Simulated influences of Lake Agassiz on the climate of central North America 11,000 years ago

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Eleven thousand years ago, large lakes existed in central and eastern North America along the margin of the Laurentide Ice Sheet. The large-scale North American climate at this time has been simulated with atmospheric general circulation models, but these relatively coarse global models do not resolve potentially important features of the mesoscale circulation that arise from interactions among the atmosphere, ice sheet, and proglacial lakes. Here we present simulations of the climate of central and eastern North America 11,000 years ago with a high-resolution, regional climate model nested within a general circulation model. The simulated climate is in general agreement with that inferred from palaeoclimatological evidence. Our experiments indicate that through mesoscale atmospheric feedbacks, the annual delivery of moisture to the Laurentide Ice Sheet was diminished at times of a large, cold Lake Agassiz relative to periods of lower lake stands. The resulting changes in the mass balance of the ice sheet may have contributed to fluctuations of the ice margin, thus affecting the routing of fresh water to the North Atlantic Ocean. A retreating ice margin during periods of high lake level may have opened an outlet for discharge of Lake Agassiz into the North Atlantic. A subsequent advance of the ice margin due to greater moisture delivery associated with a low lake level could have dammed the outlet, thereby reducing discharge to the North Atlantic. These variations may have been decisive in causing the Younger Dryas cold event.

We used the GENESIS v2.01 atmosphere general circulation model (AGCM) to simulate the global climate of 11 kyr BP (11,000 years before present). The simulations were run at a nominal atmospheric resolution of 3.75° by 3.75° (latitude by longitude) with 18 vertical layers and an interactive, land–surface physics package. Specified boundary conditions for the AGCM included 11-kyr BP values for eccentricity, obliquity and precession; an atmospheric CO₂ concentration of 270 parts per million by volume, p.p.m.v.; Dorman-Sellers global vegetation; and reconstructions of continental ice sheets 11 kyr ago. Global sea surface temperatures (SSTs) and sea ice were computed by GENESIS using a 50-m mixed-layer ocean model. The GENESIS simulation was initialized from an existing 11-kyr BP simulation and run continuously for 20 years to ensure that the simulated climate and SSTs were in equilibrium. The last five years of the GENESIS simulations were used to derive initial and continuous 12-hour (diurnal) lateral boundary conditions (vertical profiles of temperature, humidity, wind and pressure) for the regional model.

The global climate simulation is similar to others for the period around 11 kyr BP (refs 1, 2) which typically display the waning of the continental ice sheets and rising insolation on Northern Hemisphere atmospheric circulation (Fig. 1). Over the continental interior of North America, the features of the simulated 11-kyr BP climate include: greater summer warming in regions farther from the ice sheet (which occurs in response to the interaction between the large expansion of ice sheet and greater-than-present summer insolation), colder-than-present winter temperatures (which occurs in response to the negative winter insolation anomaly), and precipitation patterns that reflect the reorganization of atmospheric circulation by the ice sheet and insolation. In the AGCM, however, finer-scale topographic detail and surface–atmosphere feedbacks that may be important to climate at regional scales are not resolved.

To resolve these regional-scale feedbacks and processes, we applied the NCAR RegCM2 regional climate model. Our palaeoclimatic version of the RegCM2 has an interactive land-surface physics package (the biosphere-atmosphere transfer scheme, BATS) and includes an interactive, one-dimensional (vertical) lake model. A domain size of 3,375 km × 3,825 km, a horizontal grid spacing of 45 km × 45 km (yielding ~80 RegCM2 grid points for each GENESIS grid box) and 17 vertical levels, extending from ~40 m above the ground to the upper troposphere, were used in the model. A total of 249 lake grid points were prescribed: 185 represent Lake Agassiz (ranging in depth from 10 to 200 m, ref. 14), and the remainder represent other large lakes (all depths set to 25 m). As in the GENESIS simulation, we specified orbital parameters and CO₂ concentration at 11 kyr BP, and a higher-resolution version of the reconstructed Laurentide Ice Sheet (LIS) was used in the RegCM2.

We constrained the simulated temperatures of the grid points representing Lake Agassiz to be ±5°C based on several lines of evidence. During the time of our simulation, the ostracod Candonia
Surface elevation and simulated climate fields over North America at 11 kyr BP.

**Figure 1**

The nominal resolution of the GENESIS atmosphere model, shown as the coarse continental outline and large grid boxes, is 3.75° by 3.75° (400 km by 400 km) latitude by longitude. The resolution of the RegCM2 model used in this study (inset box) is 45 km by 45 km, which yields ~80 grid cells for each AGCM grid cell. The AGCM-derived boundary conditions are assimilated into the RegCM2 every 12 h over an additional 8 grid-point strip, roughly the distance of one AGCM grid cell, along the entire boundary of the model. The figure illustrates that the patterns simulated by the RegCM2 are not simple interpolations of the patterns in the AGCM, but instead reflect the variations of topography and surface characteristics on the higher-resolution grid of the model.
interior of the ice sheet (Fig. 3). Annual precipitation (Fig. 2) is reduced by >120 mm (~30%) over portions of the ice sheet and the Superior Lobe, whereas July precipitation (not shown) is reduced by >50 mm (~90%) around the lake and by 40 mm (~50%) over the ice margin and into the interior. [We note that precipitation is enhanced somewhat by atmospheric heating and elevated moisture levels before the lake freezes in late autumn (November in Fig. 3) but this is offset by drying during the rest of the year.] This generally negative precipitation feedback opposes previous hypotheses27,29, and contrasts with simulations of the US Great Basin in which lake–atmosphere feedbacks enhanced precipitation during the Last Glacial Maximum31.

Heat in excess of that required to maintain the lake at a temperature of 5°C (derived mainly from solar heating at the lake surface) would probably have been consumed in warming cold meltwater from the LIS and in melting icebergs and shelf ice. The heat required to raise the estimated inflow of 0.02 Sv of melt water (ref. 18) from 0°C to 5°C is ~10^{14} MJ. Accounting for heat needed to warm the melt water, at an ice temperature of ~5°C enough excess heat is available from the constrained temperatures (~10^{14} MJ) to melt ~2,500 km^3 of ice annually, suggesting that the internal heating of the lake would have contributed to significant ablation of the ice in contact with the lake.

Our results suggest a mechanism for linking the atmosphere–lake–ice system to the retreat and advance of the Superior Lobe, which, in turn, played an important role during the last deglaciation in damming eastward-draining outlets of Lake Agassiz, and thus in controlling the routing of a substantial fraction of continental runoff to the North Atlantic3,4,18. During the large (Lockhart) phase of Lake Agassiz, (which pre-dates eastward drainage to the St Lawrence before 13 kyr BP), the lake would have suppressed precipitation and contributed to retreat of the ice margin in contact with lake water, reinforcing deglaciation. At ~13 kyr BP, the Superior Lobe had receded far enough to allow the lake to drain eastward to the St Lawrence River, supplying ~0.05 Sv of additional fresh water to the North Atlantic16 which triggered the Younger Dryas cold interval3,4. With the lake diminished in size, moisture delivery to the ice margin would have increased, supporting the hypothesis that the Marquette ice advance into the Superior basin was related to changes in mass balance rather than to surging or ice streaming30.

The resulting damming of the eastern outlets would have ended the Younger Dryas cold reversal3,4 and allowed the lake to expand to its maximum size (Emerson phase) simulated here.

Our results depend on using the geological record as guidance in limiting the maximum surface temperature of Lake Agassiz, and on the driving boundary conditions derived from GENESIS. In climate simulations, as in nature, the climate of a 5-year period may vary from that of other 5-year periods. The climate forcing arising with the interplay of the LIS and insolation is robust in controlling both the simulated large-scale (AGCM) and regional-scale (RegCM2) circulations. Taken together with the strong thermal forcing of the lake in RegCM2, our results would probably be reproducible for any different period of our GENESIS simulation, even if the actual temperature of the lake was several degrees warmer than suggested.
by the ostracod data. The ability to simulate finer-scale climate processes in complex palaeoenvironmental settings offers the opportunity to test climate hypotheses at the landscape scale; it also suggests that a nested modelling approach will be useful in investigating a wide range of surface–atmosphere feedbacks associated with regional climates of the past, present and future.

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