

## CLIMATE SCIENCE

# Earth's narrow escape from a big freeze

An equation has been derived that allows the timing of the onset of glaciations to be predicted. This confirms that Earth has just missed entering a new glacial period, and is unlikely to enter one for another 50,000 years. [SEE LETTER P.200](#)

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A subject of much debate is whether atmospheric levels of carbon dioxide were already significantly altered by emissions associated with human activities before the Industrial Revolution in the eighteenth century. One estimate suggests that the atmospheric concentration of CO<sub>2</sub> would have been only 240 parts per million (p.p.m.) in an agriculture-free world, rather than 280 p.p.m., as was measured just before the Industrial Revolution<sup>1</sup>. On page 200 of this issue, Ganopolski *et al.*<sup>2</sup> report modelling studies confirming that we would now be entering an ice age if the concentration had remained at 240 p.p.m. By contrast, they report that glacial inception — the onset of an ice age — could not have occurred at CO<sub>2</sub> concentrations that were typical of the eighteenth century.

The Quaternary period has conventionally been divided into two epochs: the Pleistocene, which lasted from about 2.59 million to 12,000 years ago, and the Holocene, which followed the Pleistocene and continues to the present day. The Pleistocene was a time of great, successive glaciations interspersed with interglacial periods, during which environmental conditions were similar to those occurring today. During the Holocene — the latest interglacial period — humans invented agriculture, and their impact on the environment increased at an exponential rate. One of the signatures of this impact is the rising concentration of CO<sub>2</sub> in the atmosphere. But at what point does this impact become sufficiently large to affect climate and glacial inception?

A modelling study<sup>3</sup> in 2000 established that pre-industrial levels of CO<sub>2</sub> were high enough to guarantee a period of interglacial

conditions for at least 50,000 years (Fig. 1). Consistent with Ganopolski and colleagues' findings, this earlier study also predicted that the next glacial inception (which would have led to a glaciation that reached an ice maximum 60,000 years from now), could not now occur owing to the warming effect of anthropogenic emissions. Moreover, probabilistic assessments<sup>4,5</sup> of the timing of the next glacial inception have been provided by



**Figure 1 | An eighteenth-century smokehouse.** The atmospheric level of carbon dioxide just before the Industrial Revolution was 280 parts per million and may already have been affected by emissions associated with human activities. Ganopolski *et al.*<sup>2</sup> report models suggesting that atmospheric CO<sub>2</sub> levels typical of the eighteenth century were high enough to prevent the onset of a glacial period for 50,000 years.

using simple dynamical systems for climate prediction, calibrated using data about past CO<sub>2</sub> levels and ice volumes. All of these studies used different models and assumptions, but they broadly agree on the potential timing for a glacial inception because their forecasts are determined by predictable drops in incoming solar radiation (insolation) in the Northern Hemisphere caused by changes in Earth's orbit.

Ganopolski and co-workers' study is an advance on previous work because it provides a simple equation for predicting when glacial inception will occur. The researchers observed that, in the Earth-system model they used for their study (CLIMBER-2), ice begins to form when insolation in the Northern Hemisphere at the summer solstice falls below a certain value that depends logarithmically on the concentration of atmospheric CO<sub>2</sub>. They were thus able to work out an equation that describes this behaviour.

To calibrate the equation, the authors performed several simulations that differed by the value of a parameter that controls cloud height in their model. This sampling process effectively generates a family of model versions, which the authors tested to see which ones predicted past glacial inceptions. Past glaciations and interglacials have been identified on the basis of isotopic data from marine sediments, and they follow a numbering scheme in which isotope 'stages' with odd numbers roughly correspond to interglacials. The authors paid special attention to the glacial inceptions after marine isotope stages 19 and 11, and to the period after marine isotope stage 1 (that is, the Holocene), because insolation evolved in a similar way at those times but led to different outcomes (stage 1 did not produce a glacial inception). Only the parameter values that yielded correct simulations of all past glacial inceptions were used to establish the equation.

The authors were thus able to confirm that Earth had a narrow escape from glacial inception during the Holocene: the increase in atmospheric CO<sub>2</sub> levels during this period was sufficient to prevent the planet from entering a glacial period. The authors also report that an interglacial climate would have continued for at least 20,000 years, and more plausibly for 50,000 years, if CO<sub>2</sub> concentrations had been sustained at levels typical of the eighteenth century. However, almost 500 gigatonnes of carbon (GTC; 1 GTC is equivalent

FLORILEGIUS/ALAMY

## ECOLOGY

# A trail map for trait-based studies

Global assessments of variation in plant functional traits and the way that these traits influence competitive interactions provide a launching pad for future ecological studies. [SEE ARTICLE P.167](#) & [LETTER P.204](#)

JONATHAN M. LEVINE

to 3.6 gigatonnes of CO<sub>2</sub>) have been released into the atmosphere since the Industrial Revolution. Ganopolski *et al.* show that this means that we will probably skip the next glacial inception too: emissions of 1,000 GTC (a scenario that is quite likely) will almost guarantee 100,000 years without any glaciation.

Such long-term consequences may seem surprising, given that the emissions will occur over a few centuries at most and that anthropogenic CO<sub>2</sub> will eventually be absorbed by the oceans. But for this absorption to occur, carbonate minerals in the ocean will need to be dissolved, to counteract the increase in ocean acidity that occurs when CO<sub>2</sub> is absorbed, and which limits the amount of CO<sub>2</sub> that can be dissolved. This takes time. In fact, the mean half-life of CO<sub>2</sub> in the atmosphere is of the order of 35,000 years<sup>6</sup>. Consequently, anthropogenic CO<sub>2</sub> will still be in the atmosphere in 50,000 years' time, and even 100,000 years, which is enough to prevent any glaciation.

The method used by Ganopolski *et al.* is known as 'perturbed physics' sampling. This means that the different scenarios for future climate were sampled by modifying one parameter, which controls one of the physical effects described by the model. But no model is perfect, and all the possible errors associated with the model cannot be entirely compensated for by adjusting this parameter. To provide better predictions, we need to pay special attention to climate processes that are currently not well quantified.

Among them, the causes of CO<sub>2</sub> changes during past interglacial periods and during the early stages of glaciation remain a matter of controversy. For example, we are uncertain about the amplitude and dynamics of carbon sequestered in peatlands<sup>1,7</sup>. More fundamentally, we do not yet know whether natural CO<sub>2</sub> dynamics have an active role in causing glacial inception, or whether they passively amplify the effects of accumulating ice at northern high latitudes. In spite of these uncertainties, Ganopolski and colleagues' main conclusion is likely to stand. It reinforces previous assessments asserting that humanity's collective footprint on Earth already extends beyond any imaginable future of our society. ■

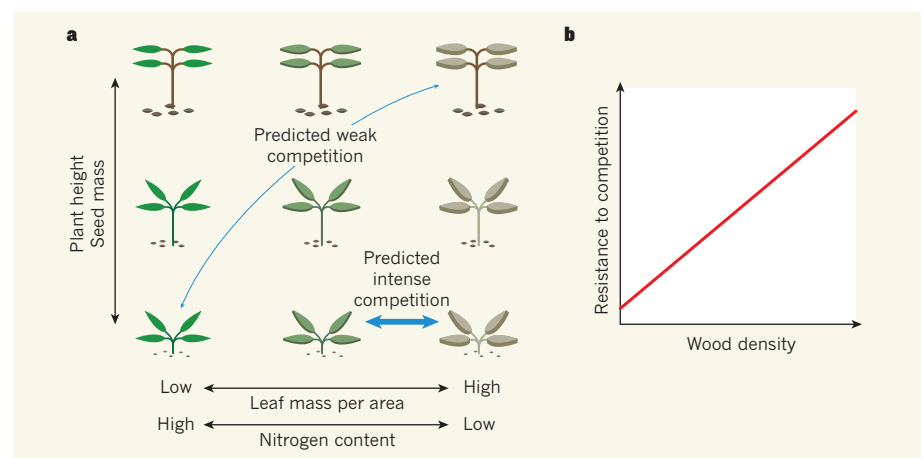
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Ecologists explore the processes that govern the natural world around us. But this can seem an uphill battle when nature presents such a wide diversity of species, each with its own set of interactions with the environment. One way to make sense of this diversity and its mechanistic underpinnings is to focus not on species but on the functional traits they possess, such as plant height, seed size or leaf area. Two papers in this issue advance our understanding of how traits vary between plant species, and the ramifications of this variation for competitive interactions. Díaz *et al.*<sup>1</sup> (page 167) document the patterns of functional-trait variation among plant species worldwide and reveal fundamental constraints on plant form that allow the organisms to survive natural selection, physiological challenges and competitive exclusion. Kunstler *et al.*<sup>2</sup> (page 204) show how functional traits consistently predict the competitive interactions between trees in six forested biomes, with effects counter to expectations from classic theory.

In the nineteenth century, Alexander von Humboldt and Charles Darwin wrote at length about the surprising diversity in form and function of organisms on Earth, and this topic still intrigues naturalists today. For much of the history of ecology, most patterns of diversity and abundance have been studied at the species level. But a growing number of ecologists, and plant ecologists in particular, think that studies focused on functional traits present greater opportunity for generality and predictability, and a tighter connection to organismal function<sup>3–6</sup>. Indeed, it is a species' traits that determine the organism's growth, dynamics and interactions, not its taxonomic nomenclature. The implication is that a more productive way of asking, for example, the classic question of what processes maintain the diversity of species is to ask what processes explain the dispersion of traits among community members.

Díaz *et al.* have laid the groundwork for this approach and a wide range of ecological and evolutionary investigations by quantifying the dimensionality of plant 'trait space' — the multivariate space in which a plant can be



**Figure 1 | Trait dimensions and competition.** **a**, Díaz *et al.*<sup>1</sup> conducted an analysis of six plant traits across more than 45,000 species and found that most of the variation between species in this six-dimensional trait space lies along a two-dimensional plane. One dimension describes variation in leaves having an acquisitive strategy (low leaf mass per unit area and high nitrogen content) versus a conservative one (high leaf mass per unit area and low nitrogen content)<sup>6</sup>. The other dimension corresponds to variation in plant size (height and seed mass). Following classic ecological theory, species that are more similar to one another in the trait space should compete more intensely than would more different taxa. **b**, However, by working with a global data set of forest-tree growth, Kunstler *et al.*<sup>2</sup> found little to no support for this expectation. Instead, certain trait values were predictive of competitive superiority, such as greater wood density being associated with greater resistance to competition.

# Critical insolation–CO<sub>2</sub> relation for diagnosing past and future glacial inception

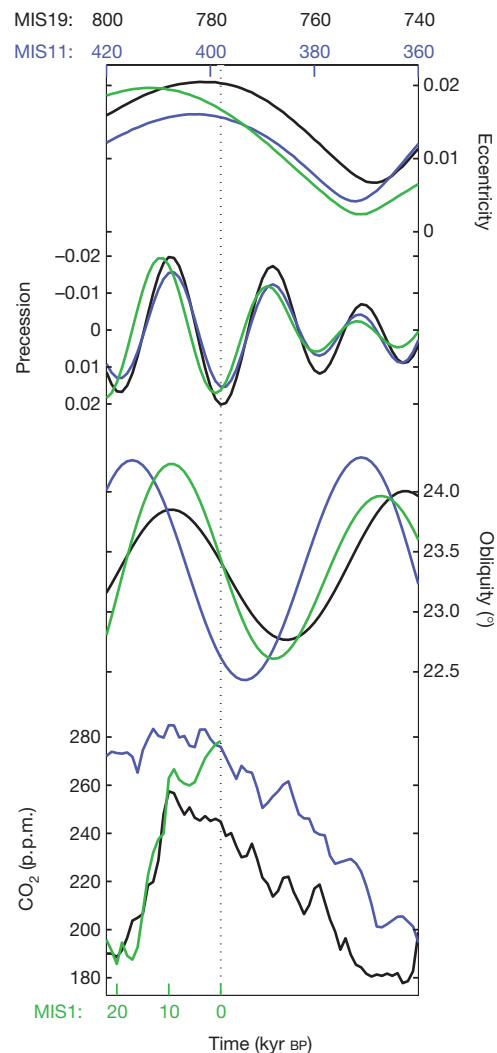
A. Ganopolski<sup>1</sup>, R. Winkelmann<sup>1,2</sup> & H. J. Schellnhuber<sup>1,3</sup>

The past rapid growth of Northern Hemisphere continental ice sheets, which terminated warm and stable climate periods, is generally attributed to reduced summer insolation in boreal latitudes<sup>1–3</sup>. Yet such summer insolation is near to its minimum at present<sup>4</sup>, and there are no signs of a new ice age<sup>5</sup>. This challenges our understanding of the mechanisms driving glacial cycles and our ability to predict the next glacial inception<sup>6</sup>. Here we propose a critical functional relationship between boreal summer insolation and global carbon dioxide (CO<sub>2</sub>) concentration, which explains the beginning of the past eight glacial cycles and might anticipate future periods of glacial inception. Using an ensemble of simulations generated by an Earth system model of intermediate complexity constrained by palaeoclimatic data, we suggest that glacial inception was narrowly missed before the beginning of the Industrial Revolution. The missed inception can be accounted for by the combined effect of relatively high late-Holocene CO<sub>2</sub> concentrations and the low orbital eccentricity of the Earth<sup>7</sup>. Additionally, our analysis suggests that even in the absence of human perturbations no substantial build-up of ice sheets would occur within the next several thousand years and that the current interglacial would probably last for another 50,000 years. However, moderate anthropogenic cumulative CO<sub>2</sub> emissions of 1,000 to 1,500 gigatonnes of carbon will postpone the next glacial inception by at least 100,000 years<sup>8,9</sup>. Our simulations demonstrate that under natural conditions alone the Earth system would be expected to remain in the present delicately balanced interglacial climate state, steering clear of both large-scale glaciation of the Northern Hemisphere and its complete deglaciation, for an unusually long time.

In accordance with classical Milankovitch theory<sup>1</sup>, interglacials—warm intervals with the lowest global ice volume—occur during periods of high summer insolation in the boreal latitudes of the Northern Hemisphere. In the past, a decrease in Northern Hemisphere insolation to below its present-day level always led to the end of interglacials and rapid growth of continental ice sheets<sup>2,3</sup>, accompanied by a reduction in CO<sub>2</sub> concentration<sup>10,11</sup>. However, at present, although summer insolation at 65° N is close to its minimum<sup>4</sup>, there is no evidence for the beginning of a new ice age. On the contrary, sea level, which reflects changes in global ice volume, remained essentially constant over the past several millennia<sup>5,12</sup>.

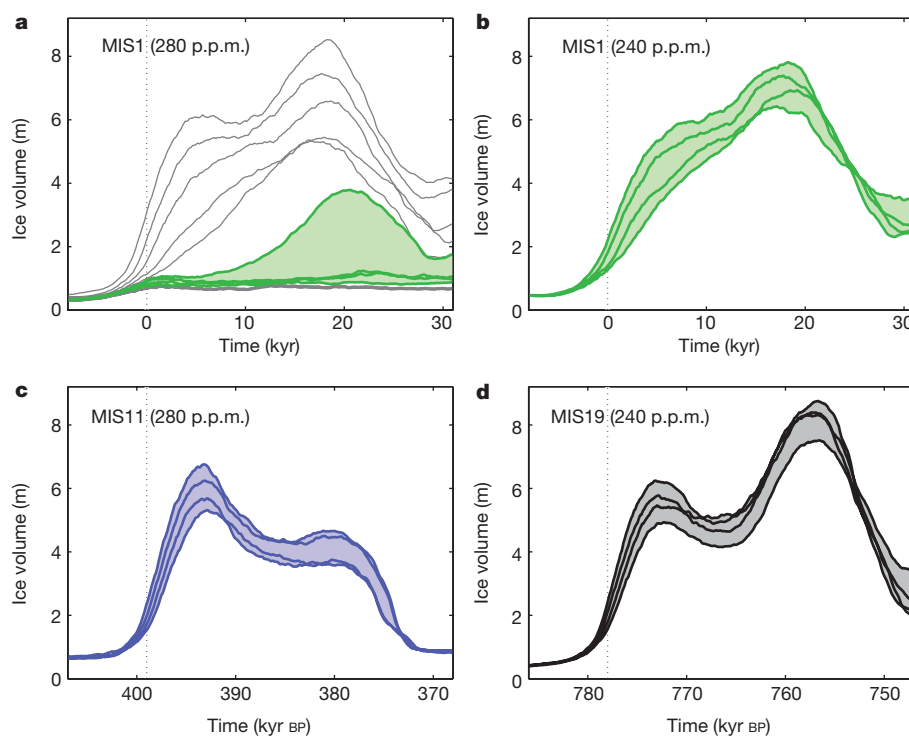
The most straightforward explanation for the lack of glacial inception at present is that the current insolation minimum is not deep enough because of the low orbital eccentricity of the Earth. However, glacial inceptions have occurred in the past under similar orbital configurations. Marine Isotope Stage (MIS) 11 (about 400,000 years before present, 400 kyr BP) is often considered a close palaeo-analogue for the current interglacial (the Holocene, or MIS1) owing to the similarly low values of the eccentricity of Earth's orbit and similar CO<sub>2</sub> level at that time<sup>7</sup> (Fig. 1). The only difference between the insolation minimum at about 400 kyr BP and the present one is a lower obliquity during MIS11.

With respect to the orbital parameters, MIS19 (about 800 kyr BP) is an even closer analogue for the Holocene (see Fig. 1). Following this analogy, it has been suggested that the current interglacial would end naturally within the next 1,500 years if the CO<sub>2</sub> concentration had stayed at a level of about 240 parts per million (p.p.m.), as was the case at the end of MIS19 (ref. 13). However, during the late Holocene before the beginning of the industrial era, the CO<sub>2</sub> concentration was about



**Figure 1 | Orbital parameters.** Comparison of Earth's orbital parameters and CO<sub>2</sub> concentrations for MIS1 (green), MIS11 (blue) and MIS19 (black). The vertical dashed line corresponds to the present day for MIS1 and the minima of the precessional component of insolation for MIS11 and MIS19.

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**Figure 2 | Evolution of the Northern Hemisphere ice volume.** Ice volume (excluding the Greenland Ice Sheet) is given in metres of sea-level equivalent for the Holocene and near future with a CO<sub>2</sub> concentration of 280 p.p.m. (a), the Holocene and near future with a CO<sub>2</sub> concentration of 240 p.p.m. (b), MIS11 with a CO<sub>2</sub> concentration of 280 p.p.m. (c), and MIS19 with a CO<sub>2</sub> concentration of 240 p.p.m. (d). Individual model

280 p.p.m., a level that is also typical for several previous interglacials. Therefore, MIS19, with its low CO<sub>2</sub> level, may not be a proper analogue for the present interglacial either.

A key question we address here is whether subtle differences in orbital configurations and CO<sub>2</sub> concentration between MIS11 and MIS19 and the Holocene are sufficient to explain the fundamentally different evolution of the climate system in the vicinity of its present state. This could have important implications for the future evolution of the Earth system.

The results presented here are based on simulations with the Earth system model of intermediate complexity CLIMBER-2 (ref. 14), which includes the three-dimensional thermomechanical ice sheet model SICOPOLIS<sup>15</sup>. The CLIMBER-2 model has been successfully applied for simulating the last eight glacial cycles<sup>16</sup>. It is known that glacial inception is associated with highly nonlinear dynamics of the climate–cryosphere system<sup>17</sup>. Previous studies<sup>4,18</sup> demonstrated high sensitivity of the timing of the next glacial inception to modelling parameters and prescribed CO<sub>2</sub> concentration. This is consistent with the finding that glacial inception represents a bifurcation transition between interglacial and glacial climate states and that under the current orbital configuration and CO<sub>2</sub> concentration, the Earth system is very close to this bifurcation point<sup>19,20</sup>. To ensure that the model correctly simulates the position of this bifurcation transition in the phase space of external forcings, we use the well established fact that glacial inception occurred at the end of MIS19 and MIS11, but not in the recent past. We quantify these constraints as following: for MIS19 and MIS11 only model versions that simulate a build-up of ice sheets with a total volume of at least 5 m sea-level equivalent are accepted. For the Holocene, on the contrary, all model versions simulating more than 1 m sea-level equivalent of ice growth before today are rejected. Note that these constraints are only applied to the Northern Hemisphere and do not include the Greenland Ice Sheet.

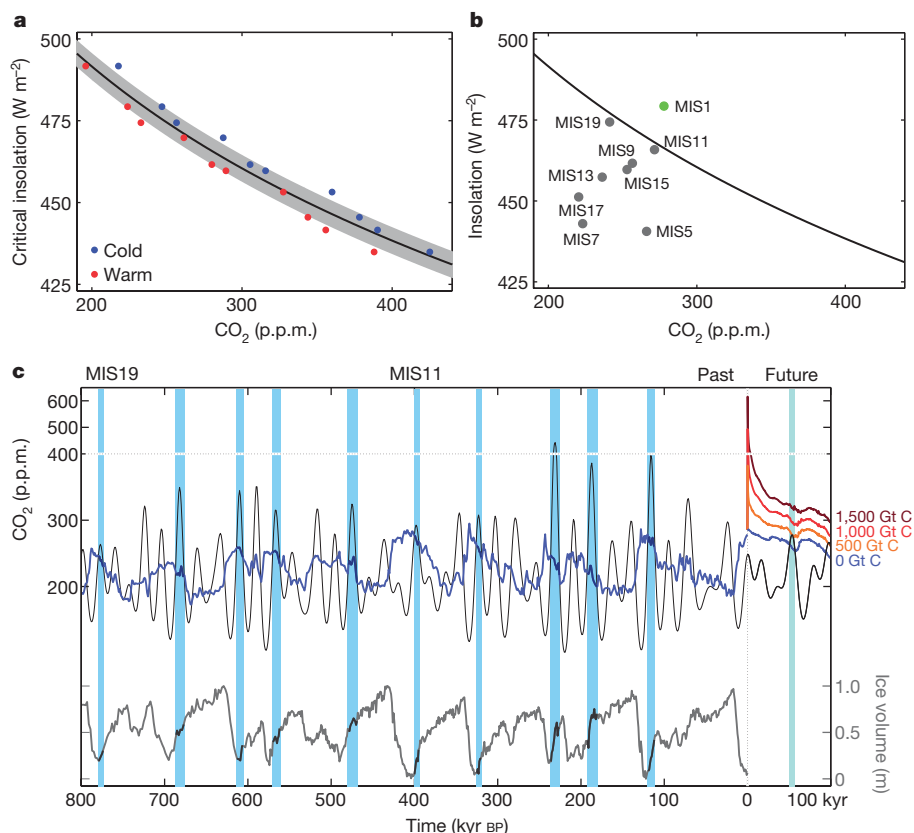
simulations from the subset of model versions compatible with the empirical constraints are shown; the shading illustrates the entire range. For MIS1 (the Holocene), with a CO<sub>2</sub> concentration of 280 p.p.m. (a), the model realizations that are not compatible with the observational constraints are shown as grey lines. The vertical dashed lines correspond to the minima of the precessional component of insolation.

By perturbing one of the model parameters, which affects the surface temperature in a uniform manner, we created an ensemble of twenty model realizations that differ only slightly in their unperturbed climate state (see Methods). We then applied these model realizations to simulate MIS19, MIS11 and the Holocene forced by changing orbital parameters and the prescribed CO<sub>2</sub> concentrations typical for each interglacial (240 p.p.m. for MIS19, and 280 p.p.m. for MIS11 and the Holocene). We selected those realizations that are compatible with the observational constraints described above. Only four model versions pass this test successfully.

None of these model versions simulate substantial ice sheet growth within the next several thousands of years under the pre-industrial CO<sub>2</sub> concentration of 280 p.p.m. (Fig. 2). Three of the four model versions predict the next glacial inception about 50,000 years from now, which is consistent with previous modelling results. Only the coldest model version simulates a slow growth of medium-sized ice caps in the future, mostly over the Canadian Archipelago and Scandinavia. This slow growth is attributed to decreasing obliquity, which becomes the dominant astronomical factor under the currently very low eccentricity. However, even in this case, the ice volume only crosses the glaciation threshold 20,000 years from now.

The situation is completely different for a CO<sub>2</sub> concentration of 240 p.p.m., which is close to that observed at the end of MIS19. In this case all four model versions simulate rapid ice growth several thousands of years before the present and large ice sheets exist already at the present time (Extended Data Fig. 1). This means that the Earth system would already be well on the way towards a new glacial state if the pre-industrial CO<sub>2</sub> level had been merely 40 p.p.m. lower than it was during the late Holocene, which is consistent with previous results<sup>13,21</sup>.

Whether this narrow escape from glacial inception was natural remains debatable. It has been proposed<sup>21</sup> that pre-industrial land-use at least partly contributed to the high Holocene CO<sub>2</sub> level, but the magnitude of this contribution is very uncertain<sup>22,23</sup>. This escape from



**Figure 3 | Critical insolation–CO<sub>2</sub> relation.** **a**, Best-fit logarithmic relation (black line) between the maximum summer insolation at 65° N and the CO<sub>2</sub> threshold for glacial inception; grey shaded area indicates ±1 s.d. Blue dots correspond to the coldest model version and red dots to the warmest. **b**, The locations of previous glacial inceptions in insolation–CO<sub>2</sub> phase space relative to the best-fit logarithmic curve from **a**. Glacial inception is only possible when the point is located below the insolation–CO<sub>2</sub> curve. **c**, The timing of past and future glacial inceptions can be explained by the CO<sub>2</sub> concentration and the insolation–CO<sub>2</sub> relation. The thin grey line depicts the CO<sub>2</sub> threshold value for

glacial inception in the recent past makes it very unlikely that glaciation will start in the near future without a considerable drop in CO<sub>2</sub> concentration. That is, glaciation did not begin even under the most favourable conditions in the past millennium for it to do so, and we do not anticipate such conditions occurring again in the foreseeable future. This is apparent from a stability analysis of the Earth system in the phase space of orbital forcing and CO<sub>2</sub> concentration.

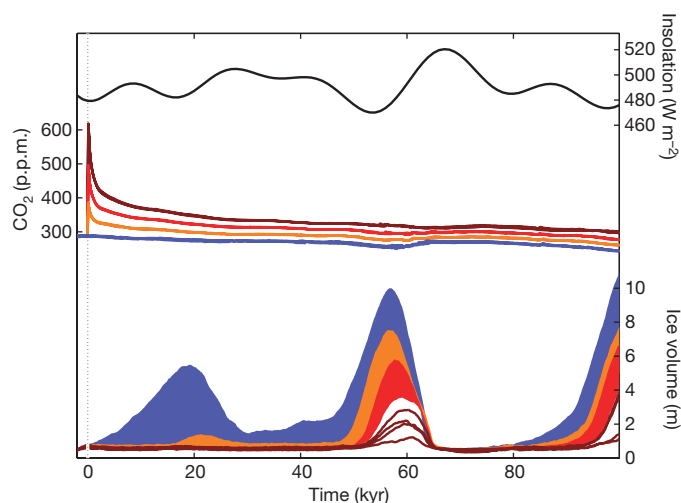
Using a range of model realizations consistent with palaeoclimatic constraints, we mapped the threshold value of CO<sub>2</sub> leading to glacial inception depending on the maximum summer insolation at 65° N. The maximum summer insolation at 65° N is the most common metric for the orbital forcing. It has been shown that for given CO<sub>2</sub> concentration, the insolation threshold for glacial inception depends also on obliquity, but this dependence is rather weak<sup>19</sup>. For the sake of simplicity and consistency with our previous results, we therefore use maximum summer insolation at 65° N as the proxy for orbital forcing.

Figure 3a shows that the individual points in the insolation–CO<sub>2</sub> space representing different combinations of orbital parameters are clustered around the logarithmic curve. This is consistent with the fact that radiative forcing of CO<sub>2</sub> is proportional to the logarithm of CO<sub>2</sub> concentration and that in the CLIMBER-2 model, similar to many other climate models, the temperature response to CO<sub>2</sub> and orbital forcing is linear within the considered range of CO<sub>2</sub> concentrations. The critical summer insolation at 65° N can be described as  $S = \alpha \ln([\text{CO}_2]/280) + \beta$ , where  $\alpha = -77 \text{ W m}^{-2}$  and  $\beta = 466 \text{ W m}^{-2}$  and [CO<sub>2</sub>] is the concentration of CO<sub>2</sub> in parts per million (see Methods).

glacial inception, derived as a function of the maximum summer insolation at 65° N. The CO<sub>2</sub> concentration from ice core data<sup>10,11</sup> for the past 800,000 years is shown (blue line), along with the CO<sub>2</sub> scenarios of 0 Gt C cumulative anthropogenic emissions (blue line), 500 Gt C (orange line), 1,000 Gt C (red line) and 1,500 Gt C (dark red line). Pale blue vertical bars indicate the time periods when the reconstructed value is below the critical CO<sub>2</sub> concentration, and the light blue bar shows the timing of a possible next glacial inception. The horizontal dotted line indicates the present-day CO<sub>2</sub> level. The lower curve depicts a proxy for the global ice volume<sup>25</sup> (thick grey line).

The validity of the critical insolation–CO<sub>2</sub> concentration relationship is confirmed for all previous glacial inceptions, because each of the past glaciations occurred when the CO<sub>2</sub> concentration was lower than the threshold value (Fig. 3b, c). The conditions for glacial inception are not met in the near future. For the orbital forcing of the late Holocene, the CO<sub>2</sub> concentration remains above the threshold value owing to the currently low eccentricity. Only in about 50,000 years from now, the threshold CO<sub>2</sub> value approaches the pre-industrial CO<sub>2</sub> concentration. Therefore, even without anthropogenic perturbations, the Holocene would be an unusually long interglacial. This also implies that the Holocene has no proper palaeoclimate analogue within at least the past million years.

Owing to the extremely long lifetime of anthropogenic CO<sub>2</sub> in the atmosphere, past and future anthropogenic CO<sub>2</sub> emissions will have a strong impact on the timing of the next glacial inception<sup>8,9</sup>. In order to estimate the earliest possible onset of a new glaciation, we forced the four valid model realizations by orbital variations and different CO<sub>2</sub> concentration scenarios computed for the next 100,000 years with the CLIMBER-2 model (see Methods). Initial conditions were based on results from simulations of the last glacial cycle<sup>24</sup>. Without anthropogenic greenhouse gas emissions, the CO<sub>2</sub> concentration gradually declines in the future and oscillates slightly on the orbital timescale. Note that the long-term natural future evolution of CO<sub>2</sub> concentration is sensitive to model parameters and is not well constrained by empirical data. Assuming that anthropogenic CO<sub>2</sub> emissions will be reduced to zero on a centennial timescale (not considering the possibility of negative CO<sub>2</sub> emissions), the long-term evolution of the CO<sub>2</sub>



**Figure 4 | The next glacial inception.** The top panel shows the temporal evolution of the maximum summer insolation at 65° N. The middle panel shows the simulated CO<sub>2</sub> concentration during the next 100,000 years for different cumulative CO<sub>2</sub> emission scenarios: 0 Gt C anthropogenic emissions (blue), 500 Gt C (orange), 1,000 Gt C (red) and 1,500 Gt C (dark red line). The bottom panel shows simulated ice volume corresponding to the different CO<sub>2</sub> emission scenarios. Individual simulations are shown for the 1,500 Gt C scenario; for the other scenarios, the range is given as shading.

concentration depends solely on the total cumulative carbon emissions within the next centuries.

Under three scenarios with cumulative emissions of 500 gigatonnes of carbon (Gt C), 1,000 Gt C and 1,500 Gt C, we simulate the ice volume on the Northern Hemisphere for the next 100,000 years. Even for a total of 500 Gt C cumulative emissions, which is only slightly above the present-day value, the evolution of the Northern Hemisphere ice sheets is affected over tens of thousands of years (Fig. 4). In the 1,000 Gt C scenario, the probability of glacial inception during the next 100,000 years is notably reduced, and under cumulative emissions of 1,500 Gt C, glacial inception is very unlikely within the entire 100,000 years. This confirms our conclusions from the critical insolation threshold for glacial inception. Because all 2013 Intergovernmental Panel on Climate Change scenarios—except Representative Concentration Pathway 2.6 (RCP2.6), which leads to the total radiative forcing of greenhouse gases of 2.6 W m<sup>-2</sup> in 2100—imply that cumulative carbon emission will exceed 1,000 Gt in the twenty-first century, our results suggest that anthropogenic interference will make the initiation of the next ice age impossible over a time period comparable to the duration of previous glacial cycles.

**Online Content** Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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**Author Contributions** A.G. and H.J.S. designed the paper. A.G. developed the methodology and performed the research (with contributions from R.W.). A.G., R.W. and H.J.S. interpreted the results and wrote the paper.

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## METHODS

**Model.** For this study we used the Earth system model of intermediate complexity CLIMBER-2 (ref. 14), which incorporates the three-dimensional thermo-mechanical ice sheet model SICOPOLIS<sup>15</sup>. SICOPOLIS is applied only to the Northern Hemisphere with a spatial resolution of  $1.5^\circ \times 0.75^\circ$  and is fully interactively coupled to a low-resolution climate component. Key model parameters were selected to reproduce the magnitude of global ice volume variations during the last glacial cycle. Using the same set of model parameters, the model was then successfully applied to simulate the last eight glacial cycles<sup>16</sup>. The model also includes a global carbon cycle component that has been used to simulate CO<sub>2</sub> variations during the last glacial cycle<sup>24</sup>. In the present study we use CLIMBER-2 in both configurations: (1) with interactive carbon cycle and prescribed modern ice sheets and (2) with interactive ice sheets and prescribed CO<sub>2</sub> concentration.

**Model ensemble.** Although the glacial cycles simulated with the standard version of CLIMBER-2 are in good agreement with palaeoclimate data<sup>16</sup> and satisfy our palaeoclimate constraints it is possible that other model versions with slightly different model parameters are also compatible with palaeoclimate constraints. To assess how tightly palaeoclimate data constrain model parameters and to assess one of the sources of possible uncertainties in the CO<sub>2</sub>–insolation relationship we created an ensemble of twenty CLIMBER-2 realizations by perturbing one of the model parameters: namely, parameter  $C_1$ , which controls the effective cloud height in the atmospheric model component<sup>14</sup>. The advantage of this parameter is that it affects the equilibrium surface air temperature in a rather uniform manner, similar to changes in the CO<sub>2</sub> concentration. However, a number of other model parameters can be used for the same purpose. By varying this parameter by  $\pm 5\%$  we created a set of model realizations that differ by only  $\pm 1^\circ\text{C}$  in their global mean temperatures, a range that is comparable to the inter-model differences of CMIP-5 climate models<sup>26</sup>.

From the twenty-member ensemble we then selected those simulations that are in agreement with observational constraints provided by glacial inceptions at the end of MIS11 and MIS5, and the lack of glacial inception in the recent past. To select the model realizations compatible with the empirical constraints we performed a set of simulations for MIS19, MIS11 and the current interglacial using the entire ensemble of the CLIMBER-2 model realizations. For the current interglacial, the model was run for 60,000 years into the future, starting 10,000 years before present from an equilibrium state. The MIS11 and MIS19 simulations begin 10,000 years before the respective insolation minima (410 kyr BP and 790 kyr BP, respectively), which triggered glacial inceptions. In all experiments the CO<sub>2</sub> concentration is fixed to the typical value for the given interglacial, that is, 280 p.p.m. for MIS11 and MIS1, and 240 p.p.m. for MIS19. These numbers are representative of the end of interglacials for MIS19, MIS11 and the late Holocene. Only four model realizations (including the standard one) were found to be consistent with all three palaeoclimate constraints.

**Future simulations.** Simulations of climate evolution over the next 100,000 years were performed in two steps. First, we computed the CO<sub>2</sub> concentration using the CLIMBER-2 model in the same configuration as in ref. 24. As initial conditions we used the state of the Earth system obtained at the end of the last glacial cycle simulation. (Note that the model simulates the present-day CO<sub>2</sub> concentration as close to the pre-industrial 280 p.p.m. level without any anthropogenic emissions.) Then the model was run for 100,000 years with the fully interactive carbon cycle forced by anthropogenic emissions and orbital parameters. Present-day ice sheets were prescribed during the entire runs. In the run without anthropogenic emissions, CO<sub>2</sub> gradually declines during the next 100,000 years owing to a small imbalance between volcanic outgassing and weathering. Assuming zero anthropogenic emissions beyond the next several centuries, the long-term CO<sub>2</sub> concentration depends only on the total cumulative carbon emissions. Therefore we used very simplistic emission scenarios which correspond to cumulative carbon emissions of 500 Gt C, 1,000 Gt C and 1,500 Gt C. For each emission scenario we performed one 100,000-year-long experiment with the standard version of the model. We then ran each of the four valid CLIMBER-2 model versions with the interactive ice sheets forced by the different CO<sub>2</sub> scenarios.

**Insolation–CO<sub>2</sub> relationship.** To find the relationship between insolation and CO<sub>2</sub> concentration we performed 20 simulations with 10 different orbital configurations and the coldest and warmest of the four valid model versions. Note that the difference in global surface air temperatures between these two model versions does not exceed  $0.5^\circ\text{C}$  under interglacial conditions. We chose orbital configurations that correspond to present-day conditions and eight previous minima of summer insolation, seven of which correspond to well defined glacial inceptions during the past 800 kyr. The last orbital configuration at 480 kyr BP, which corresponds to one of the shallowest minima in summer insolation, was chosen to span a broader range of summer insolation. All simulations started from the same pre-industrial equilibrium states both for the climate components

and ice sheets. Initial CO<sub>2</sub> concentration was set to 500 p.p.m. for the coldest three orbits and 400 p.p.m. for the other five. The orbital parameters were kept constant during each experiment and CO<sub>2</sub> concentration decreased linearly with time at the rate of 1 p.p.m. per 1,000 climate model years (see Extended Data Fig. 2). To be as close to the quasi-equilibrium for the ice sheets as possible, we used an acceleration technique with asynchronous coupling between climate and ice sheets, which effectively increases the length of integration for the ice sheet by a factor of 10. This implies that for the ice sheet component the rate of CO<sub>2</sub> change was only 1 p.p.m. per 10,000 years. Each experiment lasted 200,000 climate model years or 2 million ice-sheet model years.

We performed several additional experiments with a slower rate of change and found that this rate is sufficient to detect ‘glacial inception’ with an accuracy of about 5 p.p.m. in the CO<sub>2</sub> space. As a criterion for glacial inception we consider the growth of Northern Hemisphere ice sheets (excluding Greenland) of more than 5 m in sea-level equivalent (Extended Data Fig. 2). With the early model version it was shown<sup>19</sup> that for a given CO<sub>2</sub> concentration the onset of glacial inception to the first approximation depends only on the maximum summer insolation at  $65^\circ\text{N}$ . This is also supported by Fig. 3a. We used least-squares methods to fit the data to the logarithmic curve. The choice of a logarithmic curve is natural because the radiative forcing of CO<sub>2</sub> is proportional to the logarithm of CO<sub>2</sub> concentration.

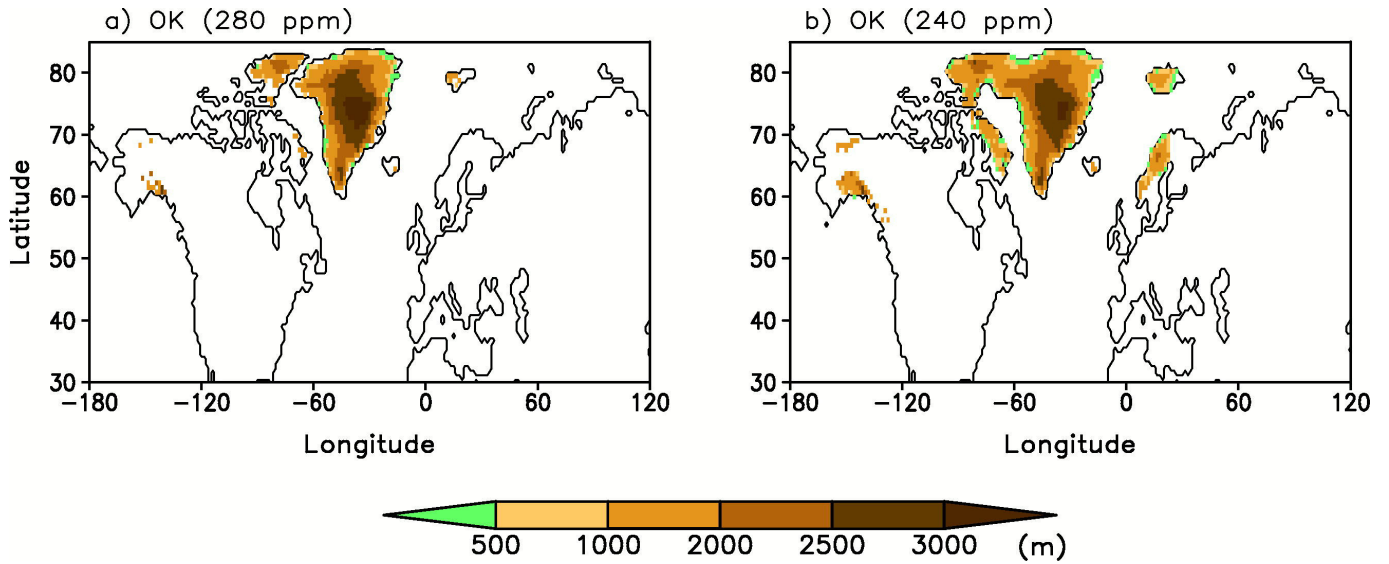
The shaded area in Fig. 3a represents the uncertainty range of critical insolation  $\pm 4\text{ W m}^{-2}$  (one standard deviation). In the vicinity of pre-industrial CO<sub>2</sub> concentration, this uncertainty in insolation corresponds to the uncertainty in the CO<sub>2</sub> threshold value of  $\pm 20$  p.p.m. The absolute uncertainties are lower for low CO<sub>2</sub> and higher for high CO<sub>2</sub> concentrations. This total uncertainty originates from three sources: (1) uncertainties resulting from the existence of several model versions, all of which are consistent with our palaeoclimate constraints, (2) the fact that the critical insolation depends not only on total summer insolation, but, to a lesser degree, also on individual contributions from precession and obliquity<sup>19</sup>, and (3) errors related to the methods of tracing the threshold CO<sub>2</sub> values. Although past glacial inceptions provide a tight constraint on a range of model parameters (Fig. 3), it is necessary to note that a single-model ensemble obtained by perturbation of model parameters may considerably underestimate the range of uncertainties compared to multi-model ensembles, owing to the lack of structural uncertainties. More objective estimates of uncertainties in the insolation–CO<sub>2</sub> relationship would therefore only be possible when a number of different Earth system models are available for this type of study.

We found that our new insolation–CO<sub>2</sub> relationship differs from that in ref. 8, primarily in that the new insolation–CO<sub>2</sub> graph is concave, unlike the convex shape in ref. 8. This difference can be explained by the much faster rates of changes of the forcing used in ref. 8, which do not allow us to detect bifurcation points with sufficient accuracy. The new methodology and greatly increased computer performance allow us now to determine the critical CO<sub>2</sub> value much more accurately to obtain a physically sound insolation–CO<sub>2</sub> relationship.

**Timing of past and future glacial inceptions.** Using the insolation–CO<sub>2</sub> relationship and orbital parameters<sup>27</sup> we computed the value of the critical CO<sub>2</sub> concentration every 1,000 years (Fig. 3c and Extended Data Fig. 3). If the critical CO<sub>2</sub> concentration is above its actual value and the system is in an interglacial state then glacial inception should begin. When the system is already in a glacial state the critical relationship is not applicable. This is because the strong nonlinearity and extremely long response time of the climate–cryosphere system mean that its dynamics depend not only on the instantaneous forcing but also on its past evolution. Therefore our criterion for glacial inception can only be applied to interglacial states, that is, under conditions similar to the Holocene with respect to both global ice volume and temperatures. Some interglacials, such as the Holocene (MIS1), Eem (MIS5e), MIS9 and MIS11, are clearly defined in the various palaeoclimate records (Extended Data Fig. 3). The situation is less clear for MIS7 and MIS15, where several interglacials per one glacial cycle can be identified<sup>28</sup>. For these two cases we show in Fig. 3 two different glacial inceptions.

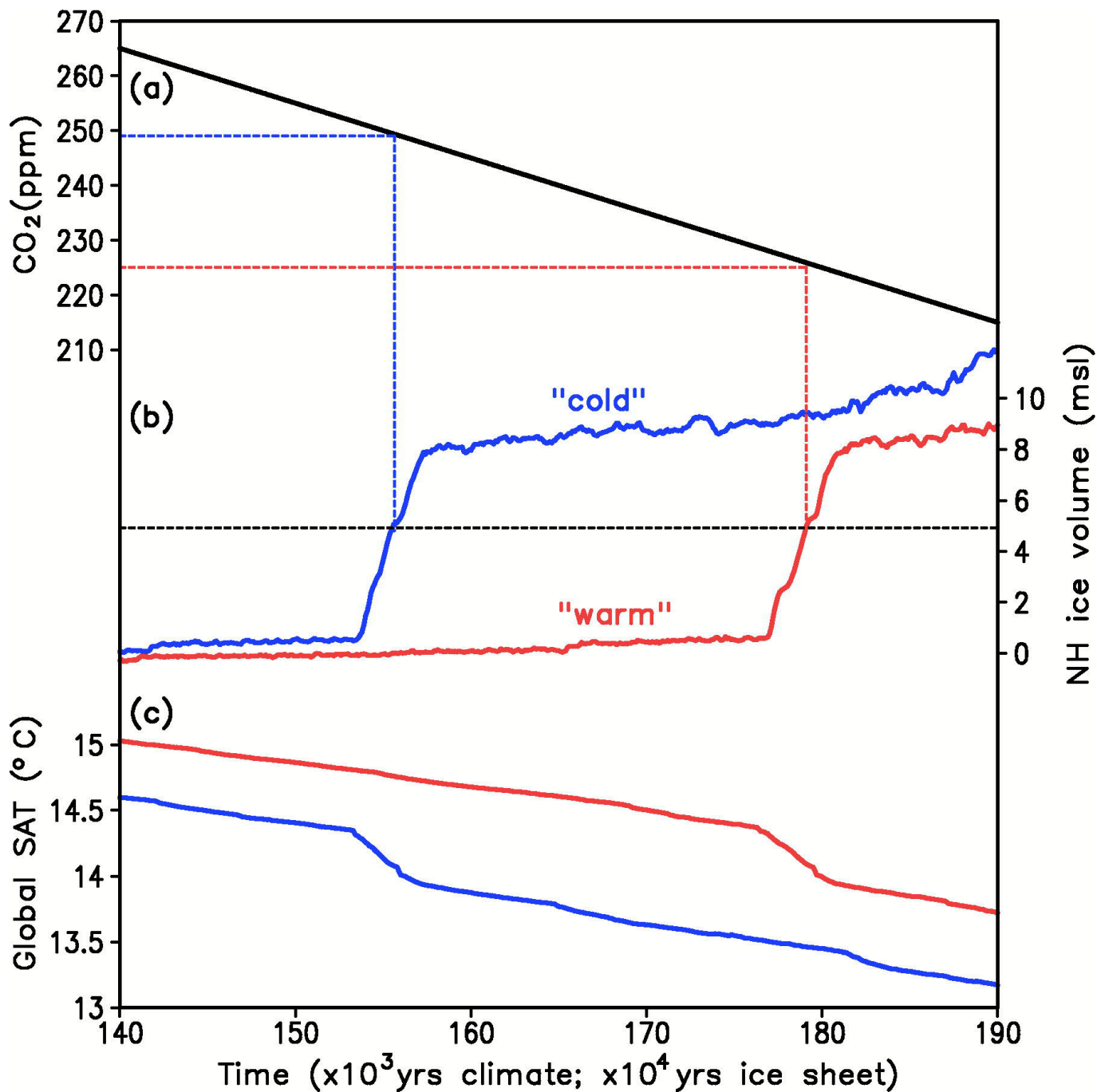
**Code availability.** Code for the ice sheet model SICOPOLIS can be accessed at <http://www.sicopolis.net>. Code for the Earth system model CLIMBER-2 model is not available owing to a lack of comprehensive technical description.

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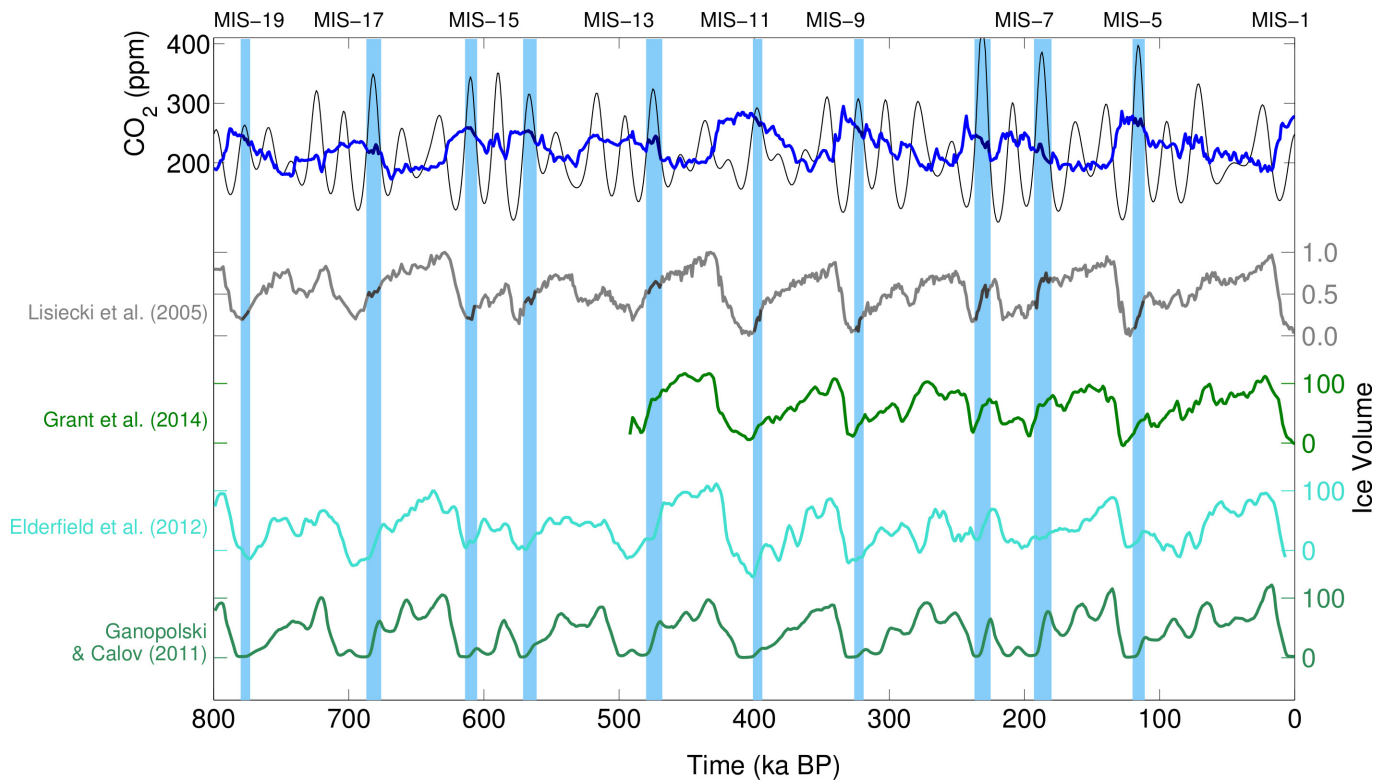
**Extended Data Figure 1 | Ice sheet at 0 kyr BP.** The extension and elevation of simulated Northern Hemisphere ice sheets at the time corresponding to present-day (0 kyr BP, 'OK') insolation are shown for constant CO<sub>2</sub> concentrations of 280 p.p.m. (a) and 240 p.p.m. (b). Experiments were performed with the coldest of the accepted model versions.





**Extended Data Figure 2 | Detection of the critical  $\text{CO}_2$  value.** For the orbital configuration corresponding to 777 kyr BP we show the prescribed  $\text{CO}_2$  concentration (a), the simulated Northern Hemisphere (NH) ice volume in metres of sea-level equivalent (msl; b), and the simulated global mean surface air temperature (SAT) (c). Blue lines correspond to

the coldest of accepted model versions and red lines to the warmest. The figure shows only the part of 200,000-year-long simulations for which glacial inceptions are simulated by both model versions. We note that the simulation time is ten times larger for the ice-sheet component than for the climate component (see bottom axis).



**Extended Data Figure 3 | Past glacial inceptions.** Past glacial inceptions, detected using the critical insolation–CO<sub>2</sub> relation, are shown in comparison to three different reconstructions of ice-volume variations over the past 800 kyr (refs 25, 29 and 30) and results of model simulations<sup>16</sup>.