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Mountain uplift and the threshold for sustained Northern Hemisphere Glaciation

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Abstract

The Miocene (∼24 to ∼5 million years ago) was a period of relative global warmth (e.g. Zachos et al. 2001) characterised by the glaciation of Antarctica only. Paradoxically, the majority of available proxy data suggest that during the Miocene pCO_2 was similar, or even lower, than the pre-industrial levels (280 ppmv; Pagani et al., 1999; Pearson and Palmer, 2000; Kürschner et al., 1996, 2008) and at times probably crossed the modelled threshold value required for sustained glaciation in the Northern Hemisphere (DeConto et al., 2008). Records of ice rafted debris and the oxygen isotope composition of benthic foraminifera suggest that at several times over the last 25 million years substantial amounts of continental ice did build up in the Northern Hemisphere but none of these led to sustained glaciation. In this contribution we review evidence that suggests that in the Miocene the North American Cordillera was, at least in parts, considerably lower than today. We present new GCM simulations that imply that Late Miocene uplift of the North American Cordillera would have resulted in significant cooling of Northern North American Continent. Offline ice sheet modelling, driven by these GCM outputs, suggests that with a reduced topography inception of the Cordilleran ice sheet is prohibited, and there is a small, but potentially significant, reduction in the amount of ice grown on Baffin Island. This suggests uplift of the North American Cordillera in the Late Miocene may have played an important role in priming the climate for the intensification of Northern Hemisphere glaciation in the Late Pliocene.

1 Introduction

The Cenozoic is a time period characterised by a gradual deterioration of global climate which culminated in bipolar continental glaciation around 3 million years ago (Fig. 1; Mudlesee and Raymo, 2005). The near accepted paradigm evokes a gradual decline in pCO_2 caused by enhanced weathering (Raymo and Ruddiman, 1992; Raymo et al., 1988) as the driver for this well documented climate change. Reconstructing the concentration of atmospheric CO_2 beyond the reach of the Quaternary ice cores is, however, a notoriously difficult task. Nonetheless there is a growing consensus that pCO_2 did decline over the Cenozoic, but not exactly sympathetically with climate as the paradigm suggests (Fig. 1). This is likely because the pCO_2 records are not perfect (e.g. Pagani et al., 2005) and other phenomenon such as ocean circulation, continental configuration, and surface albedo (vegetation and ice coverage) also influence climate. Considering CO_2 alone, and based on climate model simulations, DeConto et al. (2008) recently proposed that two threshold pCO_2 values exist, that when crossed enable full bipolar continental glaciation to be triggered by orbital forcing. The first, at ~800 ppmv, was crossed at ~34 Ma (Pearson et al., 2009) and was associated with the continental glaciation of Antarctica. The second, at ~280 ppmv was crossed in the Late Pliocene and resulted in sustained continental glaciation in the Northern Hemisphere. What is puzzling is that pCO_2 reconstructions, despite their variability, all broadly agree that for much of the last 25 million years pCO_2 hovered around this second threshold value, and at times may have even crossed it (Fig. 1). Accumulations of ice rafted debris in the North Atlantic, and significant benthic $\delta^{18}O$ excursions, testify that transient ice sheets did indeed accumulate at several times over the last 25 million years, yet Northern Hemisphere glaciation did not begin in earnest until ~3 Ma (Fig. 1). Also, recent modelling (Lunt et al., 2008a), and boron and alkenone based pCO_2 reconstructions over the last 5 million years, confirm that the intensification of Northern Hemisphere glaciation (INHG) at ~3 Ma is associated with a drop in pCO_2 from 350–400 to 260–280 ppmv (Seki et al., 2009). This therefore suggests that for the Late Pliocene the 280 ppmv threshold is appropriate. However, the lack of sustained glaciation in the Northern Hemisphere in the Miocene, despite, at times, pCO_2 possibly lower than 280 ppmv (Fig. 1), indicates that this may not be the case for this period, and a lower threshold would be more appropriate. Some other environmental factor, one which favours glaciation, may have changed in the Late Miocene/Pliocene in order to raise the pCO_2 threshold value from a lower Miocene value to 280 ppmv, thereby facilitating INHG. A number of phenomena have been suggested that may fulfil this role, such as: the closure of the Panama Isthmus (e.g. Driscoll and Haug, 1998), reorganisation of the Indonesian seaway (Cane and Molnar, 2001), and shoaling of the Bering Straits (Marincovich and Gladenkov, 1999). In addition, DeConto et al. (2008) showed that in simulations with globally reduced topography (half modern topography) the threshold pCO_2 value for NHG was lowered to 140–210 ppmv (compare their supplementary Fig. 3 with Fig. 3 in their main paper). These coupled general circulation model (GCM)-ice sheet model simulations confirm early modelling studies (e.g. Kutzbach et al., 1989) that highlighted the importance of global topography in determining climate and the potential role surface uplift may play in triggering climate change. However DeConto et al.'s approach is rather simplistic and it is considered very unlikely that topography increased globally sometime in the Late Cenozoic (England and Molnar, 1990). Also, although very instructive, the modelling strategy used by DeConto et al. (2008) was not designed to investigate this specific problem and an Eocene palaeogeography was used rather than a more appropriate (for the problem we address here) modern or Late Pliocene continental configuration.

In this contribution we revisit the hypothesis of Ruddiman et al. (1989) concerning the uplift of the North American Cordillera. We first present a new summary of evidence regarding the topographic evolution of this region. We then present new modelling results using a high resolution, fully coupled ocean-atmosphere GCM (HadCM3) and offline ice sheet model (GLIMMER) that highlight that the climate of the Northern Hemisphere is particularly sensitive to the topography of western North America that presents itself to westerly atmospheric circulation. We show that even a relatively small change in elevation of the North American Cordillera is sufficient to cool the Northern Hemisphere and influence ice sheet coverage during cold orbital stages. If large parts of the North American Cordillera did uplift during the Late Miocene/Early Pliocene then they may have played a vital role in favouring INHG and thereby, at least in part, explain why, during the Miocene, the Northern Hemisphere is largely ice free despite, on average, relatively low levels of pCO_2.

1.1 Climatic and atmospheric influence of the North American Cordillera

General circulation models, run with a much reduced orography relative to the modern, highlight that without the current north-south mountain barrier to westerly atmospheric circulation that exists along the west coast of the North American continent (herein referred to as the North American Cordillera), the winters of NE North American continent would be significantly warmer and the continental interior of the US would be much wetter than today (Kutzbach et al., 1989; Seager et al., 2002). Indeed, contrary to popular belief, the relative frigidity of the winter time climate in NE North America and Canada has more to do with the coastal mountains of the North American Cordillera influencing atmospheric circulation than it does with the Gulf Stream providing warmth to maritime Europe (Seager et al., 2002). In the absence of the present mountain barrier, atmospheric circulation would be more or less zonal (as it is in the Southern Hemisphere around the Antarctic continent). However, with the significant mountain barrier atmospheric Rossby waves are generated and the jet-stream is deflected down stream of the barrier stabilising a cooler polar winter air mass over NE North America (e.g. Seager et al., 2002). Broccoli and Manabe (1992, 1997) also suggested that, because the tracks of major storms responsible for much of the mid-latitudes' precipitation are parallel to the upper tropospheric jet, in the absence of the mountain barrier moisture transport to the continental interior would be enhanced and consequently the prairies of the continental interior would also be much wetter.

1.2 Topographic evolution of the North American Cordillera

It has been known for some time that the rise and fall of mountain ranges and the formation of mountainous plateau regions on geological timescales (e.g. the Tibetan Plateau and North American Cordillera) can directly influence global climate (e.g. Ruddiman et al., 1989). It has also been proposed that reorganisation of atmospheric and oceanic circulation as a direct consequence of a phase of global Late Cenozoic mountain formation played an important part in the Late Cenozoic climatic deterioration,

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which led to the intensification of Northern Hemisphere glaciation in the Late Pliocene (Ruddiman et al., 1989; Mudlesee and Raymo, 2005). However, it is now relatively well established that parts, but not all, of the North American Cordillera have been areas of high elevation since their formation in the Early Cenozoic (e.g. Wolfe et al., 1998; Horton et al., 2004; Kent-Corson et al., 2006). Due to the nature of North American tectonics, continental material has been accreting to the west coast of the North American Continent since the Jurassic (150–205 Ma), with the most recent major orogenic event being the Laramide Orogeny that climaxed at ~75 Ma (Burchfiel et al., 1992). Parts of this orogenic area subsequently experienced tectonic collapse initiating in the north as early as 55 Ma (Parrish et al., 1988) and reaching the south (central Nevada) by 35 Ma (Kent-Corson et al., 2006 and references therein) forming a number of large basins separated by mountain ranges (e.g. Hyndman et al., 2005). The height of the ranges prior to the Pliocene is known in a number of places from paleobotanical analysis (e.g. Wolfe et al., 1998) and through numerous studies using $\delta^{18}O$ based paleoaltimetry (e.g. Kent-Corson et al., 2006; Horton et al., 2004). These studies have been interpreted as indicating that surface uplift propagated from north (British Columbia) to south (Nevada) from the Eocene to Oligocene, accompanied by the development of topographic highs and magmatism associated with the delamination of the mantle lithosphere (Kent-Corson et al., 2006; Horton et al., 2004). The prevailing view is that although some Late Cenozoic surface uplift may have occurred (e.g. see Sahagian et al., 2002), the Colorado Plateau and much of the rest of the North American Cordillera have been long standing features of high elevation (>2 km) and if anything have become lower since the Middle Miocene. The Basin and Range and the Sierra Nevada have similar histories with both ranges being extant in the Miocene and either dropping in height since then (Wolfe et al., 1998; Horton et al., 2004) or, for the Sierra Nevada, maintaining a similar to present altitude (Chamberlain and Poage, 2000).

However, a growing body of evidence suggests that the coastal mountain ranges of the NW North American Cordillera (i.e. the Cascades of the northwestern US, the Coast Range Mountains of British Columbia, St Elias Mountains of NW BC to SE Alaksa and Coast Range of Alaska) did indeed develop in the Middle to Late Miocene and alpine glaciation in these ranges is thought to have begun at around 7–9 million years ago (Denton and Armstrong, 1969; Clague, 1991) which is likely coincident with their attainment of near-present height.

The data pertaining to the elevation of the NW North American Cordillera comes in three strands that will be discussed here in turn – (i) Paleobotanical and oxygen isotope paleoaltimetry; (ii) geological indicators of uplift, (iii) thermochronological indicators of rock uplift. The geographic locations that are relevant to this evidence are highlighted in Fig. 2.

Paleobotanical data on Miocene-Pliocene flora (Martin and Rouse, 1966; Rouse and Mathews, 1979; White et al., 1997) has been recovered from the lee of the Alaskan Coast Range, St. Elias Mountains, and Coast Mountains of Canada (Fig. 2). These preserve evidence of both global climatic trends, for example general Cenozoic cooling and the Pliocene warm interval (White et al., 1997), as well as more regional climatic effects indicative of increased seasonality and more continental – colder – drier climate since 7 Ma ago in the lee of Alaskan and St. Elias Ranges (White et al., 1997) and 11 Ma in the lee of the Canadian Coast Range (Martin and Rouse, 1966; Rouse and Mathews, 1979), consistent with the development of a significant rain shadow at this time. This view is also supported by oxygen isotope analysis. Kohn et al. (2002), using fossil herbivore teeth from the Oregon Plateau (Fig. 2), show an isotopic change consistent with the development of the modern topographic coastal barrier in Oregon (from the Cascades) between 7.2 and 3 Ma. Oxygen data in clay minerals in paleosols in eastern Washington State (Fig. 2) show a similar effect beginning sometime after 11 Ma consistent with the development of the modern ∼1.5 km of relief at this time (Takeuchi and Larson, 2005). In a paleosol based reconstruction of precipitation patterns in Oregon (Fig. 2), also in the lee of the Cascades, Retallack (2004) note a drying trend initiating shortly after ∼15 Ma. Furthermore, to the east in Nebraska, Passey et al. (2002) note a decline in the $\delta^{18}O$ of fossil equid teeth indicative of drying at 13–10 Ma, and in Montana and Idaho (Fig. 2) Kent-Corson et al. (2006) show a near synchronous shift in paleosol $\delta^{18}O$ also thought to be related to formation of the Cascade Mountains. In total, a number of studies support the development of the modern topographic barrier and associated rain shadow in the NW of the North American continent in its near entirety sometime shortly after the Mid- to Late Miocene (i.e. after 15–10 Ma).

Sedimentary and volcanic deposits of Late Cenozoic age also have a bearing on this problem and support these conclusions. Miocene (7–14 Ma) volcanic rocks erupted in part on relatively level and low-relief erosion surfaces are exposed both on the central plateau in Canada as well as at significant elevations in the St. Elias Mountains (Campbell and Dodds, 1978) and on the east side of the southern British Columbia Coast Range Mountains (Parrish, 1983; Souther and Yorath, 1992; Fig. 2). In several places, ∼7 Ma sheets of lava have been tilted (with local folding) up to 15–20° away from the axial part of the mountains producing in places >2 km of uplift of the base of the lava sheets (Parrish, 1983). These lavas therefore provided a well constrained upper age limit for the surface uplift in the Coast Range Mountains of British Columbia. Similarly, in the Washington Cascades to the south (Fig. 2), Middle Miocene (∼15 Ma) lavas are tilted and uplifted in the eastern Cascades and reach elevations near Mount Rainer 1.5 km higher than similar units exposed further to the east (Swanson, 1997). In addition in numerous locations sedimentary rocks of Miocene age demonstrate regional warping and uplift occurred post 15 Ma (e.g. Reidel et al., 1994).

Finally, low temperature thermochronometric studies have been conducted at numerous places in the western Cordillera from 47 °N to 63° N (as summarised in Reiners et al., 2002 and references therein; Fig. 2). These studies constitute a regional scale database that indicates a significant acceleration of rock exhumation rate during the Late Miocene (Reiners et al., 2002; Parrish, 1983; O'Sullivan and Parrish, 1995; Fitzgerald et al., 1995; O'Sullivan and Currie, 1996; Farley et al., 2001). On its own such information should be interpreted in terms of surface uplift with caution. However, numerous studies have demonstrated that the amount of rock uplift and erosion in mountainous terranes are closely coupled with local relief (e.g. Montgomery and Brandon, 2002). This, in combination with the evidence discussed above, suggests that the acceleration in rock uplift rate during the Late Miocene of the coastal mountains north of ~47° N is, at least in part, consistent with an increase in relief and topography at this time.

Reconstructing the topographic evolution of a mountainous region is a rather difficult task and reconstructions such as those discussed above are typically contentious. Nevertheless, in the absence of better reconstructions we feel it is reasonable to suggest that some surface uplift of the North American Cordillera as a whole may have occurred since the Miocene (as suggested by Ruddiman et al., 1989). We feel however that there is considerably stronger evidence (reviewed above) to suggest that the westernmost Cordillera, north of about 45° N, has undergone significant surface uplift since the Late Miocene.

2 Methodology

All the GCM simulations described in this paper are carried out using the UK Met Office coupled ocean-atmosphere GCM (HadCM3, version 4.5, Gordon et al., 2000). The resolution of the atmospheric and land components is 3.75° in longitude by 2.5° in latitude, with 19 vertical levels in the atmosphere. The resolution of the ocean model is 1.25° by 1.25° with 20 levels in the vertical. Parameterisations include the radiation scheme of Edwards and Slingo (1996), the convection scheme of Gregory et al. (1997), and the MOSES-1 land-surface scheme, whose representation of evaporation includes the dependence of stomatal resistance on temperature, vapour pressure and CO_2 concentration (Cox et al., 1999). The ocean model uses the Gent and McWilliams (1990) mixing scheme. There is no explicit horizontal tracer diffusion in the model. The horizontal resolution allows the use of a smaller coefficient of horizontal momentum viscosity leading to an improved simulation of ocean velocities compared to earlier versions of the model. The sea ice model uses a simple thermodynamic scheme and contains parameterisations of ice concentration (Hibler, 1979) and ice drift and leads (Cattle and Crossley, 1995). In simulations of the present-day climate, the model has been shown to simulate SST in good agreement with modern observations, without the need for flux corrections (Gregory and Mitchell, 1997). This model has previously been used in several Cenozoic modelling studies (Lunt et al., 2008a, b, 2009).

We carried out two fully coupled atmosphere-ocean GCM simulations using HadCM3 version 4.5. We initially carried out a pre-industrial control simulation with modern orography (smoothed to the model resolution of 3.75° longitude by 2.5° latitude). A further simulation with a reduced topography in the west of North America was then carried out. In all other regards this perturbed simulation had identical boundary conditions ($p\mathrm{CO_2}$, ice sheet, vegetation) to the pre-industrial control simulation. In this experiment termed "low-45N", we truncated the topography north of 45° N at 750 m in accordance with the evidence summarised in Sect. 1.2. Due to the spatial resolution of the model this is roughly equivalent to reducing the average height of these ranges by ~500 m. This experiment is in keeping with the geological evidence for pre-Pliocene surface uplift although we acknowledge such topography may never have existed in this simplified form. Figure 3 shows the topographic differences between the pre-industrial control run and this simulation with a reduced topography. In comparison to previous modelling studies of this kind (e.g. DeConto et al., 2008) the GCM used here has a higher spatial resolution, allowing a more accurate representation of global topography, and a fully coupled ocean-atmosphere rather than a slab ocean.

Although the climate model used allows a more accurate simulation of climate it is computationally intensive and this precludes the full coupling of an ice sheet model to the GCM. We have used an offline ice sheet model, following Lunt et al. (2008a), to examine the effect of uplift on Laurentide and Cordilleran Ice Sheet inception. However, because these offline ice sheet simulations do not include crucial feedbacks (e.g. albedo feedback) it is important to note that the ice sheets simulated repre-

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sent minimum configurations. Therefore, although the simulated ice sheets are much smaller than those in fully coupled models they can still provide information regarding glacial inception (e.g. Lunt et al., 2008a).

The 3-D thermomechanical ice sheet model used in this work is GLIMMER version 1.0.4. The core of the model is based on the ice sheet model described by Payne (1999). The ice dynamics are represented with the widely-used shallow-ice approximation, and a full three-dimensional thermodynamic model is used to determine the ice flow law parameter. The model is formulated on a Cartesian x-y grid, and takes as input the surface mass-balance and air temperature at each time step. In the present work, the ice dynamics time step is one year. To simulate the surface mass-balance, we use the positive degree day (PDD) approach described by Reeh (1991). The use of PDD mass-balance models is well-established in coupled atmosphere-ice sheet palaeoclimate modelling studies (e.g. DeConto and Pollard, 2003; Lunt et al., 2007, 2008a, b, 2009). GLIMMER includes a representation of the isostatic response of the lithosphere, which is assumed to behave elastically, based on the model of Lambeck and Nakiboglu (1980). The forcing data from HadCM3 are transformed onto the ice model grid using bilinear interpolation, which ensures that precipitation is conserved in the atmosphere-ice-sheet coupling. In the case of the surface air temperature field, a vertical lapse-rate correction is used to take account of the difference between the high-resolution topography seen within GLIMMER, and that represented with HadCM3. The use of a lapse-rate correction to better represent the local temperature is established in previous work (e.g. Pollard and Thompson, 1997). We use anomaly coupling to force the ice sheet model, and use values for the PDD factors of 0.008 for ice and 0.003 $\mathrm{m\,day^{-1}\,^{\circ}C^{-1}}$ for snow. For the baseline climate to which the anomalies are applied, we use a standard temperature and precipitation climatology derived from ERA-40 reanalysis. The GLIMMER ice sheet model uses a single value for the lapse-rate correction which we set to a value of 7.0 $\mathrm{K\,km^{-1}}$. For the standard pre-industrial ice sheet simulations we use the bedrock topography derived from the standard ETOPO5 dataset. For the "low-45N" simulation, we truncated along the west coast to 750 m northwards of $\sim$45° N, in a similar way as in the corresponding GCM simulation.

Because the timescale for equilibrium of the North American ice sheets is comparable with orbital timescales, it is important to carry out transient ice sheet simulations which include orbital effects. We use a time variable orbital anomaly representing the insolation experienced during a transition from near-average orbital conditions to glacial orbital conditions and back again, over half a precessional cycle, that is, 10 000 years. In order to do this, we carry out an additional GCM simulation under 'cold-orbit' forcing; that is orbital conditions for 115 kyr BP, but otherwise pre-industrial boundary conditions. This gives us an anomaly relative to pre-industrial which represents the maximum orbital forcing over the 10 000 years. Then, for the final ice sheet simulations, we use the original GCM climate (high-mountain or low-mountain), superimposed with the time-varying orbital component. More details of this approach can be found in Lunt et al. (2008a).

3 Results

Figure 4 shows the magnitude of surface air temperature (at 2 m), precipitation, snow accumulation, and surface albedo warm and cold season anomalies for the reduced topography simulation. In all cases, the anomalies are for the "pre-industrial control" minus the "low-45N" simulation, therefore reflecting changes associated with uplift and the establishment of the modern orography. The limited model spin up time (<ocean overturning) means only changes in atmospheric circulation and the ocean mixed layer can be examined. However, from these figures the local and more distant hemispheric effects of uplift are clearly observable. For instance, the uplifted area is colder (Fig. 4a, b), and to the west of the uplifted area precipitation and temperature has clearly increased (Fig. 4c, d) reflecting the intensification of orographic precipitation. There are also several far-field effects that warrant further discussion. The most significant observation is the strong winter and weaker summer cooling of the NE American continent and the Canadian Arctic (Fig. 4a, b); this results in a year round increase in sea-ice

extent in the Canadian Arctic and off Greenland, and an increase in snow accumulation and coverage in the northern US and Canada, with an associated increase in albedo (Fig. 4e, f). These far-field temperature lows are coincident with the 500 mb height anomaly (not shown) implying that the mountain uplift led to a deepening of the Rossby wave trough over this region. The consequent deflection of storm tracks is also visible on the precipitation anomaly (Fig. 4c, d), which shows a predominantly winter reduction in the penetration of storms and associated precipitation in the continental interior and reduced precipitation over much of Greenland and NE Canada.

Figure 5 shows the results of the ice sheet model described above, in conjunction with an additional cold-orbit GCM simulation, for the control (Fig. 5a) and "low-45N" simulation (Fig. 5b). In the control (cold-orbit) simulation (Fig. 5a), unsurprisingly, the ice sheet model predicts the inception of ice sheets in the islands of the Canadian Arctic and in the high mountains of the NW Cordillera. It is important to note that since the ice sheet model is not fully coupled to the GCM the positive feedbacks relating to ice growth are not represented so the ice sheets shown are minima (see Lunt et al., 2008a for further discussion). It is however clear that, due to temperature changes associated with uplift, in the "low-45N" simulation (Fig. 4a, b), there is no Cordilleran Ice Sheet and there is a minor reduction of ice on Baffin Island.

4 Discussion

There are several important regional and far-field climatic shifts evident in our GCM results associated with uplift that are consistent with existing studies of the Miocene climate. This therefore provides additional support for there being a period of Cordilleran mountain uplift in the Late Miocene. For instance, perhaps the most regionally significant far-field anomalies are the changes in precipitation patterns and the development of a rainy season (decrease in winter, increase in summer) in the continental interior (Fig. 4c, d). There are a number of studies that document such a climatic shift occurring at this time, for instance Retallack (1997) notes a marked drying in fossil paleosols and an expansion of the American Prairie in the Late Miocene. Similarly, Fox (2000), using mammalian fossils, documents a drying of the North American continent associated with an increase in seasonality in the Late Miocene, including the development of a wet season. Kohn and Fremd (2008) also record a decrease in faunal diversity in the Western US between 12 and 7 Ma thought to coincide with increased aridity and seasonality.

For this study the most significant results however are the strong winter and generally weaker summer cooling of the Northern North American Continent and the associated cryosphere response (snow accumulation, sea-ice and albedo increases). Lunt et al. (2008a) examined the influence of Cordilleran uplift on ice sheet growth on Greenland during the Mid Pliocene using an offline ice sheet model similar to that used here. They used a pCO_2 value of 400 ppmv, and a more extreme uplift scenario, and concluded that uplift was not sufficient, on its own, to significantly enhance Greenland glaciation when compared to the effect of lowering pCO_2 to 280 ppmv. Nevertheless, Lunt et al. (2008a) did model a small increase in the ice present on Greenland as a result of the cooling and precipitation changes similar to those shown in Fig. 4. Again, since these simulations did not include a number of crucial ice sheet related feedbacks they should be considered the minimum response. Nonetheless, the ice sheet model results of our experiments (Fig. 5) show that the more minor uplift simulated by our "low-45N" simulation also resulted in a significant North American ice sheet response. As we noted above, with reduced mountains the Cordilleran Ice Sheet fails to incept entirely and the amount of ice on Baffin Island is reduced (Fig. 5). Although the resultant change is relatively minor in Baffin this area is thought to be critical for the inception of the Laurentide Ice sheet (e.g. Vettoretti and Peltier, 2004) and once again, the modelled ice sheet responses do not include all feedbacks and so the changes are minimum responses. The modelled response for the Cordilleran Ice sheet to uplift is however very large, and this may have had a significant impact on the growth of ice in the Northern Hemisphere as a whole through ice sheet-climate feedbacks (e.g. the albedo feedback and through atmospheric and ocean circulation).

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In total, our simulations imply that a reduction in the height of the North American Cordillera inhibits Northern Hemisphere glaciation. Since we do not have a fully coupled GCM-ice sheet model we cannot determine exactly how these changes in topography influence the level of CO_2 required to allow orbital forcing to kick-start INHG. However, given the direction of the climate trends described here we can say with confidence that the threshold CO_2 value required is lower when the height of the North American Cordillera is reduced. The magnitude of the change in threshold pCO_2 value will likely depend on the lateral extent and height of the uplifted range. As we noted earlier, topographic reconstructions are notoriously difficult, however, if our "low-45N" simulation represents the minimum amount of surface uplift that occurred since the Late Miocene, Cordilleran uplift may have played a crucial role in priming the Northern Hemisphere for glaciation during the Late Pliocene. We therefore propose that in the Late Miocene glaciation in the Northern Hemisphere was prohibited, despite relatively low pCO_2 values, by the comparative warmth of the northern part of North America as a consequence of the reduced height of the North American Cordillera. Until better palaeotopographic reconstructions are available the exact role of mountain uplift in determining the climate of the Late Cenozoic will continue to be uncertain and relatively unconstrained.

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References

Broccoli, A. J. and Manabe, S.: The effects of orography on midlatitude Northern Hemisphere dry climates, J. Climate, 5, 1181–1201, 1992.

Broccoli, A. J. and Manabe, S.: Mountains and midlatitude aridity, in: Tectonic uplift and climate change, edited by: Ruddiman, W. F., Plenum Press, New York, 89–121, 1997.

Burchfiel, B. C., Cowan, D. S., and Davis, G. A.: Tectonic overview of the cordilleran orogen in the western united states, in: The cordilleran orogen: Conterminous US, edited by: Burchfiel, B. C., Lipman, P. W., and Zoback, M. L., Geol. Soc. Am., The Geology of North America, Boulder, Colorado, 407–479, 1992.

Campbell, R. B. and Dodds, C. J.: Operation St. Elias, Yukon Territory, Geological Survey of Canada, Paper, 78-1a, 35–41, 1978.

Cane, M. A. and Molnar, P.: Closing of the Indonesian Seaway as a precursor to East African Aridification around 3–4 million years ago, Nature, 411, 157–162, 2001.

Cattle, H. and Crossley, J.: Modelling arctic climate change, Phil. Trans. Royal Soc., A352, 201–213, 1995.

Chamberlain, C. P. and Poage, M. A.: Reconstructing the paleotopography of mountain belts from the isotopic composition of authigenic minerals, Geology, 28, 115–118, 2000.

Clague, J. J.: Quaternary glaciation and sedimentation, in: Geology of the cordilleran orogen in Canada, edited by: Gabrielse, H., and Yorath, C. J., Geological Survey of Canada, Ottawa, 419–434, 1991.

Cox, P., Betts, R., Bunton, C., Essery, R., Rowntree, P. R., and Smith, J.: The impact of new land-surface physics on the GCM simulation and climate sensitivity, Clim. Dynam., 15, 183–203, 1999.

DeConto, R. M. and Pollard, D.: Rapid Cenozoic glaciation of Antarctica induced by declining atmospheric CO_2, Nature, 421, 245–249, 2003.

DeConto, R. M., Pollard, D., Wilson, P. A., Palike, H., Lear, C. H., and Pagani, M.: Thresholds for Cenozoic bipolar glaciation, Nature, 455, 652–656, 2008.

Denton, G. H. and Armstrong, R. L.: Miocene-Pliocene glaciations in southern Alaska, Am. J. Sci., 267, 1121–1142, 1969.

Driscoll, N. W. and Haug, G. H.: A short circuit in thermohaline circulation: A cause for Northern Hemisphere Glaciation?, Science, 282, 436–438, 1998.

Edwards, J. M. and Slingo, A.: Studies with a flexible new radiation code 1: Choosing a config-

uration for a large-scale model, Q. J. Roy. Meteor. Soc., 122, 689–719, 1996.
England, P. and Molnar, P.: Surface uplift, uplift of rocks and exhumation of rocks, Geology, 18, 1173–1177, 1990.
Farley, K. A., Rusmore, M. E., and Bogue, S. W.: Post 10-ma uplift and exhumation of the northern Coast Mountains, British Columbia, Geology, 29, 99–102, 2001.
Fitzgerald, P. G., Sorkhabi, R. B., Redfield, T. F., and Stump, E.: Uplift and denudation of the central Alaska Range: A case study in the use of fission track thermochronology to determine absolute uplift parameters, J. Geophys. Res., 100, 20175–20191, 1995.
Fox, D. L.: Growth increments in *gomphotherium* tusks and implications for late Miocene climate change in North America, Palaeogeogr. Palaeoclim. Palaeoecol., 156, 327–348, 2000.
Gent, P. R. and McWilliams, J. C.: Isopycnal mixing in ocean circulation models, J. Phys. Oceanogr., 20, 150–155, 1990.
Gordon, C., Cooper, C., Senior, C. A., Banks, H., Gregory, J. M., Johns, T. C., Mitchell, J. F. B., and Wood, R. A.: The simulation of sst, sea ice extents and ocean heat transports in a version of the hadley centre coupled model without flux adjustments, Clim. Dynam., 16, 147–168, 2000.
Gregory, D., Kershaw, R., and Inness, P. M.: Parametrisation of momentum transport by convection ii: Tests in single column and general circulation models, Q. J. R. Metero. Soc., 123, 1153–1183, 1997.
Gregory, J. M. and Mitchell, J. F. B.: The climate response to CO_2 of the hadley centre coupled AOGCM with and without flux adjustment, Geophys. Res. Lett., 24, 1943–1946, 1997.
Hibler, W. D.: A dynamic thermodynamic sea ice model, J. Phys. Oceanogr., 9, 815–846, 1979.
Horton, T. W., Sjostrom, D. J., Abruzzese, M. J., Poage, M. A., Waldbauer, J. R., Hren, M., Wooden, J., and Chamberlain, C. P.: Spatial and temporal variation of Cenozoic surface elevation in the Great Basin and Sierra Nevada, Am. J. Sci., 304, 832–888, 2004.
Hyndman, R. D., Currie, C. A., and Mazzotti, S. P.: Subduction zone backarcs, mobile belts, and orogenic heat, GSA Today, 15, 4–10, 2005.
Kent-Corson, M. L., Sherman, L. S., Mulch, A., and Chamberlain, C. P.: Cenozoic topographic and climatic response to changing tectonic boundary conditions in western North America, Earth Planet. Sci. Lett., 252, 453–466, 2006.
Kohn, M. J. and Fremd, T. J.: Miocene tectonics and climate forcing of biodiversity, western United States, Geology, 36, 783–786, doi:710.1130/G24928A.24921, 2008.
Kohn, M. J., Miselis, J. L., and Fremd, T. J.: Oxygen isotope evidence for progressive uplift of

the Cascade Range, Oregon, Earth Planet. Sci. Lett., 204, 151–165, 2002.

Kürschner, W. M., van der Burgh, J., Visscher, H., and Dilcher, D. L.: Oak leaves as biosensors of Late Neogene and Early Pleistocene paleoatmospheric CO_2 concentrations, Mar. Micropalentol., 27, 299–312, 1996.

Kürschner, W. M., Kvacek, Z., and Dilcher, D. L.: The impact of Miocene atmospheric carbon dioxide fluctuations on climate and the evolution of terrestrial ecosystems, PNAS, 105, 440–453, 2008.

Kutzbach, J. E., Guetter, P. J., Ruddiman, W. F., and Prell, W. L.: Sensitivity of climate to Late Cenozoic uplift in southern Asia and the American West: Numerical experiments, J. Geophys. Res., 94, 18393–18407, 1989.

Lambeck, K. and Nakiboglu, S. M.: Seamount loading and stress in the ocean lithosphere, J. Geophys. Res., 85, 6403–6418, 1980.

Lunt, D. J., Haywood, A. M., Foster, G. L., and Stone, E. J.: The arctic cryosphere in the mid-pliocene and the future, Phil. Trans. Roy. Soc. A, 367, 49–67, doi:10.1098/rsta.2008.0218, 2009.

Lunt, D. J., Foster, G. L., Haywood, A. M., and Stone, E. J.: Late Pliocene Greenland glaciation controlled by a decline in atmospheric CO_2 levels, Nature, 454, 1102–1105, 2008a.

Lunt, D. J., Valdes, P. J., Haywood, A. M., and Rutt, I. C.: Closure of the Panama Seaway during the Pliocene: Implications for climate and Northern Hemisphere Glaciation, Clim. Dynam. 30, 1–18, 2008b.

Marincovich, L. J. and Gladenkov, A. Y.: Evidence for an early opening of the Bering Strait, Nature, 397, 149–151, 1999.

Martin, H. E. and Rouse, G. E.: Palynology of late tertiary sediments from Queen Charlotte Islands, British Columbia, Can. J. Bot., 44, 171–208, 1966.

Montgomery, D. R. and Brandon, M. T.: Topographic controls on erosion rates in tectonically active mountain ranges, Earth Planet. Sci. Lett., 673, 1–9, 2002.

Mudelsee, M. and Raymo, M. E.: Slow dynamics of the Northern Hemisphere Glaciation, Paleoceanography, 20, doi:10.1029/2005PA001153, 2005.

O'Sullivan, P. B. and Parrish, R. R.: The importance of apatite composition and single-grain ages when interpreting fission-track data from plutonic rocks: A case study from the Coast Ranges, British Columbia, Earth Planet. Sci. Lett., 132, 213–224, 1995.

O'Sullivan, P. B. and Currie, L. D.: Thermotectonic history of Mt Logan, Yukon territory, Canada: Implications of multiple episodes of Middle to Late Cenozoic denudation, Earth Planet. Sci.

Lett., 144, 251–261, 1996.
Pagani, M., Freeman, K. H., and Arthur, M. A.: Late Miocene atmospheric CO_2 concentrations and the expansion of C_4 grasses, Science, 285, 876–879, 1999.
Pagani, M., Lemarchand, D., Spivack, A., and Gaillardet, J.: A critical evaluation of the boron isotope-pH proxy: The accuracy of ancient pH estimates, Geochim. Cosmochim. Acta, 69, 953–961, 2005.
Parrish, R. R.: Cenozoic thermal evolution and tectonics of the coast mountains of British Columbia 1. Fission-track dating, apparent uplift rates, and patterns of uplift, Tectonics, 2, 601–631, 1983.
Parrish, R. R., Carr, S. D., and Parkinson, D. L.: Eocene extensional tectonics and geochronology of the southern Omineca Belt, British-Columbia and Washington, Tectonics, 7, 181–212, 1988.
Passey, B. H., Cerling, T. E., Perkins, M. E., Voorhies, M. R., Harris, J. M., and Tucker, S. T.: Environmental change in the Great Plains: An isotopic record from fossil horses, J. Geol., 110, 123–140, 2002.
Payne, A. J.: A thermomechanical model of ice flow in west antarctica, Clim. Dynam., 15, 115–125, 1999.
Pearson, P. N. and Palmer, M. R.: Atmospheric carbon dioxide concentrations over the past 60 million years, Nature, 406, 695–699, 2000.
Pearson, P. N., Foster, G. L., and Wade, B. S.: Atmospheric carbon dioxide through the Eocene-Oligocene climate transition, Nature, 461, 1110–1113, doi:10.1038/nature08447, 2009.
Pollard, D. and Thompson, S. L.: Driving a high-resolution dynamic ice sheet model with gcm climate: Ice-sheet initiation at 116 000 bp, Ann. Glaciol., 25, 296–304, 1997.
Raymo, M. E., Ruddiman, W. F., and Froelich, P. N.: Influence of Late Cenozoic mountain building on ocean geochemical cycles, Geology, 16, 649–653, 1988.
Raymo, M. E. and Ruddiman, W. F.: Tectonic forcing of Cenozoic climate, Nature, 359, 117–122, 1992.
Reeh, N.: Parameterization of melt rate and surface temperature on the Greenland ice sheet, Polarforschung, 59, 113–128, 1991.
Reidel, S. P., Campbell, N. P., Fecht, K. R., and Lindsey, K. A.: Late Cenozoic structure and stratigraphy of south-central Wasthington, Washington Division of Geology and Earth Resources Bulletin, 80, 159–180, 1994.
Reiners, P. W., Ehlers, T. A., Garver, J. I., Gran Mitchell, S., Montgomery, D. R., Vance, J. A.,

and Nicolescu, S.: Late miocene exhumation and uplift of the washington cascade range, Geology, 30, 767–770, 2002.
Retallack, G. J.: Neogene expansion of the North American prairie, Palios, 12, 380–390, 1997.
Retallack, G. J.: Late Oligocene bunch grassland and Early Miocene sod grassland paleosols from central Oregon, USA, Palaeogeogr. Palaeoclim. Palaeoecol., 207, 203–237, 2004.
Rouse, G. E. and Mathews, W. H.: Tertiary geology and palynology of the Quesnel area, British Columbia, B. Can. Petrol. Geol., 27, 418–445, 1979.
Ruddiman, W. F. and Kutzbach, J. E.: Forcing of the Late Cenozoic Northern Hemisphere climate by plateau uplift in southern Asia and the America West, J. Geophys. Res., 94, 18409–18427, 1989.
Sahagian, D., Proussevitch, A., and Carlson, W.: Timing of Colorado plateau uplift: Initial constraints from vesicular basalt-derived paleoelevations, Geology, 30, 807–810, 2002.
Seager, R., Battisti, D. S., Yin, J., Gordon, N., Naik, N., Clement, A. C., and Cane, M. A.: Is the gulf stream responsible for europe's mild winters, Q. J. R. Meterol. Soc., 128, 2563–2586, 2002.
Seki, O., Foster, G. L., Schmidt, D. N., Mackensen, A., Kawamura, K., and Pancost, R. D.: Alkenone and boron based Plio-Pleistocene pCO_2 records, Earth Planet. Sci. Lett., in review, 2009.
Souther, J. G. and Yorath, C. J.: Neogene assemblages, in: Geology of the Cordilleran Orogen in Canada, edited by: Gabrielae, H., and Yorath, C. J., Geol. Surv. of Can., Geology of Canada, 373–401, 1992.
Swanson, D. A.: Uplift of the southern Washington Cascades in the past 17 million years, Geological Society of America Abstracts with Programs, 29, p. 68, 1997.
Takeuchi, A. and Larson, P. B.: Oxygen isotope evidence for the Late Cenozoic development of an orographic rain shadow in eastern Washington, USA, Geology, 33, 313–316, 2005.
Vettoretti, G. and Peltier, W. R.: Sensitivity of glacial inception to orbital and greenhouse gas climate forcing, Quarternary Sci. Rev., 23, 499–519, 2004.
White, J. M., Ager, T. A., Adam, D. P., Leopold, E. B., Liu, G., Jette, H., and Schweger, C. E.: An 18 million year record of vegetation and climate change in northwestern Canada and Alaska: Tectonic and global climatic correlates, Palaeogeogr. Palaeoclim. Palaeoecol., 130, 293–306, 1997.
Winkler, A.: The climate history of the high northern latitudes since the middle Miocene: Indications from sedimentological and clay mineralogical analyses (ODP leg 151, central Fram

strait), Reports on Polar Research, Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, 344, 117 pp., 1999.
Wolfe, J. A., Forest, C. E., and Molnar, P.: Paleobotanical evidence of Eocene and Oligocene paleoaltitudes in midlatitude western North America, Geol. Soc. Am. Bull., 110, 664–678, 1998.
Zachos, J., Pagani, M., Sloan, L., Thomas, E., and Billups, K.: Trends, rhythms, and aberrations in global climate 65 Ma to present, Science, 292, 686–693, 2001.
Zachos, J. C., Dickens, G. R., and Zeebe, R. E.: An Early Cenozoic perspective on greenhouse warming and carbon-cycle dynamics, Nature, 451, 279–283, 2008.

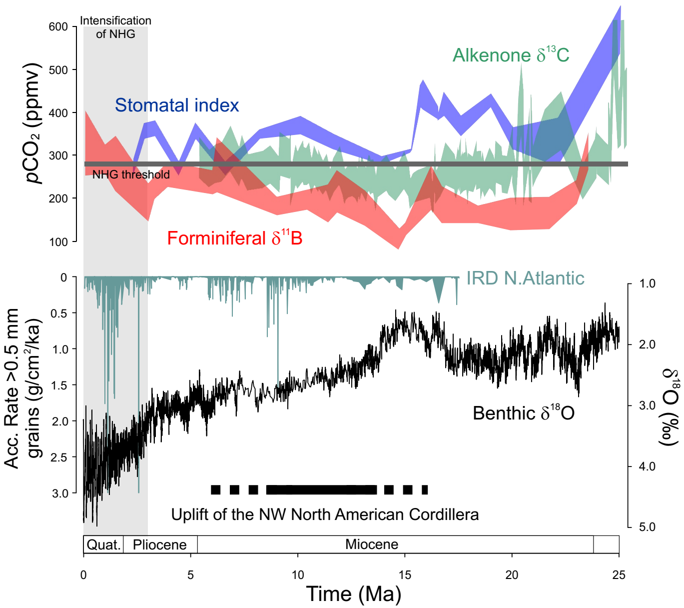

Fig. 1. Miocene, Pliocene and Quaternary pCO_2 (top) and climate records. The atmospheric concentration of CO_2 (top) during this time period is reconstructed using stomatal index of fossil leaves (blue; Kürschner et al., 2008; Kürschner et al,. 1996), the δ^{13}C of marine alkenones (green; Pagani et al., 1999) and the δ^{11}B of marine planktic foraminifera (red; Pearson and Palmer, 2000). The threshold pCO_2 value necessary for sustained glaciation in the Northern Hemisphere is shown as a horizontal grey band (DeConto et al., 2008). Also shown is a record of ice rafted debris (IRD) in the North Atlantic (middle; ODP Site 151–909; Winkler, 1999) and the global compilation of benthic foraminifera δ^{18}O of Zachos et al. (2008; bottom). The vertical grey bar shows the time period when there was sustained glaciation in the Northern Hemisphere, note the sharp decline in δ^{18}O and increase in IRD at this time. Also shown by the dotted horizontal black band is the timing of uplift of the NW North American Cordillera as reviewed here.

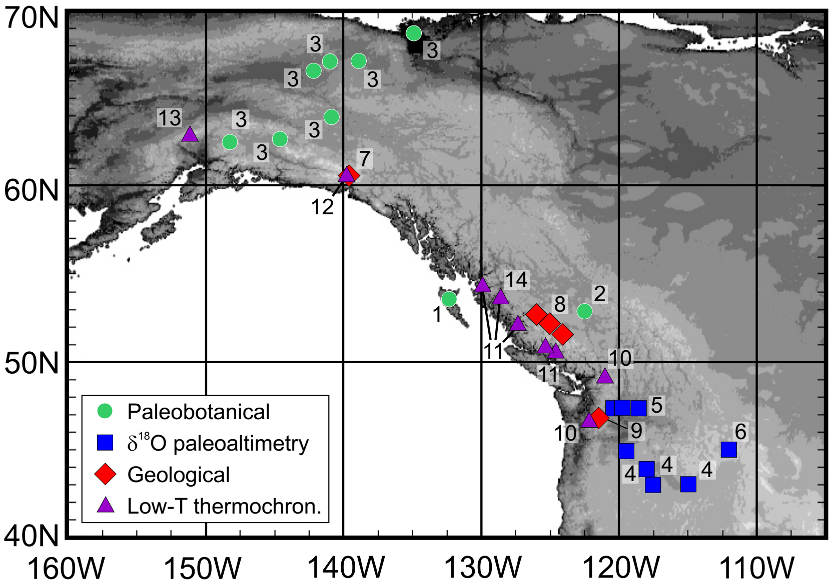

Fig. 2. Digital elevation model of the North American Continent showing the location of much of the published data used in text divided according to the data type. **(1)** Martin and Rouse (1966), **(2)** Rouse and Mathews (1979), **(3)** White et al. (1997), **(4)** Kohn et al. (2002), **(5)** Takeuchi and Larson (2005), **(6)** Kent-Corson et al. (2006), **(7)** Campbell and Dodds (1978), **(8)** Parrish (1983), **(9)** Swanson (1997), **(10)** Reiners et al. (2002), **(11)** Parrish (1983), **(12)** O'Sullivan and Currie (1996), **(13)** Fitzgerald et al. (1995), **(14)** Farley et al. (2001).

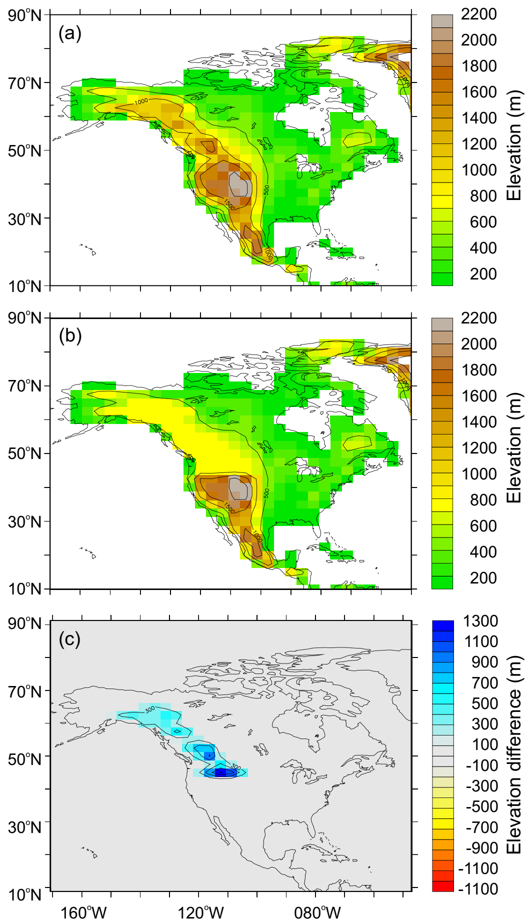

Fig. 3. Topographic boundary conditions of North America. **(a)** modern configuration used for the pre-industrial control; **(b)** “low-45N” configuration; **(c)** anomaly plot for “low-45N” plot.

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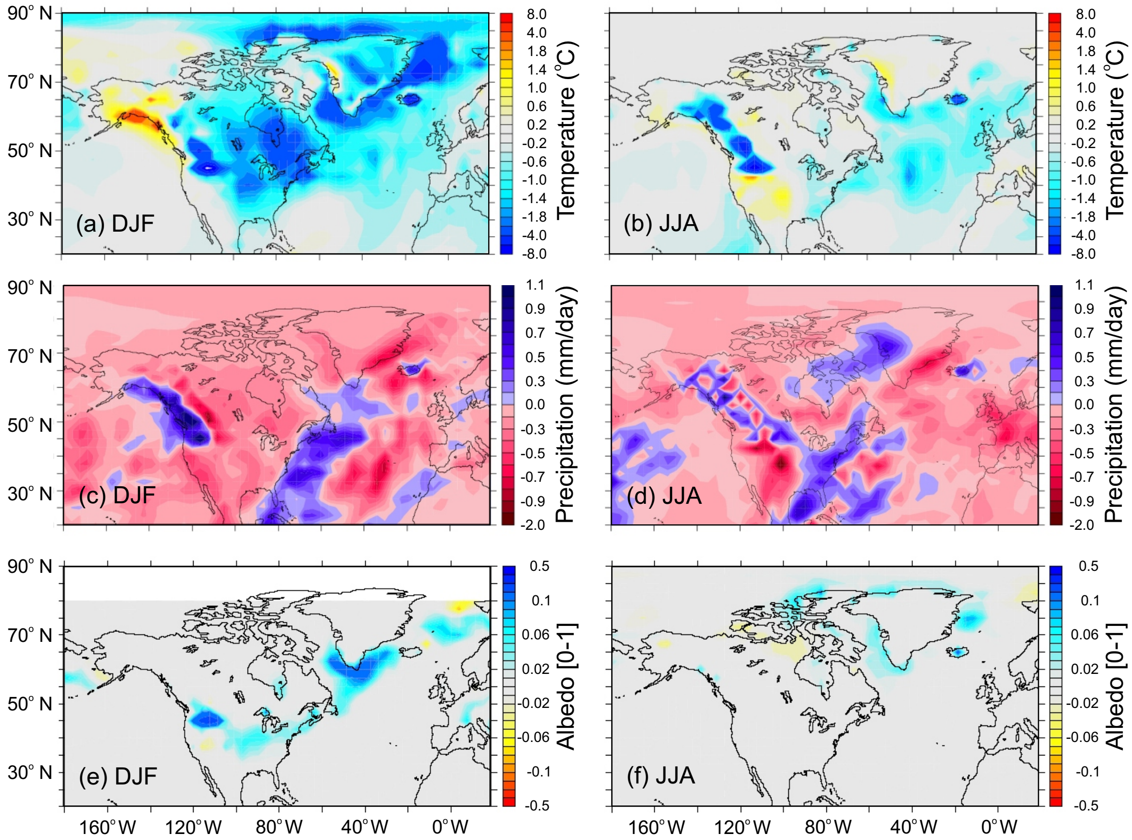

Fig. 4. Seasonal (December-January-February and June-July-August) anomalies of pre-industrial control minus "low-45N" configuration (i.e. reflecting the climate change as a consequence of mountain uplift). (**a** and **b**) surface air temperature at 2 m [degrees C]; (**c** and **d**) precipitation (mm/day); (**e** and **f**) surface albedo.

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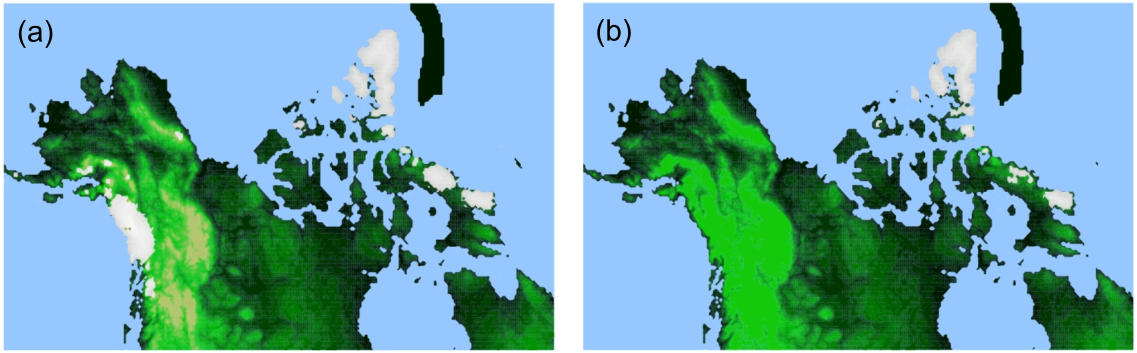

Fig. 5. Ice sheet configurations for the **(a)** pre-industrial control and **(b)** low-45N mountains simulations (see text for details).

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