometries as indicated by the text labels.

Shifts of thresholds for Snowball-Earth inception for different single global volcanic eruptions (Figure 3)

The different scenarios of single eruptions are ordered by their approximate peak reduction of the net incoming solar flux density, assuming an effective global albedo of 0.3. Since the perturbations act on very cold states with higher albedo here, the actual peak reduction of the net incoming solar flux density is somewhat smaller.

The perturbations were initialised on either the warmest (red dots) or the coldest equilibrium state (blue dots) simulated at the respective CO_2 concentrations.

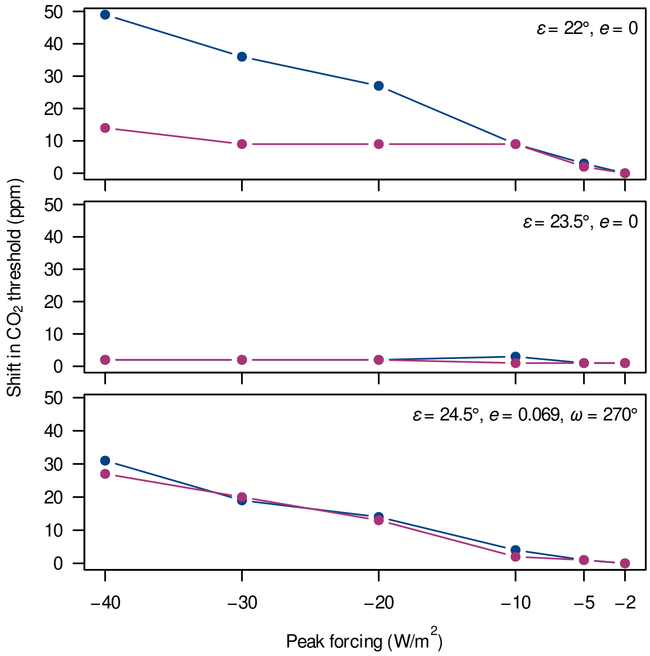

Figure 3: Shift in CO_2 thresholds due to single global volcanic perturbations in three different orbital configurations, each indicated within the panels. Perturbations were initialised either on the warmest (red) or coldest partially ice-covered attractor (blue) simulated at the respective CO_2 level. For example, a shift of 10 ppm means that a perturbation triggers a Snowball inception at a CO_2 concentration 10 ppm above the one expected from unperturbed simulations.

Shifts of thresholds for Snowball-Earth inception for different parametrisations of sequential global volcanic eruptions (Figure 5)

Sequences of global volcanic eruptions (Figure 4) are generated with the max-autoregressive model

$$\Delta S_0(t_i) = -\max\{-\Delta S_0(t_{i-1})/\mathrm{e}, -\Sigma(t_i)\} \quad \text{with} \quad \Delta S_0(t_0) = 0,$$

where ΔS_0 is the change in solar constant, t_i the year with index i, and $\Sigma(t_i)$ is simulated as a pseudo-random sequence obeying

$$\Sigma(t_i) \overset{\mathrm{d}}{=} \begin{cases} \frac{4\sqrt{1-e^2}}{0.7}\Pi(t_i) \text{ with } \mathrm{Prob}(\Pi(t_i) \in [x + \mathrm{d}x]) = \mathrm{d}x\, g_{\beta,\xi,u}(x) & \text{if } b_p(t_i) = \text{eruption}, \\ 0 & \text{if } b_p(t_i) = \text{no eruption}, \end{cases}$$

where 'd' over the equality sign implies equality in distribution and $b_p(t_i)$ is a Bernoulli process deciding about 'eruption' or 'no eruption' in each year t_i. $g_{\beta,\xi,u}$ is a generalised Pareto distribution of the form

$$g_{\beta,\xi,u}(x) = \frac{1}{\beta}\left(1 + \frac{\xi}{\beta}\frac{u - x}{1\,\mathrm{W/m^2}}\right)^{-1/\xi-1}$$

where $\beta > 0, \xi$ are real numbers; u, x are given in $\mathrm{W/m^2}$ and ensure that $u > x$ and the term in parentheses is positive.

Here, each scenario is determined by the three parameters β (shape), u (threshold for smallest eruptions), and p (probability of having an eruption in a given year).

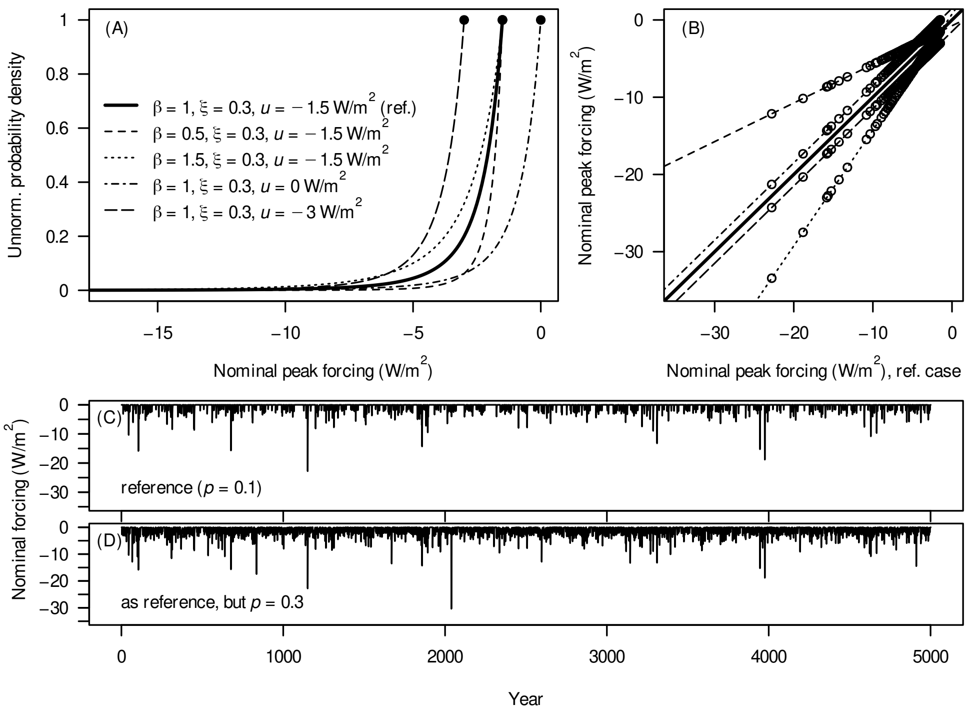

Figure 4: A: Different forms of the generalised Pareto distribution determining the nominal peak forcing in the max-autoregressive model, displayed as unnormalized probability-density functions, i.e. having a maximum value of 1. Dots denote the upper limits of each function's domain and range. E.g. the function with $u = 3\,\mathrm{W/m^2}$ allows for peak forcings at or below $-3\,\mathrm{W/m^2}$ only, while all functions are unbounded from below. B: Nominal peak volcanic forcing in the simulations with each of the distributions from panel A, compared to the reference scenario (diagonal line) at each time step of the generated volcanic time series. C: Nominal volcanic forcing in the reference scenario. D: Same as panel C but for the scenario with increased eruption probability.

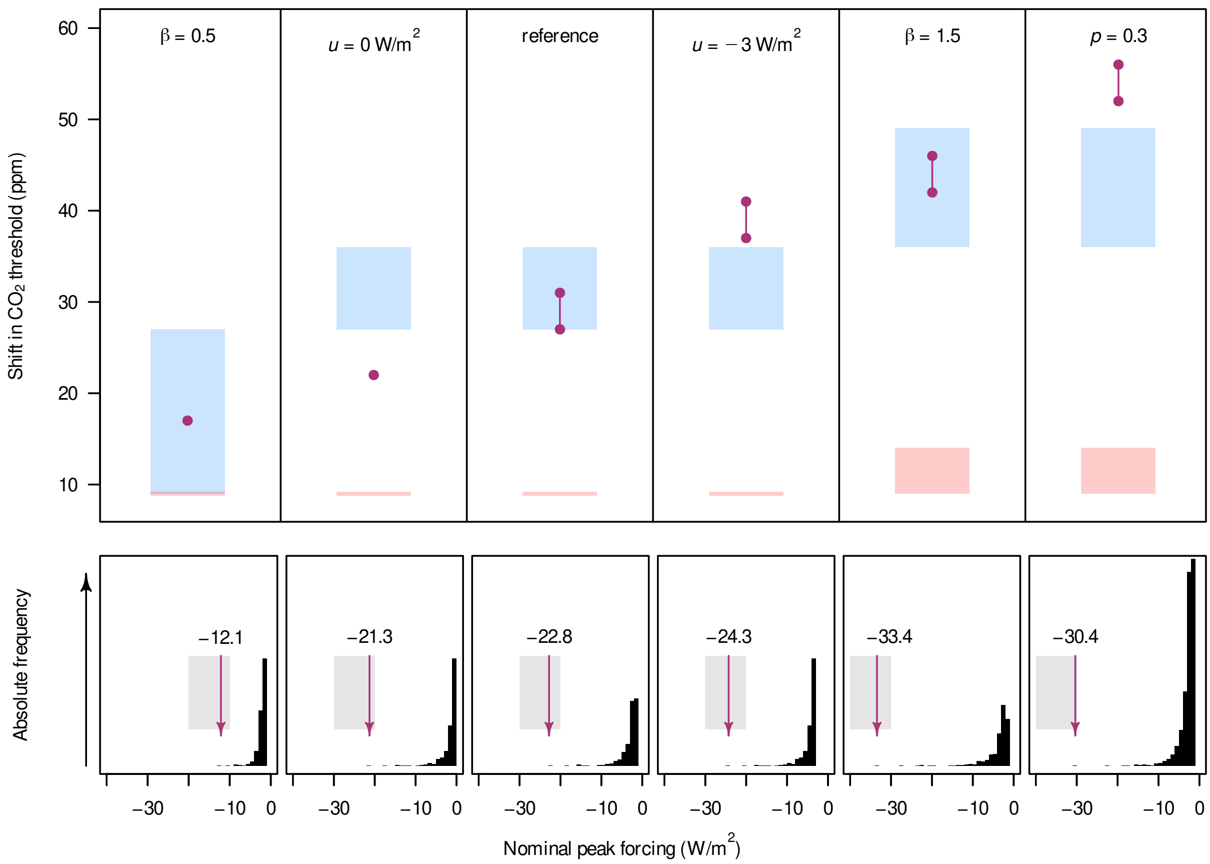

Figure 5: Shift in CO_2 thresholds for six different scenarios of sequential volcanic perturbations. Blue and red areas indicate the ranges expected from single-eruption simulations, comparing the largest event in the time series (marked by arrows) with the existing single-eruption simulations. Panels at the bottom show histograms of the sequences. The reference scenario is $\{p = 0.1, \beta = 1, \xi = 0.3, u = -1.5\,\mathrm{W/m^2}\}$.