Importance of freshwater injections into the Arctic Ocean in triggering the Younger Dryas cooling

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The cause of past climate change has been the focus of many studies in recent years. Various explanations have been advanced to explain the record of Quaternary climate change identified in sediments on continents, in oceans, and in the ice caps of Greenland and Antarctica. Important in this is the scale of change—both temporal and spatial—and our best records, especially in terms of chronological resolution, come from the past several hundred thousand years. A number of climate fluctuations, some of them abrupt and some of them short, have been linked to changes in the flux of freshwater to the oceans that, if large enough, might have impacted on ocean circulation and, in turn, have resulted in a change in climate. Broecker et al. (1) were among the first to propose that an injection of freshwater from North America was responsible for the anomalous Younger Dryas (YD) cooling, ~12.9 to 11.5 ka, known from Europe and other circum-Atlantic continental regions. In their hypothesis, an outburst of water from glacial Lake Agassiz (once the largest lake in the world) eastward through the Great Lakes and St. Lawrence Valley to the North Atlantic, which coincided in time with the YD, was identified as the mechanism for slowing thermohaline circulation (THC) and, in turn, for triggering the YD cooling. Subsequent field research led others to conclude that changes in overflow routing from this giant lake were responsible for the Preboreal oscillation and 8.2-ka event (2–5). Coupled ocean/atmosphere modeling seemed to confirm these interpretations (6–9), although the coarse nature of the models, which injected freshwater uniformly over large areas, was recognized as a limitation. In PNAS, Condron and Winsor (10) present a high-resolution model that brings important insight into the role of freshwater injections into the North Atlantic during the YD.

Since the initial description of the hypothesis that freshwater outbursts from Lake Agassiz triggered a change in THC and the YD cooling (1), research on the late-glacial melting of the Laurentide Ice Sheet (LIS) and routing of its meltwater to the oceans during the YD (including that stored in and released from Lake Agassiz) has raised some questions. First, was the routing of Lake Agassiz overflow—and that of much of the western interior of North America—really east through the Great Lakes/St. Lawrence during the YD (11–13)? Second, was the contribution from Lake Agassiz overflow enough to trigger a change in THC and sustain it for >1,000 y (3, 14, 15)? Third, was an increasing outflow of meltwater from the melting LIS itself—rather than an abrupt injection of rerouted overflow from a large proglacial lake—enough to bring about a large change in ocean circulation, perhaps after crossing some threshold, at the specific times known from records in Greenland ice cores and stratigraphic sequences in North America, Europe, and elsewhere (16)?

Fig. 1. Boulder concentration in gravel pit in the Athabasca River Valley that connects the Lake Agassiz and Mackenzie River basins, near Fort McMurray, AB, Canada, attributed to overflow from Lake Agassiz during the YD by Teller et al. (12) and Murton et al. (18).

Condron and Winsor (10) incorporate these questions into their research by using a high-resolution (1/6°, 18 km) global coupled ocean sea-ice circulation model to assess the impact of a large (5 Sv), abrupt, 1-y injection of freshwater from North America through two different routes, namely (*i*) to the North Atlantic Ocean through the St. Lawrence Valley and (*ii*) to the Arctic Ocean through the Mackenzie River in northern Canada. The authors state that "this model captures the circulation of the ocean and sea ice at 10 to 15 times higher resolution than previous models attempting to understand how meltwater acts to trigger the YD" (10). The goal of Condron and Winsor (10) is to understand the influence of geographically different discharge locations on deep convection in the ocean and on the strength of Atlantic Meridional Overturning Circulation (AMOC), which is similar to THC. The authors assume that the LIS was the main source of the freshwater, and use a flux greater than that known to have been released during the YD from Lake Agassiz to perturb the ocean. They choose a "modern-day" ocean, rather than make assumptions about what ocean conditions were like during late-glacial time or "pre-condition" THC by other meltwater additions, as Fanning and Weaver (8) and others suggested might make the ocean more sensitive. In fact, preconditioning may have allowed a flux smaller than the 5 Sv used by Condron and Winsor (10) to perturb AMOC and cause the YD cooling.

In the Condron and Winsor (10) model, the Mackenzie River route (see Fig. 1) has two scenarios for the interconnectivity of the Arctic Ocean to the North Atlantic Ocean: (*i*) Mackenzie River open to the Labrador Sea and (*ii*) Mackenzie River closed to the Labrador Sea but open to the North Atlantic north of Greenland to the Fram Strait (Greenland–Iceland–Norwegian Sea). As noted by Condron and Winsor (10), the eastward routing of runoff from Lake Agassiz and its drainage basin has been questioned (11–13, 17, 18), and recent

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evidence from sediment in the Arctic Ocean basin (19, 20), as well as modeling of the impact of freshwater discharge to the Arctic Ocean from the LIS (16) have strengthened arguments for a northwest route to the Arctic Ocean. Modeling of the impact of freshwater additions to the Arctic Ocean, however, has been limited and at coarse scales (17, 21). The three geographic routings modeled by Condron and Winsor (10) led them to conclude that "only meltwater released from the Mackenzie Valley creates a classic 'freshwater cap' that inhibits open ocean deep convection. The water column of the central Labrador and Greenland Seas is unaltered by meltwater discharge from the St. Lawrence Valley" (10) because, when 5 Sv of meltwater was injected into the North Atlantic at the mouth of the St. Lawrence River, it turned south along the coast, as outflow does today, rather than move offshore into the convection region. In contrast, routing of a 1-y slug of water into the Arctic Ocean and then to the North Atlantic via the Greenland–Iceland–Norwegian Sea "provides a mechanism unique to the Arctic that is capable of turning a short-duration (∼1 y), high-magnitude meltwater discharge event into a significantly larger. . . meltwater event" (10) that reduces ocean deep convectionby 32% (vs. 9% if the slug of water arrives via the St. Lawrence Valley) and the northward transport of heat by 29%.

This research adds important insight into the routing of much of North America's runoff during the YD.

Although the fluxes chosen by Condron and Winsor (10) may be argued, and they could have added a range of lower fluxes so that smaller water sources than the melting LIS might be considered as triggers for changes in THC (e.g., Lake Agassiz and other ice-marginal lakes), this research adds important insight into the routing of much of North America's runoff during the YD. Because continental and ocean records have been used to argue for both an eastern and a northwestern routing of meltwater from North America and the 2-million-km^2 Lake Agassiz drainage basin, the Condron and Winsor high-resolution modeling (10) is an especially valuable addition in terms of resolving the question, and illustrates the importance of fine-scale modeling whereby freshwater is injected at specific points in the ocean rather than being spread out over large regions. As well, it provides support for the hypothesis that freshwater triggered the YD cooling.

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