Obliquity forcing with 8–12 times preindustrial levels of atmospheric pCO_2 during the Late Ordovician glaciation

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ABSTRACT

Results from coupled ice-sheet and atmospheric general circulation models show that the waxing and waning of ice sheets during the Late Ordovician were very sensitive to changes in atmospheric pCO_2 and orbital forcing at the obliquity time scale (30–40 k.y.). Without orbital forcing, ice sheets can grow with pCO_2 level as high as 10 times preindustrial atmospheric level (PAL). However, with orbital forcing, ice sheets can grow only with pCO_2 levels of 8 times PAL or lower. These results indicate that the threshold of pCO_2 for the initiation of glaciation is on the lower end of previously published estimates of 8–20 times PAL. The ice-sheet model results further indicate that during exceptionally long periods of low summer insolation and low pCO_2 levels (8–10 times PAL), large ice sheets could have formed that were able to sustain permanent glaciation under subsequently higher pCO_2 values. This finding suggests that in order to end the Late Ordovician glaciation with a rise in pCO_2, atmospheric pCO_2 must have risen to at least 12 times PAL. Ice sheets therefore introduce nonlinearities and hysteresis effects to the Ordovician climate system. These nonlinearities might have also played a role in the initiation and termination of other glaciations in Earth history.

Keywords: Late Ordovician, climate model, ice sheet model, obliquity, glaciation.

INTRODUCTION

Changes of atmospheric pCO_2 are generally considered as the main climate driver over geologic time (e.g., Frakes et al., 1992; Crowley and Berner, 2001). However, Veizer et al. (2000) suggested that for part of the Phanerozoic, atmospheric CO_2 concentrations were not the principal driver for global climate. These authors used an energy-balance model that incorporated proxy data for the Phanerozoic atmospheric CO_2 concentration. Their model predicted temperatures that are inconsistent with the geologic climate record. One of the mismatches is the Late Ordovician glaciation, which occurred under pCO_2 levels of 14 $\pm$ 6 times preindustrial atmospheric levels (PAL) (Berner and Kothavala, 2001; Yapp and Poths, 1992) and lasted less than 1 m.y. (Brenchley et al., 1995, 2003). Several numerical climate model studies found a high sensitivity of the formation of permanent snow cover with respect to pCO_2 values for the Late Ordovician paleogeography (Crowley and Baum, 1991, 1995; Gibbs et al., 1997, 2000; Poussart et al., 1999). These studies suggested that glaciation started with pCO_2 levels to 10 times PAL.

The Upper Ordovician rock record indicates that Milankovitch cycles controlled ice-sheet growth (Sutcliffe et al., 2000) and halite deposition (Williams, 1991) and suggests that orbital forcing had a significant effect on the Late Ordovician climate system. Because obliquity changes the amplitude of the seasonal cycle and alters the equator-to-pole insolation gradient, obliquity cycles can control whether ice sheets that were initiated during the coldest orbit could survive subsequent orbital variations around a warmer mean. Here we extend previous sensitivity studies by performing simulations involving an ice-sheet model coupled with an atmospheric general circulation model (AGCM) under a range of atmospheric pCO_2 values and warm- and cold-summer orbits that vary over the obliquity time scale (30–40 k.y.). This approach has been successfully used to investigate other pre-Pleistocene glaciations (e.g., Hyde et al., 1999). Our study goes beyond earlier Ordovician climate studies in that it adds a true ice-sheet model; prior work only looked at snow budgets to estimate the onset of glaciation.

We show how orbital forcing at the obliquity time scale affects the growth of ice sheets and their mean sizes, and we investigate the pCO_2 levels required to build and maintain these ice sheets. We also investigate hysteresis effects of CO_2 levels required for deglaciation of these ice sheets.

METHODS

We performed AGCM experiments for the Late Ordovician with GENESIS version 2.0 (Thompson and Pollard, 1997) and coupled the output to a three-dimensional ice-sheet model (Pollard and Thompson, 1997). The GENESIS model includes a $2° \times 2°$ land-surface model incorporating physical effects of vegetation, a six-layer soil model, a snow model, a three-layer thermodynamic sea-ice model, and a slab mixed-layer ocean (Thompson and Pollard, 1997). The model has 18 vertical layers and a spectral resolution of $\sim3.75° \times 3.75°$. The GENESIS experiments were run for 40 model years until they reached equilibrium. The ice-sheet model has a $1° \times 1°$ resolution and thermodynamics following Ritz et al. (1997). The model includes a 2-km-thick bedrock with vertical heat diffusion. The monthly mean temperature and precipitation values of the averaged past 10 yr of the stored AGCM climate results were used to drive the ice-sheet model through long-term runs of several 10^5 yr duration, with either invariant climate or with prescribed climate cyclicity, as described subsequently. The AGCM's atmospheric temperatures were interpolated to the fine-grid ice-sheet topography by using a constant lapse rate of 6.5 °C/km. The surface mass balance was calculated with a degree-day method, as in many coupled climate and ice-sheet studies (e.g., Ritz et al., 1997; Pollard and Thompson, 1997). The coupled atmosphere and ice-sheet model compares well with the geologic record of Antarctica (DeConto and Pollard, 2003), gives realistic orbital sensitivity for the Pleistocene ice volumes (Pollard et al., 2000), and its global sensitivity to doubled

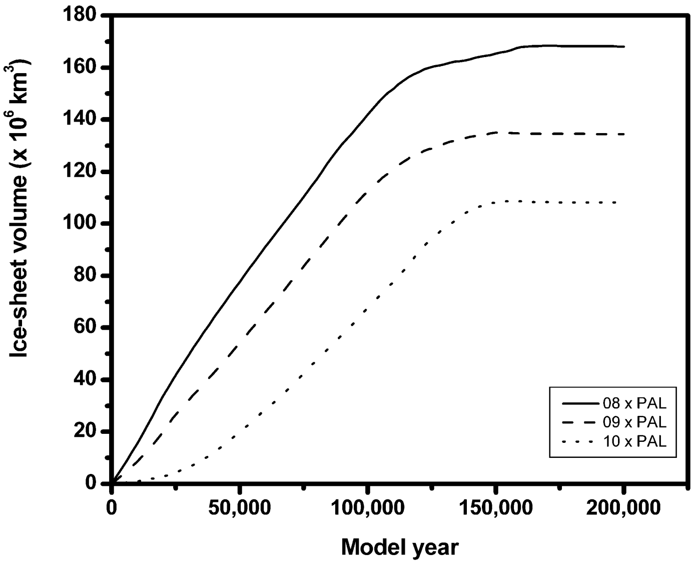

Figure 1. Ice-sheet volumes for simulations without orbital forcing. PAL—preindustrial atmospheric level.

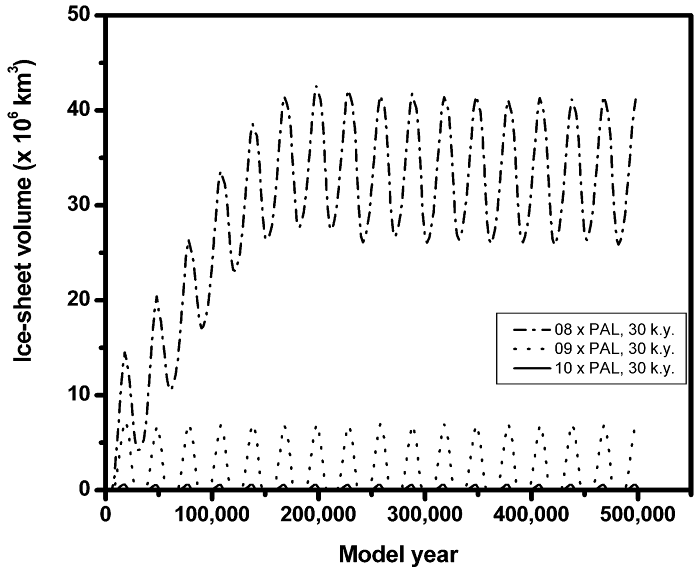

Figure 2. Ice-sheet volumes for simulations with orbital-forcing periodicities of 30 k.y. PAL—preindustrial atmospheric level.

CO_2, 2.5 °C, is within ''consensus'' range (Thompson and Pollard, 1997).

We used Late Ordovician paleogeographic reconstructions with a low sea level (Scotese and McKerrow, 1991). Because no topographic maps for the Late Ordovician have been published, the approach of Crowley and Baum (1995) was followed, and a uniform land elevation of 500 m for all land grid points and 250 m for all coastal areas was specified. Crowley and Baum (1995) showed that this topography was sufficient to generate permanent summer snow cover, which is essential for the formation of ice.

Geochemical modeling (Berner and Kothavala, 2001) and geochemical data from Ordovician paleosols (Yapp and Poths, 1992) indicate that Late Ordovician pCO_2 levels were higher than today, ~14 ± 6 times preindustrial pCO_2. We performed our simulations with pCO_2 levels of 8, 9, 10, and 12 times preindustrial (280 ppm) levels.

In addition, we used reduced solar luminosity (95.5% of present-day solar constant of 1365 W/m^2), bare soil (intermediate soil-color values), and no vegetation.

For each pCO_2 level, two AGCM simulations were performed, with different orbital parameters yielding extreme cold (eccentricity 0.06, obliquity 22, precession 270) and warm (eccentricity 0.06, obliquity 24.5, precession 90) Southern Hemisphere summers. These extreme values of precession, obliquity, and eccentricity are based on their cycles of the past 5 m.y. (Berger, 1978; Berger and Loutre, 1991). By using these saved monthly mean AGCM solutions, two kinds of long-term ice-sheet runs were performed. First, the ice model was run to equilibrium by using invariant cold-summer AGCM climate. Second, the ice model was run by interpolating between the cold-summer and warm-summer climates, assuming a cosine variation of climate in time between the two extremes with periods of 40 k.y. and 30 k.y. Actual insolation variations are more complex owing to the variations of eccentricity and precession, but the simple sinusoids used here allow a clearer first look at the effects on Ordovician ice volumes. Therefore, these experiments are designed to assess the stability of the ice sheet under changing orbital parameters, with periodicities representative of modern-day and Late Ordovician obliquity cycles. Although the modern-day obliquity cycle has a periodicity of 41 k.y., the Late Ordovician obliquity periods were shorter because of Moon-Earth interactions through time (Berger and Loutre, 1994; Berger et al., 1992). This shorter Late Ordovician periodicity is supported by Fourier spectral analysis of geochemical data of halite deposits for that time period (Williams, 1991).

RESULTS

In runs without orbital forcing, none of the warm-summer orbit simulations resulted in the formation of ice sheets. Ice-sheet growth occurred only in the cold-summer orbit simulations with pCO_2 levels of 10 times PAL and lower (Fig. 1). In runs with orbital forcing and initiated with no ice, only the simulations with 8 times pCO_2 sustained permanent ice sheets (Figs. 2 and 3). In the simulations with 9 and 10 times PAL, the ice sheets were unable to grow large enough to prevent their complete melting during the next warm-summer phase (Figs. 2 and 3), producing intermittent ice-sheet buildups interrupted by ice-free periods. The increased solar insolation during the warm-summer orbit also prevents the ice sheets from accumulating as much ice as in the ice-sheet simulation without orbital forcing. Although the maximum ice-sheet volume reaches ~168 times 10^6 km^3 in the simulation with pCO_2 levels of 8 times PAL with no orbital forcing, the influence of the warm-summer orbit leads to ice-sheet volumes between ~20 and 40 × 10^6 km^3.

Ice-sheet sustainability also depends on whether there is an ice sheet present at the start of the simulation. For all simulations, except for the experiment with pCO_2 levels of 10 times PAL and a period of 40 k.y., the ice sheet that was formed under no orbital influence (Fig. 1) was big enough to be sustained, at a smaller size, during the orbital

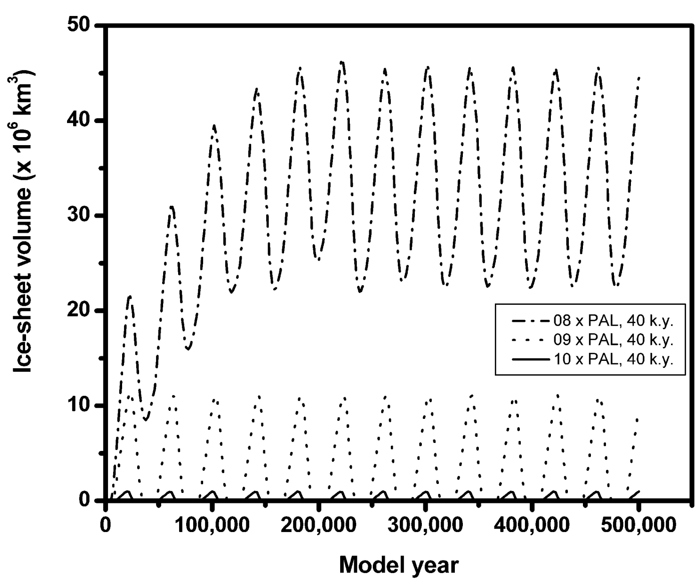

Figure 3. Ice-sheet volumes for simulations with orbital-forcing periodicities of 40 k.y. PAL—preindustrial atmospheric level.

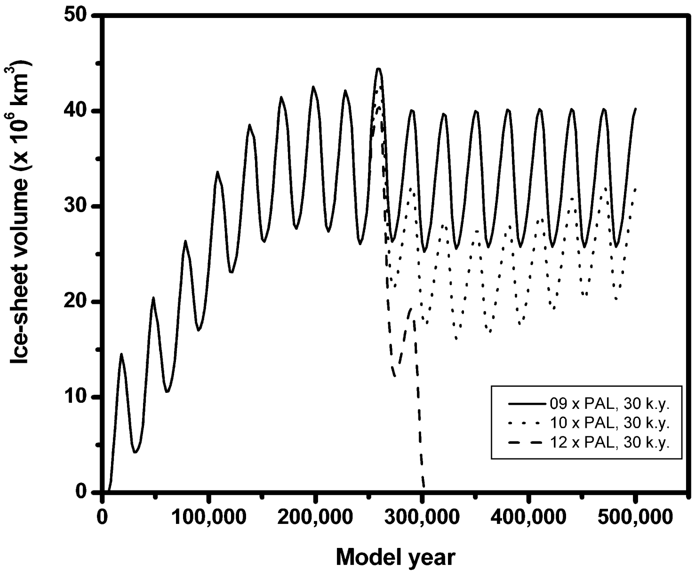

Figure 4. Ice-sheet volumes for simulations with orbital-forcing periodicities of 30 k.y. PAL—preindustrial atmospheric level and with preexisting ice-sheet volume for simulation with 8× PAL for first 250 k.y.

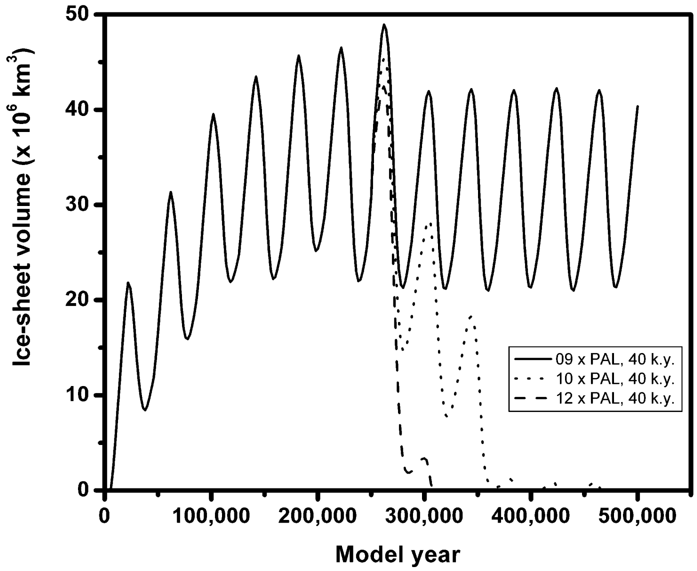

Figure 5. Ice-sheet volumes for simulations with orbital-forcing periodicities of 40 k.y. PAL—preindustrial atmospheric level and with preexisting ice-sheet volume for simulation with 8× PAL for first 250 k.y.

forcing (Figs. 4 and 5). In these cases, the ice sheet did not completely melt during the warm-summer orbit, even when pCO_2 was at a level that did not lead to permanent ice sheets when the runs started without ice sheets. Within the second warm-summer cycle, the ice sheets shrink ~40% for those cases (Fig. 5).

Our simulations indicate that without preexisting ice, permanent ice sheets cannot form with orbital forcing and pCO_2 values of 9 times PAL and higher. However, ice sheets can be sustained for pCO_2 levels of 9 times PAL (for 30 k.y. and 40 k.y. orbital periodicities) and 10 times PAL (only 30 k.y. orbital periodicities) if the runs start with preexisting ice sheets formed during a run of 8 times PAL. These observed multiple equilibria of the steady-state ice sheets therefore depend on the size of preexisting ice and the amplitude of the orbital forcing, i.e., insolation. The small ice-sheet instability (SISI) was first described by Weertman (1961) and has since then been described from different ice-sheet models (e.g., Abe-Ouchi and Blatter, 1993); it is the consequence of the large-scale geometry of the ice-sheet profile and its intersection with the poleward-dipping climatic snowline. Additional simulations are necessary to further define the atmospheric boundary conditions under which the Late Ordovician glaciation was subject to SISI.

Figure 6 shows the maximum and minimum extent of the ice sheets with pCO_2 levels of 8 times PAL and orbital-forcing periodicities of 30 k.y. The ice-sheet results show that ice-sheet coverage in the center of Gondwana was sensitive to insolation changes. During the colder periods, ice sheets extended as far toward the equator as 70°S, but melted back during warmer orbits. There are no major differences in ice thickness and distribution between the maximum and minimum extents of the ice sheet for the different orbital periodicities of 30 k.y. and 40 k.y. (not shown).

DISCUSSION

Several studies investigated the effect of astronomical orbital parameters on the stratigraphic record and ice ages during both the Quaternary and earlier epochs (e.g., de Boer and Smith, 1994; Schwarzacher, 1993). Although precise dating of Ordovician strata is difficult, there is reason to believe that obliquity influenced climate in the same way as it does today and did during the last ice age. This is supported by evidence in the rock record that shows that orbital forcing played a role in the climate system during the Ordovician (Goldhammer et al., 1993; Sutcliffe et al., 2000; Williams, 1991). Our results suggest that Milankovitch cycles at the time scale of the obliquity cycle could have had a strong influence on the waxing and waning of ice sheets during the Late Ordovician glaciation. Under the influence of warm-summer orbits, permanent ice-sheet growth occurred only with pCO_2 levels of 8 times PAL or lower. These results constrain the threshold of atmospheric pCO_2 levels to start glaciation at the lower end of previous estimates (Yapp and Poths, 1992; Berner and Kothavala, 2001). Our results further suggest that adding Milankovitch cyclicity to our simulations prevents the ice sheets from obtaining unreasonably large ice

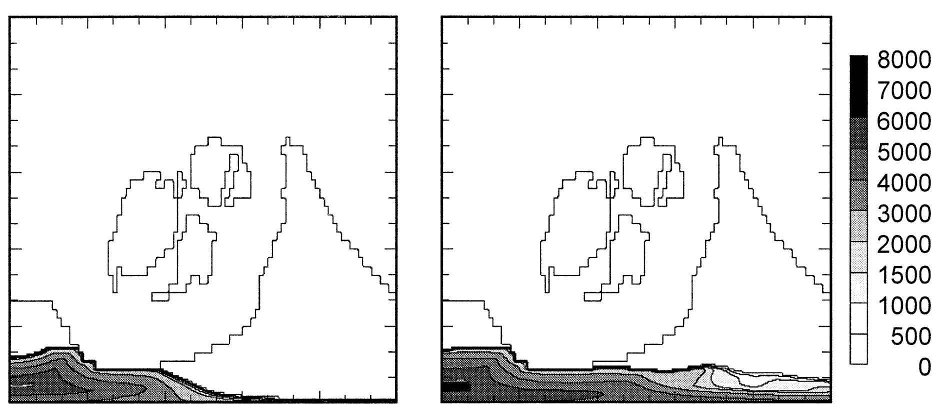

Figure 6. Ice-sheet height for simulations with atmospheric pCO_2 levels of 9× PAL (preindustrial atmospheric level) with minimal and maximal ice extent for 30 k.y. cyclicity.

volumes. Without the influence of the warm-summer orbit, the ice volume with 8 times PAL reaches ~168 times 10^6 km^3. This volume is about four times larger than the simulated Northern Hemisphere ice-sheet volume over the past 600 k.y. (Li et al., 1998).

Our ice-sheet model results also have important implications for the end of the Late Ordovician glaciation. If ice sheets grew at low pCO_2 (at and below 8 times PAL) levels, a rise in pCO_2 to levels higher than 10 times PAL would be necessary to melt the ice sheets. Our results therefore support the findings of Kump et al. (1999), who suggested that during the Late Ordovician, pCO_2 levels rose and that the initiation and demise of the Late Ordovician glaciation were due to the interplay of tectonism with carbonate and silicate weathering.

Our results further indicate that climatic changes at the obliquity time scale could have had a significant effect on the waxing and waning of ice sheets during the Late Ordovician. However, the main Milankovitch cycles—those due to precession, obliquity, and eccentricity—combine to produce more complex cycles in the amount of solar energy reaching the outer atmosphere of Earth. Because AGCMs only simulate a ''snapshot'' of climate during a Milankovitch cycle, more experiments are needed to fully investigate the sensitivity of the Late Ordovician climate system to stacked Milankovitch cycles. A related limitation of our AGCM plus ice-sheet simulations is that they are run with invariant pCO_2 levels. The combined effects of changes in orbital and pCO_2 forcing might help explain the short duration of the Late Ordovician glaciation, but more sensitivity studies are necessary to investigate these feedback cycles in more detail.

CONCLUSIONS

1. The ice-sheet model results with orbital forcing indicate that in order to initiate the growth of permanent ice sheets, the atmospheric pCO_2 level must have fallen to 8 times PAL or below. This value is at the lower end of estimates of pCO_2 levels for the Late Ordovician based on geochemical modeling (Berner and Kothavala, 2001) and geochemical data from paleosols (Yapp and Poths, 1992). In addition, it is at the lower end of most threshold estimates based on AGCM results (Crowley and Baum, 1991; Crowley and Baum, 1995; Gibbs et al., 1997, 2000; Poussart et al., 1999).

2. Our simulations indicate that large ice sheets, grown during extreme periods of low pCO_2 (8 times PAL or lower), can subsequently be sustained during periods of higher pCO_2 (9–10 times PAL) that would otherwise prevent the growth of ice from ice-free starting conditions. Thus, if atmospheric pCO_2 was the main driver of climate during the Late Ordovician, pCO_2 must have risen to >10 times PAL to melt the Gondwana ice sheet and end glaciation.

3. These results are a demonstration of interactions that may be important in other glaciations in Earth history, like the Neoproterozoic snowball Earth (e.g., Hoffman et al., 1998). Ice sheets and orbital forcing can introduce nonlinearities and bifurcations that significantly alter the response to CO_2 and CO_2 thresholds necessary for the initiation and termination of ice ages.

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