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A test of the overdue-glaciation hypothesis

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Abstract

According to a new hypothesis, greenhouse-gas concentrations in the atmosphere should have fallen throughout the last several thousand years and caused a significant cooling of Earth's climate, but early anthropogenic emissions of carbon dioxide and methane kept temperatures relatively warm. A further prediction is that ice should have begun accumulating in northeast Canada several thousand years ago. We carry out a preliminary test of this hypothesis by reducing atmospheric CO_2 and CH_4 concentrations to their estimated 'natural' levels in an experiment with the GENESIS climate model. In the absence of anthropogenic contributions, global climate is almost 2 °C cooler than today and roughly one third of the way toward full-glacial temperatures. The hypothesis of an overdue glaciation is confirmed, but at a small scale: parts of Baffin Island retain snow cover year-round, and snow cover persists on high terrain in Labrador for 11 months of the year.

1. Introduction

The relative temperature stability of the last 10,000 years has long been viewed as the result of natural climatic causes. Orbital variations are seen as having permitted a brief interglacial break between the previous glaciation and the next one, each encompassing 90% of the duration of a 100,000-year cycle. An accompanying view has persisted that humans played no significant role in altering atmospheric greenhouse-gas concentrations or affecting global climate until the 1800s, when byproducts of the industrial revolution begin to add measurably to the natural greenhouse-gas levels already in the atmosphere and to contribute to the warming trend of the last century (IPCC, 2001).

Both of these concepts have been challenged (Ruddiman, 2003). Ice-core evidence from previous interglaciations indicates that forcing by orbital-scale changes in solar radiation and greenhouse-gas concentrations should have driven Earth's climate significantly toward glacial conditions during the last several thousand years. The hypothesized reason that most of this cooling did not occur is that humans intervened in the natural operation of the climate system by adding significant amounts of CO_2 and CH_4 to the atmosphere, thereby offsetting most of the natural cooling and fortuitously producing the climatic stability of the last several thousand years. One prediction of this hypothesis is that early anthropogenic greenhouse-gas emissions stopped a glaciation that otherwise would have begun several millennia ago.

The timing of cyclic variations in CO_2 and CH_4 in Vostok ice over the last 400,000 years (Petit et al., 1999) has been assessed by tuning various gas components in the ice to other orbital-scale signals linked to the astronomical cycles of solar radiation (Shackleton, 2000; Bender, 2002; Ruddiman and Raymo, 2003). The convergence of these techniques on a similar time scale indicates that the periodicity and phase of these natural gas cycles are now known within small uncertainties. With this knowledge, anomalous behavior of gas concentrations in recent millennia can be detected (Fig. 1).

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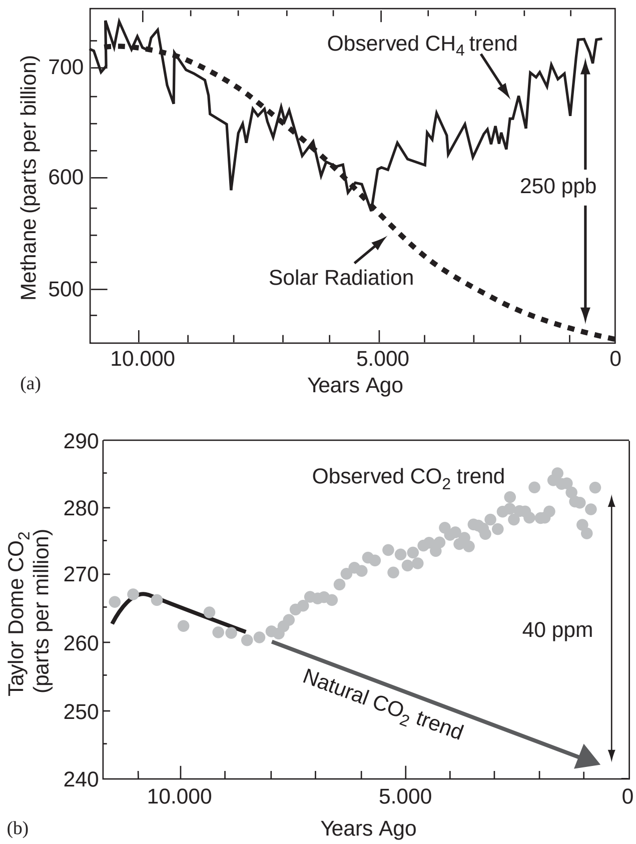

Fig. 1. Anthropogenic effects on (a) CH_4 and (b) CO_2 calculated as the difference between observed trends (Blunier et al., 1995; Indermuhle et al., 1999) and trends estimated from previous early interglacial intervals (Ruddiman, 2003).

Over the last 8000 years, the CO_2 concentration gradually rose to a level of 280–285 ppm during an interval when trends observed during the three previous interglaciations suggest that it should have fallen to 240–245 ppm (Ruddiman, 2003). Similarly, CH_4 concentrations rose to 700 ppb during the last 5000 years, a time when weakening monsoons and cooling of boreal regions at the 22,000-year orbital precession cycle predict a continuing decrease to ~450 ppb. The anomalous CO_2 rise is attributed to massive early deforestation of Eurasia, and the anomalous CH_4 increase mainly to irrigation for rice farming in southeast Asia, as well as increases in biomass burning, livestock, and other sources (Ruddiman and Thomson, 2001). The equilibrium warming estimated from these anomalies (~40 ppmCO_2, ~250 ppbCH_4) is 0.8 °C on a global basis and 2 °C in polar regions, based on the IPCC sensitivity estimate of a 2.5 °C temperature change for a doubling of CO_2 concentrations (IPCC, 2001).

The choice of the last three interglaciations (marine isotopic stages 5, 7, and 9) as analogs to the Holocene can be questioned. Eccentricity modulates precession at the 413,000-year period, and insolation variations during the Holocene have been smaller than those during these three interglaciations. Isotopic stage 11 should be a better climatic analog to stage 1, because insolation variations were closer to modern values as a result of low eccentricity.

Ruddiman (in press) examined a feature near the bottom of the Vostok ice record that has been tied to SPECMAP marine isotopic substage 11.24 (Imbrie et al., 1984) by Petit et al. (1999) and by Shackleton (2000). This feature follows a mid-summer 65°N insolation minimum dated to 397,000 years ago (Berger and Loutre, 2003) that represents a close analog to late Holocene summer insolation trends. The greenhouse-gas concentrations reached just before substage 11.24 confirm the predictions of the early anthropogenic hypothesis: CH_4 values fell to ~445 ppb (Fig. 2a), and CO_2 values to ~252 ppm (Fig. 2b).

The anthropogenic hypothesis also predicted that ice sheets would now be growing in the northern hemisphere, had it not been for the early anthropogenic greenhouse-gas emissions. Some modeling simulations linking orbitally driven changes in solar radiation to marine $\delta^{18}O$ variations have predicted that global ice volume should have reached a minimum near 6000 years ago, but then should have begun a new cycle of growth near 5000 years ago (Imbrie and Imbrie, 1980; Berger et al., 1990), although other simulations have not predicted Holocene ice growth (Berger and Loutre, 2003).

Ruddiman (in press) found three independent lines of evidence that ice sheets grew during substage 11.24: a $\delta^{18}O_{atm}$ increase of 0.6‰ in Vostok ice (Fig. 2d); $\delta^{18}O$ increases of 0.7‰ in benthic foraminifera from Pacific Ocean cores (Mix et al., 1995); and the onset of deposition of ice-rafted debris in Nordic Sea sediments (Bauch et al., 2000). The fact that ice sheets were growing during this closest analog to modern conditions supports the hypothesis that ice sheets should be present and growing today.

Northeastern Canada is a likely region of ice-sheet nucleation (Andrews and Mahaffy, 1976). An assessment with an energy-balance model found that high terrain in northeast Canada lies so near the 'glaciation limit' today that removal of the industrial-era warming would lower that threshold onto the highest plateau topography (Williams, 1978). An additional cooling of 1–2 °C was judged sufficient to lower the glaciation limit enough to encompass a broader area of northeast Canada. If this assessment is correct, removal of the pre-industrial warming contribution from the early anthropogenic greenhouse-gas emissions noted above would provide the additional cooling needed to initiate glaciation in northeastern Canada.

The stage 11 comparison also reveals a very large climatic response in the Antarctic region during substage 11.24 (Ruddiman, in press). Deuterium (δD) values in Vostok ice fell from typical full-interglacial values to levels ~75% of the way toward glacial values.

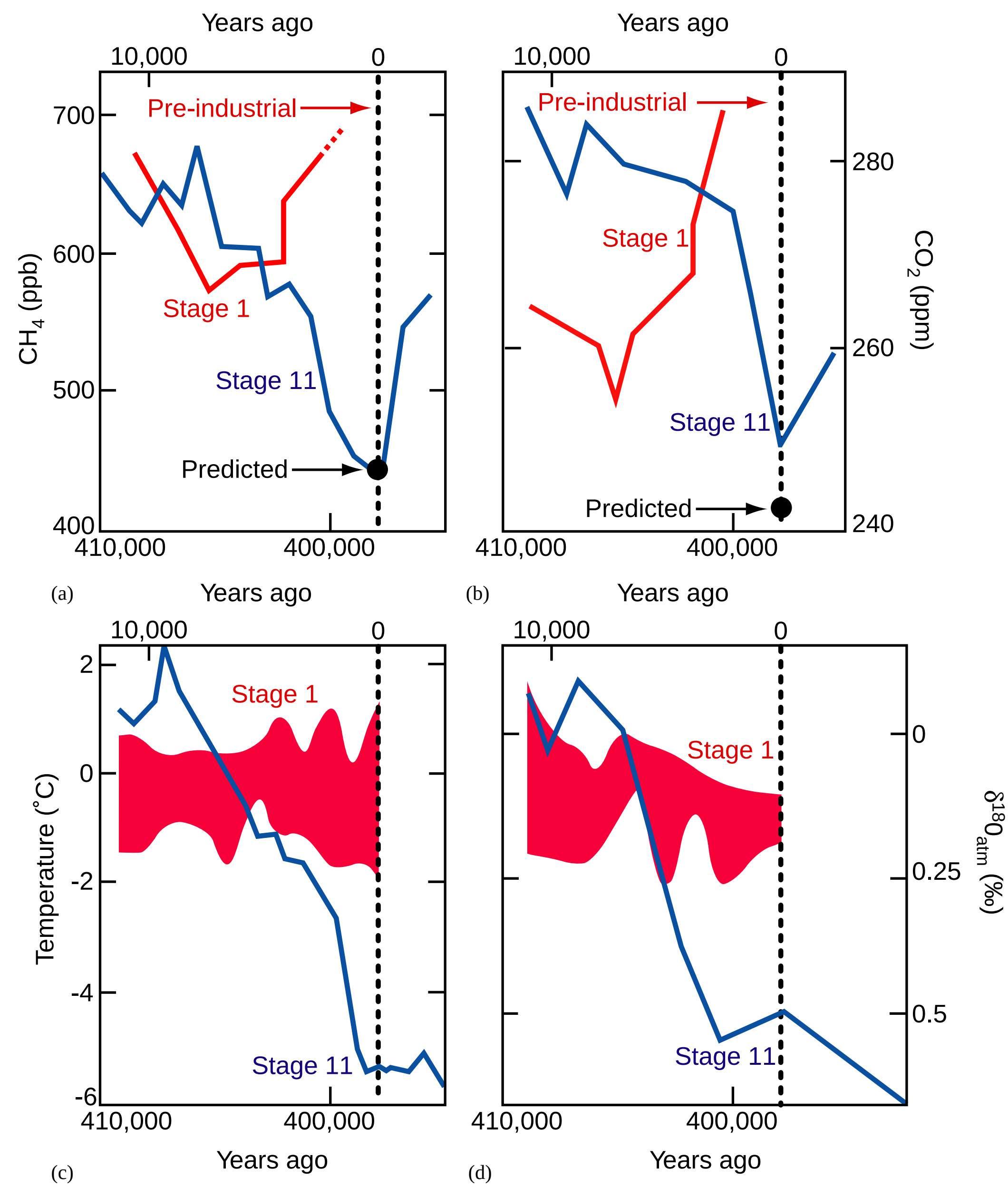

Fig. 2. Comparison of climatic proxy trends in Vostok ice (Petit et al., 1999) for the Holocene and the early interglacial portion of isotopic stage 11. (a) CH_4; (b) CO_2; (c) Antarctic temperature, reconstructed from δD changes; (d) $\delta^{18}O_{atm}$. The regions shaded in red in 2c and 2d encompass the measured range of variation of each signal during stage 1. Natural greenhouse-gas levels predicted for the late Holocene by the early anthropogenic hypothesis are also indicated.

Petit et al. (1999) used the δD trend to reconstruct the temperature of precipitation over the Antarctic ice sheet and found a 7 °C cooling from the stage 11 interglacial maximum to the substage 11.24 minimum (Fig. 2c). The implication of these results is that the modern-day Antarctic region would be much closer to glacial than interglacial temperatures if greenhouse gases were at their natural (non-anthropogenic) levels.

This study will test both the early anthropogenic hypothesis and the results from the stage 11 comparison by: (1) assessing how much colder climate would be today (particularly in the Arctic and Antarctic regions) if greenhouse gases were reduced to the natural levels indicated by previous interglaciations; and (2) exploring whether or not this cooling would have initiated a new glaciation in northeastern Canada or elsewhere.

2. Experiment: Greenhouse gases lowered to natural concentrations

We ran two experiments on the GENESIS 2 climate model (Thompson and Pollard, 1997) as a preliminary assessment of the 'overdue glaciation' hypothesis. The atmospheric component of the GENESIS 2 model has 18 vertical levels and a T31 spectral resolution, which corresponds to a grid resolution of 3.75° for calculations of dynamics and precipitation. It has a 2° grid over ocean and land surfaces for calculations of surface-atmosphere interactions. GENESIS 2 has a 50 m static mixed-layer ocean model with parameterized diffusive heat transport, adjusted heat flux in the Norwegian Sea, and interactive sea ice with sea-ice advection forced by interactive surface winds and prescribed ocean currents. We chose this model for several reasons:

First, the control-case simulation in GENESIS 2 has a climate sensitivity of 2.5 °C for a CO_2 doubling, matching closely the central value of the IPCC estimate, which is based upon results from several models (IPCC, 2001). In general, the model control agrees reasonably well with the NCEP climatological means (Kalnay et al., 1996), especially in Arctic regions where we want to test for possible increases in snow cover. Sea-ice limits also match the climatology closely (Vavrus, 1999). The model has some warm bias over northeastern Canada (up to a few degrees), especially during winter, but its simulated snow cover over Northern Hemisphere continents is quite realistic (Thompson and Pollard, 1997).

Second, by resolving topography at 2° (compared to the 2.75° resolution of T42 models), GENESIS 2 'sees' the higher plateau topography on the northeast Canadian margin that is favorable for snow accumulation and glacial inception (Andrews and Mahaffy, 1976). Some elevations in the model exceed 550 m and reach within 100 m of actual values. Third, the model includes an option that permits an internal lapse-rate adjustment based upon the difference between the model-resolved elevations and the actual topography. This adjustment brings surface temperature and other surface climate variables even closer to those at actual elevations.

CH_4 and CO_2 concentrations in the GENESIS control case are set at 1653 ppb and 345 ppm, levels appropriate for ~1980. The control simulation is evaluated by comparison to climatological means of the last ~50 years (Kalnay et al., 1996).

CH_4 and CO_2 concentrations in the atmosphere were reduced from the control-case values to the levels that would have been reached today according to the early anthropogenic hypothesis (240 ppmCO_2, 450 ppbCH_4). In addition, CFC cncentrations were reduced to zero and the N_2O concentration from 306 ppb to a pre-industrial value of 270 ppb. In effect, this experiment attempted to simulate how much cooler the world would be today if greenhouse-gas values had followed natural trends, with neither pre-industrial nor industrial-era anthropogenic emissions of greenhouse gases. Simulations of climate both for the control case and the lowered greenhouse gas experiment were made for 15 years, with the last 10 years averaged to produce the results shown here. After the first 5 years of "spin up", the lack of obvious trends in key model variables indicated that the model had reached a state of equilibrium.

Neither land cover nor aerosol values were altered from the control case, even though these factors could have altered the regional amplitudes of the temperature anomalies simulated at lower and middle latitudes. The large uncertainties with modern aerosol prescriptions and with parameterizations of their direct and indirect effects in the control case, as well as the lack of knowledge of natural pre-industrial aerosol levels, prohibited meaningful tests of possible aerosol changes. Initial estimates of some pre-industrial aerosol concentrations are now available from analyses of Greenland ice (for example, Fisher et al., 1998), but this information is insufficient for specifying aerosol loadings worldwide.

The simulated temperature difference between the control case and the low-GHG (greenhouse gas) experiment (hereafter referred to as LOWGHG) is ~2 °C on a global basis (Fig. 3a). All of the changes shown are highly significant, at the 90% level or above, relative to the natural variability in the model. The mean-annual cooling exceeds 3 °C in many high-latitude regions, including North America and northwest Europe, as well as both the North Atlantic Ocean and a wide swath of the subpolar Southern ocean where sea-ice margins shift equatorward, and over Antarctica. In winter, areas of North America and northwest Europe poleward of 55°N are 4–5 °C cooler than in the control case (Fig. 3b; Table 1). Temperature decreases in northern summer are smaller, averaging 1.2 °C across northern and eastern North America (Table 1), but are also statistically significant. The relative size of these changes is consistent with experiments showing larger climate-system sensitivity to CO_2 changes at high latitudes, especially in winter (IPCC, 2001).

Temperatures decreases in the Southern Ocean and over Antarctica average 3 °C on a mean annual basis (Fig. 3a) and 4 °C or more during southern hemisphere winter (not shown). The largest southern hemisphere cooling occurs along the regions of largest northward sea-ice advances.

Because of the pervasive cooling, increases in northern hemisphere snow cover occur in the four warmest months (Fig. 4). Most increases along the southern margin of snow cover extent are statistically significant at the 90% confidence level compared to the model's internal variability (stippled regions in Fig. 4). Over a broad region of northeastern North America, fractional snow cover (or, equivalently, average snow depth or volume) increased 7% annually and 70% in summer (Table 1).

In June, the LOWGHG simulation has more extensive snow cover than the control case in Labrador

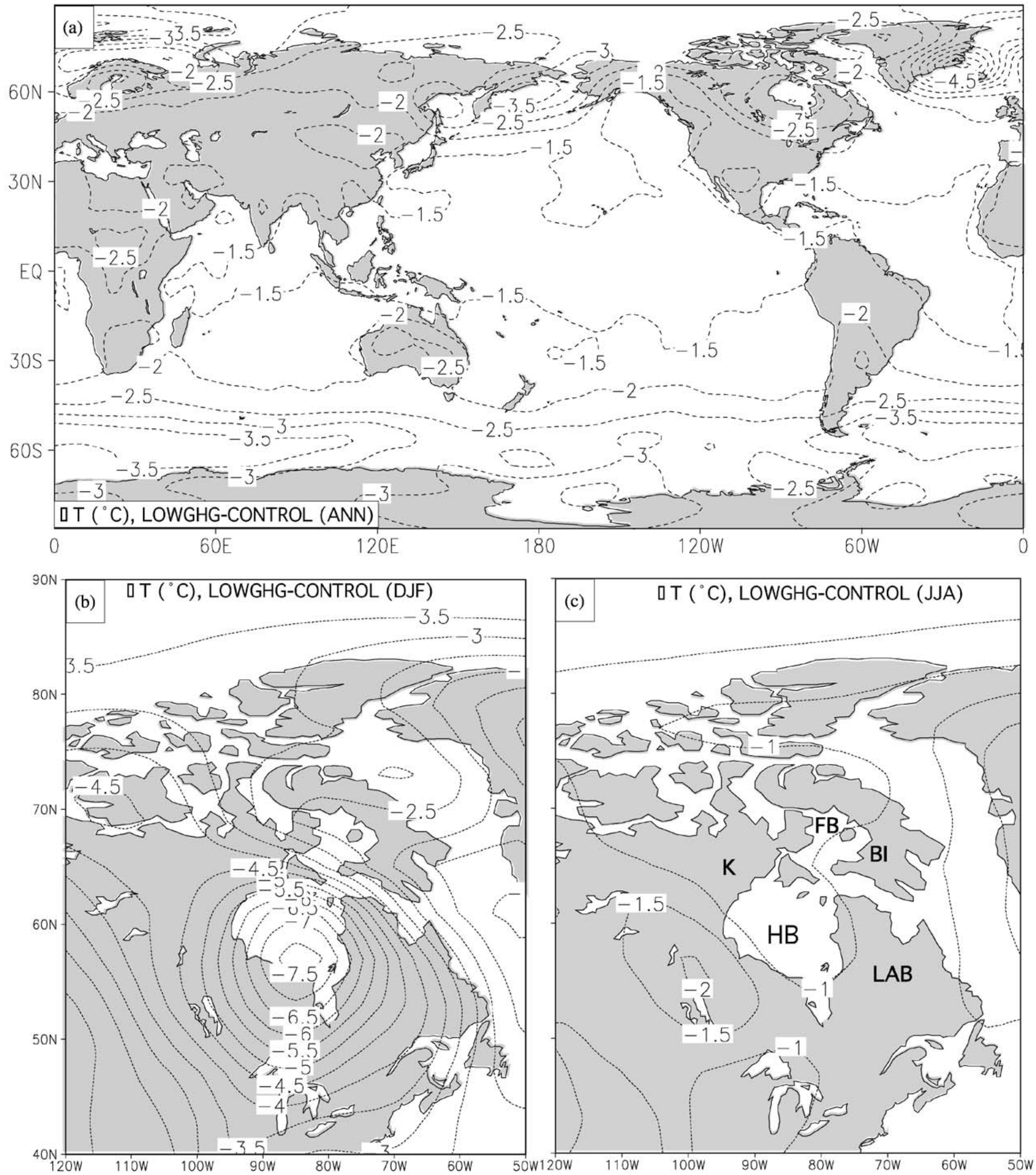

Fig. 3. Surface air temperature difference, degrees C, simulated by removing industrial-era and pre-industrial anthropogenic greenhouse gases (primarily CO_2 and CH_4) from the GENESIS 2 model: the Lowered Greenhouse Gas simulation minus the Control (LOWGHG—CONTROL). (a) annual, global, (b) DJF, North America sector, (c) JJA, North America sector. Letters (in c) denote regions mentioned in text: BI: Baffin Island, LAB: high terrain in Labrador; HB: Hudson Bay; FB: Foxe basin; K: Keewatin. Note that the large cooling centered over Hudson Bay during winter is caused by an earlier seasonal transition from open water to ice cover in the LOWGHG simulation.

east of Hudson Bay and in the Keewatin region west of Hudson Bay. In July of the LOWGHG simulation, snow persists on a high plateau in Labrador from which it disappears in the control, and several additional grid cells retain snow on Baffin Island. In August, the month of minimum snow cover, several grid cells in Baffin Island retain snow in the LOWGHG simulation, suggesting that localized ice caps could have begun to form. Although the number of grid cells with increased snowcover is small, the increased fractional overage within these cells also exceeds the 90% confidence level (Fig. 4). These were the only

Table 1
Climatic changes over Northeastern Canada (50°–80°N, 50°–95°W) from modern control simulation with GENESIS model to low greenhouse-gas (LOWGHG) experiment

	DJF	MAM	JJA	SON	ANN
Air temperature (K)	−3.7	−2.9	−1.2	−2.5	−2.6
Precipitation (mm/day)	−0.14* (−11%)	−0.14** (−15%)	−0.09** (−7%)	−0.22(−13%)	−0.15 (−11%)
Snow fraction	0.02*(+2%)	0.06(+8%)	0.02 (+71%)	0.05(+17%)	0.04 (+7%)
Sea ice fraction	0.11(+22%)	0.06 (+34%)	0.12 (+34%)	0.08 (+67%)	0.09 (+20%)

*Significant at the 95% confidence level.**Significant at the 90% confidence level.
Percent changes are shown in parentheses next to absolute values. These area-average changes of four climate variables, both seasonal and annual, are all statistically significant at the 99% level compared to the model's internal variability, with the following exceptions: the changes in DJF precipitation and snow cover are significant at the 95% level, and the change in JJA precipitation is significant at the 90% level.

cells in the northern hemisphere where snow cover persisted through the year, except across the top of the Greenland ice sheet. This year-round persistence of small amounts of snow on Baffin Island amounts to a state of 'incipient glaciation'. In September, as snow cover again returns to much of northern Canada, the Labrador region again has more snow cover in the LOWGHG case than in the control, and the enlarged region of stippling indicates that the amount of the increase in snow cover is statistically significant in regions both east and west of Hudson Bay. The Labrador region falls just one month short of year-round snow cover and a state of 'incipient glaciation'.

In the LOWGHG simulation, sea ice also persists one month longer (through August) in Hudson Bay, Foxe Basin (southwest of Baffin Island), and parts of Baffin Bay, compared to the control run (Fig. 4). Sea ice disappears completely from Hudson Bay and Foxe Basin during September in both simulations, but it returns in October. Parts of both Hudson Strait and Foxe Basin have thus moved to within one month of year-round sea-ice cover. Averaged over all ocean and inland water in northeastern North America, the sea-ice fraction increased 20% annually, with the largest percentage increases in summer and fall (Table 1).

Despite the very large temperature decreases (Fig. 3), increases in warm-season snow cover were hindered by decreases in cold-season precipitation (mostly as snow). Seasonal and annual precipitation decreased by 7–15% over a broad region centered over Hudson Bay (Table 1).

The LOWGHG simulation also produced a significant increase in annual sea-level pressure centered over southeast Greenland (Fig. 5). This weakening of the Icelandic Low results from polar cooling and more extensive sea ice, and a consequent reduction in heat and moisture transfer from the ocean to the atmosphere that energizes the Icelandic Low. The poleward flux convergence of atmospheric energy into the Arctic north of 70° was reduced by 3.2 W/m^2 (3–4%).

3. Discussion

The ~2 °C mean-annual cooling simulated by removing anthropogenic greeenhouse gases (Fig. 3a) is equivalent to roughly one third of the global-mean difference between full-interglacial and full-glacial climates (CLIMAP, 1981; Mix et al., 2001). It also represents 80% of the warming simulated by the GENESIS 2 model in response to a doubling of modern CO_2 (Thompson and Pollard, 1997). Without any anthropogenic warming, Earth's climate would no longer be in a full-interglacial state but well on its way toward the colder temperatures typical of glaciations.

In a general sense, the model results confirm the δD evidence from Vostok for a large cooling at high southern latitudes in response to modern levels of insolation and to 'natural' (non-anthropogenic) levels of greenhouse gases. But the 3–4 °C mean-annual cooling simulated in the Southern Ocean and over the Antarctic ice sheet is considerably smaller than the 7 °C cooling estimated by Petit et al. (1999) based on the δD trend (Fig. 2c). The smaller simulated cooling could in part result from the lack of a dynamical ocean in the GENESIS 2 model. In addition, the δD/temperature relationship is based on modern spatial trends over Antarctica, but δD changes through time can also occur as a result of changes in source-area humidity and seawater δD values and in the degree of supersaturation in air above the inversion layer over the ice sheet (Jouzel and Merlivat, 1984).

In the northern hemisphere, these experiments indicate that high terrain on Baffin Island would today be in a condition of 'incipient glaciation'' (Fig. 3) and that portions of Labrador and Hudson Bay would also have moved very close to such a state (Fig. 4), had greenhouse-gas concentrations followed natural trends. Our results thus provide support on a limited scale for the hypothesis that an ice sheet would now be present in northeast Canada, had humans not interfered with the climate system.

The longer persistence of snow cover in Baffin and Labrador can be compared against the pattern of retreat

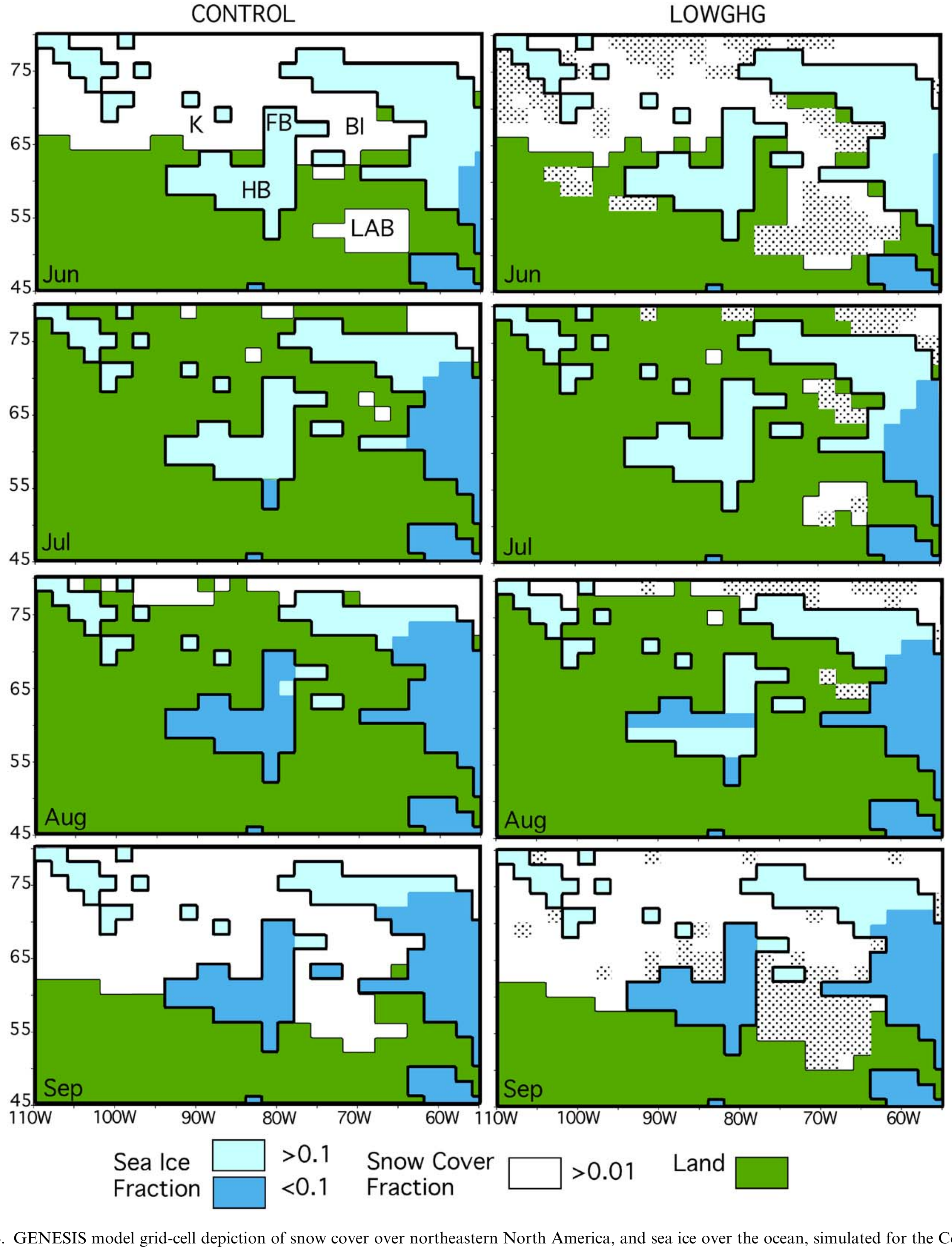

Fig. 4. GENESIS model grid-cell depiction of snow cover over northeastern North America, and sea ice over the ocean, simulated for the Control experiment (left) and for the Lowered Greenhouse-Gas experiment, LOWGHG, (right) for June, July, August, and September. Land without snow cover, or with fractional cover less than 0.01, is green. Land grid cells with fractional snow cover greater than 0.01 are white. The model calculates snow depths for each grid cell and represents amounts less than 15 cm as a volume-equivalent fractional area coverage representing the patchy character of snow fields in favorable locations. Fractional areal coverage of sea ice greater than 0.10 is light blue, and fractional coverage less than 0.10 (including open water) is darker blue. Stipple marks areas where increases in snow cover are significant at the 90% confidence level relative to the model's internal (natural) variability.

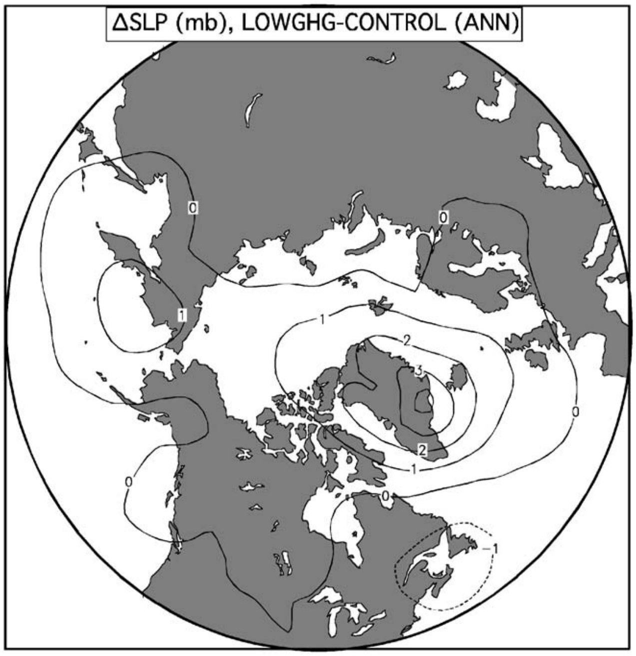

Fig. 5. Changes in mean-annual sea-level pressure (mb) simulated for the Lowered Greenhouse-Gas experiment, LOWGHG, compared to the Control case.

and final disappearance of Laurentide ice at the end of the most recent deglaciation (Fig. 6). The last place from which Laurentide ice melted—Baffin Island—is the first (and only) place it reappears in our simulation. The next-to-last place the ice sheet melted—the high terrain in central Labrador—is the region poised very near a state of incipient glaciation in this experiment.

This match is striking, given that earlier attempts to use climate models to simulate the start of the last major cycle of glaciation near 115,000 years either produced no permanent snow cover (Rind et al., 1989) or far too much (Dong and Valdes, 1995). [However, simulations of the last glacial inception appear more realistic in recent models that include interactive vegetation and ocean dynamics (Ganopolski et al., 1998; Meissner et al., 2003)]. In our experiment, incipient glaciation occurs only in North America and only in the regions thought to be the most likely sites for new glaciations to begin (Andrews and Mahaffy, 1976). New ice sheets do not necessarily have to appear in precisely the same regions from which they last disappeared, but such a link seems reasonable because both the disappearance and reappearance of the ice are thought to be controlled by a delicate mass balance between ablation and accumulation driven mainly by changes in solar radiation and greenhouse gases.

Andrews and Mahaffy (1976) summarize several hypotheses regarding the origin of the Laurentide ice sheet: (1) accumulation begins in limited regions of highland terrain in Baffin Island and Labrador; (2) 'instantaneous glacierization' occurs not just in Baffin and Labrador but also across much broader regions of lower terrain, as a result of large and abrupt cooling; and (3) permanent sea ice in shallow marine basins thickens into grounded ice shelves and then eventually into ice sheets. A fourth hypothesis (Denton and Hughes, 1981) builds on the third: ice sheets that develop over shallow-marine areas thicken and flow across drainage outlets, plugging them with ice and trapping all the snow and rain that falls within the entire Hudson Bay watershed, thereby adding any precipitation in that region to the growing mass of the ice sheet.

The incipient glaciation indicated for Baffin Island in this experiment is consistent with hypothesis 1, as is the extension of snow cover in Labrador to 11 months of the year (Fig. 4). The extension of sea-ice cover in Hudson Strait and Foxe Basin to 11 months of the year suggests that the processes invoked in hypothesis 3 may also have played a role in the glacial inception. The 'ice-plug' concept (hypothesis 4) is not ruled out by our results. This simulation provided less support for 'instantaneous' early glacierization of extensive lowland areas, including Keewatin west of Hudson Bay (hypothesis 2).

The $\delta^{18}O$ evidence cited earlier indicates a relatively large amount of ice-volume growth during the closest (stage 11) analog to late-Holocene conditions, as much as 20 meters of sea-level-equivalent. In contrast, the results from this initial simulation imply a much smaller amount of ice limited only to a few gridboxes on Baffin Island (a feature roughly the size and shape of California).

The GENESIS 2 experiment reported here probably underestimates the amount of ice that would exist today in northeast Canada without anthropogenic gases. We have intentionally limited the number of potential feedbacks in this initial test of the early anthropogenic hypothesis in order to identify the primary atmospheric effect of lowered greenhouse gases on climate. This simulation did not include the positive albedo feedback effect produced by changes in the tundra/forest boundary at high latitudes (Bonan et al., 1992). The much colder climate simulated in this initial run would have increased the area of tundra relative to forest. Because snow-covered tundra has a higher albedo than forest (when snow is present), the change in albedo should have caused further cooling. Previous sensitivity experiments with GENESIS 1 have shown that vegetation/albedo feedback increases the initial climatic impact of prescribed changes in (orbital) forcing at high latitudes (Foley et al., 1994). The imposed changes in tundra limits had the largest effect on temperature and snow cover in the spring season. For the simulation reported here, this kind of feedback would result in colder temperatures and thicker snow cover in late spring, longer-lasting snow cover in summer, and the possibility of more extensive regions of incipient glaciation.

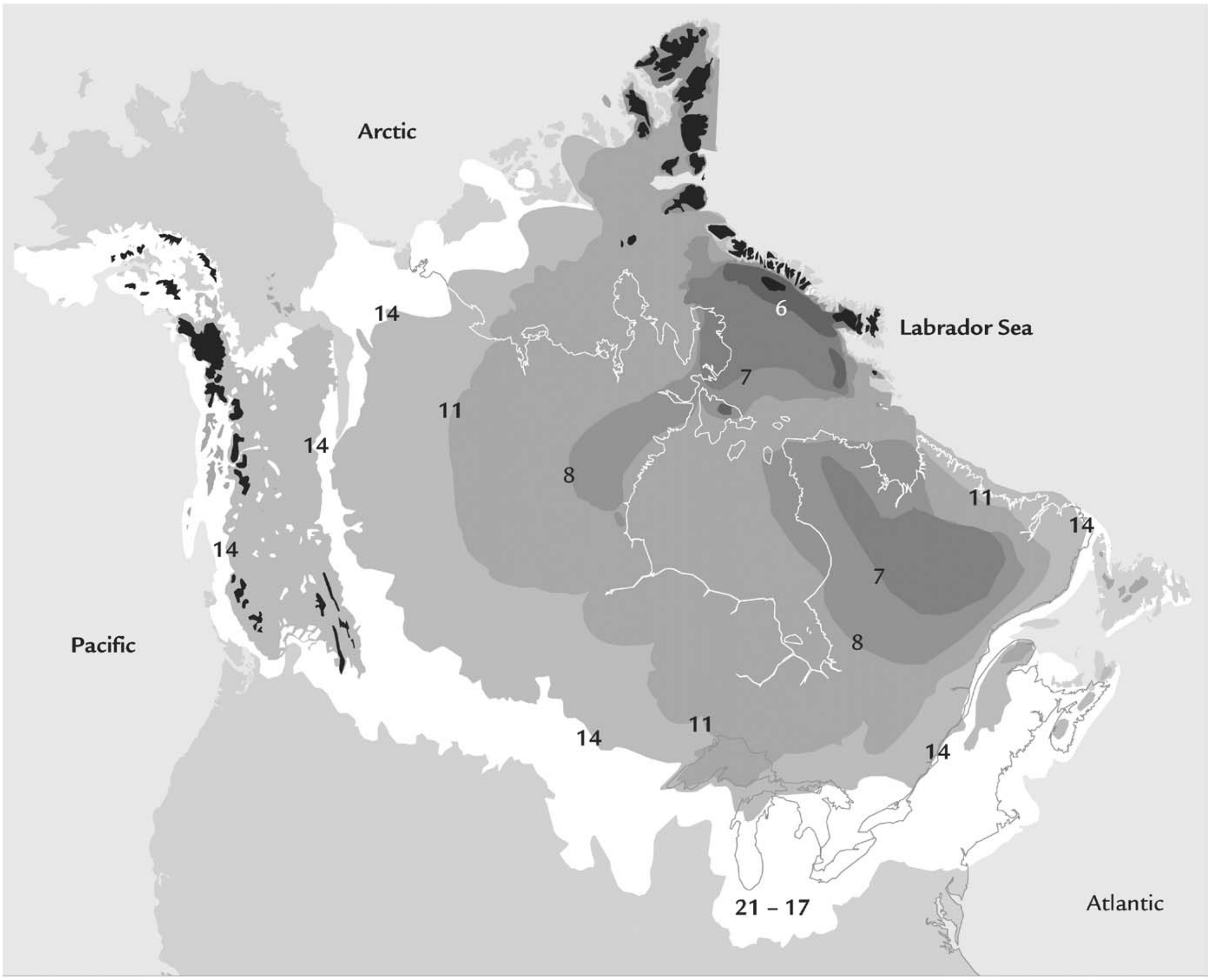

Fig. 6. Retreat positions of North American ice sheets during the most recent deglaciation, in thousands of ^{14}C years ago (Dyke and Prest, 1987).

Dynamical ocean processes may also provide positive feedback through changes in wind-driven and thermohaline circulations. Both observational evidence and model simulations indicate that cooling of the Nordic Seas and weakening of the thermohaline circulation were factors in the glacial inception near 115,000 years ago (Cortijo et al., 1994; Khodri et al., 2001; Yoshimori et al. 2002). In addition, a simulation for 6000 years ago using a model with both interactive vegetation and interactive ocean/sea-ice showed considerably enhanced climate sensitivity to orbital forcing compared to simulations with only one of these two components (Ganopolski et al., 1998).

Finally, our 'snapshot' experiment only indicates regions where overall mass-balance conditions would permit ice growth, but it does not address how growing ice sheets might have evolved through time. Growing ice sheets have positive feedback effects on local climate, including the elevation/temperature feedback from vertical ice growth, and the albedo feedback from gradually expanding snowfields and lateral ice flow (Andrews and Mahaffy, 1976). Future simulations that incorporate ice, vegetation, and ocean feedbacks, now underway and planned, are likely to enhance the climatic responses to removal of anthropogenic greenhouse gases and enable ice sheets to expand beyond their regions of inception.

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