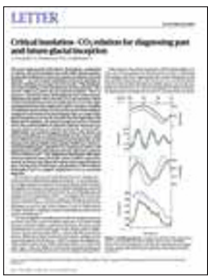
ARTICLE SUMMARY

Critical insolation–CO_2 relation for diagnosing past and future glacial inception

Andrey Ganopolski*, Ricarda Winkelmann & Hans Joachim Schellnhuber

PAPER ABSTRACT

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. Yet such summer insolation is near to its minimum at present, and there are no signs of a new ice age. This challenges our understanding of the mechanisms driving glacial cycles and our ability to predict the next glacial inception. Here we propose a critical functional relationship between boreal summer insolation and global carbon dioxide (CO_2) 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_2 concentrations and the low orbital eccentricity of the Earth. 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_2 emissions of 1,000 to 1,500 gigatonnes of carbon will postpone the next glacial inception by at least 100,000 years. 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.



DETAILS

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SUMMARY

There will be a long gap before the next ice age. What triggers an ice age? Climate models provide a new equation relating summertime sunshine in the Northern Hemisphere to the concentration of atmospheric CO_2. Together these two parameters can predict onsets of past and future ice ages.

The problem

Earth is currently in a warm interglacial period known as the Holocene. The last ice age ended 12,000 years ago, and there is no evidence for the beginning of a new glacial period. This fact puzzles climate scientists who expect the dynamics of glacial cycles to be driven by changes in Earth's orbit around the Sun. Ice ages have occurred in the past under very similar orbital parameters to those we see now, so what else is going on?

According to the orbital theory of glacial cycles, global ice volume is at its lowest when incoming solar radiation (insolation) is at its highest during the summer solstice in the Northern Hemisphere. In the past, a drop in Northern Hemisphere insolation below a certain level has always led to the end of warm intervals and the rapid growth of continental ice sheets[1]. Today, although summer insolation is close to its minimum, there is no sign that we are entering a new ice age. The orbital explanation is that the current insolation minimum is not deep enough, because the Earth's orbit is nearly circular[2]. But ice ages have occurred in the past under similar conditions. We need to consider an additional factor that seems to be driving glacial cycles[3], the amount of CO_2 in the atmosphere, which affects the temperature of the Earth by means of the greenhouse effect.

The solution

To understand which combinations of summer radiation and CO_2 concentration will lead to the onset of a new ice age, we used a climate model of intermediate complexity, CLIMBER-2. This model includes atmosphere, ocean, land and ice-sheet components[4]. To reduce model uncertainties we calibrated the model by using data on the timing of previous ice ages and on past CO_2 levels. With the model we found that ice begins to form when summer-solstice insolation at 65° N reaches a low threshold value that depends on CO_2 concentration. We found that this dependence can be described by a simple logarithmic curve (see Graphical abstract). To check this relationship, we plotted data for the past eight glacial cycles and showed that each ice age occurred when the insolation was lower than the threshold value. The only climate state above the curve is the one observed during the Holocene, helping to explain the lack of glaciation during this period.

The implications

The relationship derived from our model can also be used to predict

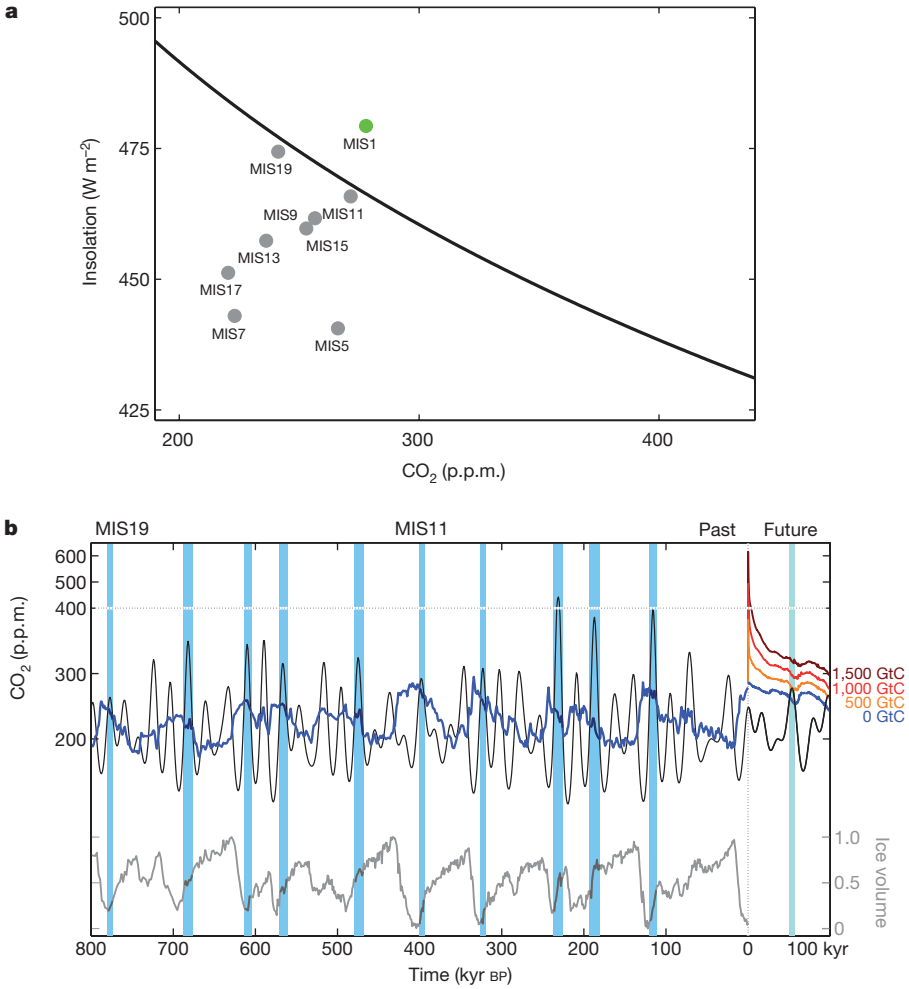
*Potsdam Institute for Climate Impact Research, 14412 Potsdam, Germany.

future ice ages. We show that the conditions for a new ice age will not be met in the near future, and that they will probably not be met for another 50,000 years. As a result, even without the human emissions of CO_2 since the Industrial Revolution, the Holocene would be an unusually long interglacial. Given the extreme longevity of CO_2 in the atmosphere, past and future anthropogenic CO_2 emissions will have a significant effect on the timing of the next ice age.

To understand future glaciation in the Northern Hemisphere over the next 100,000 years, we explored three scenarios with cumulative carbon emissions of 500, 1,000 and 1,500 Gt (1 Gt = 10^9 tonnes). With carbon emissions expected to exceed 1,000 Gt in the twenty-first century, the likelihood of a new ice age is vastly reduced. Our results suggest that human CO_2 emissions will be sufficient to prevent any glaciation during the next 100,000 years. ■

The full version of the original article is on *Nature*'s website at go.nature.com/21i6gbh

GRAPHICAL ABSTRACT



Predicting the onset of ice ages. a, Fundamental logarithmic relationship between the summer solstice insolation at 65° N and the CO_2 threshold for glaciation. Grey dots correspond to previous glaciations and the green dot represents the preindustrial climate state (early Holocene). Glacial onset is only possible when the point is located below the logarithmic curve. **b,** The timing of past and future ice ages can be explained by the relationship in (**a**). The thin black line depicts the CO_2 threshold value for glacial inception, derived as a function of the summer-solstice insolation at 65° N. The CO_2 concentration[5] for the past 800,000 years is shown (blue line), along with future CO_2 scenarios of cumulative anthropogenic emissions: 0 Gt of carbon (GtC; blue), 500 GtC (orange), 1,000 GtC (red) and 1,500 GtC (dark red). The lower grey curve depicts a proxy for the global ice volume[6].

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