What Caused the Younger Dryas Cold Event?

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The Younger Dryas Cold Event (ca. 12.9–11.6 ka) has long been viewed as the canonical abrupt climate event (Fig. 1). The North Atlantic region cooled during this interval with a weakening of Northern Hemisphere monsoon strength. The reduction in northward heat transport warmed the Southern Hemisphere due to a process commonly referred to as the bipolar-seesaw (e.g., Clark et al., 2002). Although it is generally accepted that the cold event resulted from a slowing Atlantic meridional overturning circulation (AMOC), the forcing of this AMOC reduction remains intensely debated.

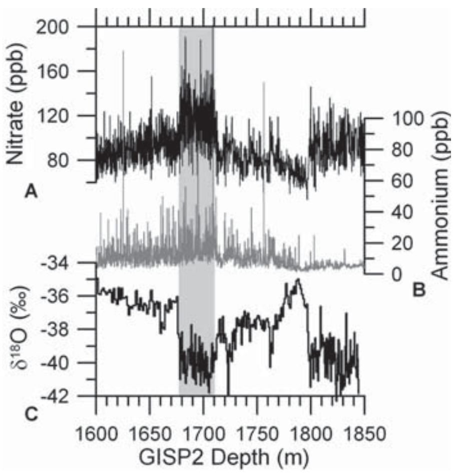

Figure 1. Nitrate (A), ammonium (B), and $\delta^{18}O$ (C) records from Greenland Ice Sheet Project 2 (GISP2) (Grootes et al., 1993; Mayewski et al., 1997). Gray bar denotes the Younger Dryas Cold Event.

The most common means of slowing AMOC involves the reduction of oceanic surface water density via an increase in freshwater discharge to the North Atlantic. The originally hypothesized source of freshwater was the eastward routing of Glacial Lake Agassiz from the Mississippi River to the St. Lawrence River, as the Laurentide Ice Sheet retreated northward out of the Great Lakes (Johnson and McClure, 1976; Rooth, 1982; Broecker, 2006). A clear Younger Dryas freshwater signal in the St. Lawrence Estuary (Keigwin and Jones, 1995; deVernal et al., 1996) only becomes apparent after accounting for other competing effects on commonly used freshwater proxies, in agreement with three other independent runoff proxies (Carlson et al., 2007). Lake Agassiz's eastern outlet history also presents an issue, as the most recent study suggested that the outlet remained closed until well after the start of the Younger Dryas, with the lake having no outlet for much of the Younger Dryas (Lowell et al., 2009). In contrast, a simple consideration of Lake Agassiz's water budget requires an outlet for the lake during the Younger Dryas (Carlson et al., 2009). This ongoing debate over the ultimate cause of the Younger Dryas has led to a search for other potential forcing mechanisms, such as an abrupt discharge of meltwater to the Arctic Ocean (Tarasov and Peltier, 2005) and a bolide impact (Firestone et al., 2007).

On page 355 of this issue of *Geology*, Melott et al. (2010) present a quantitative assessment of the effect a comet would have on atmospheric nitrate, as well as estimates of its consequence for atmospheric ammonium, providing a test for the occurrence of a bolide at the onset of the Younger Dryas. Accordingly, comets break down N_2 in the atmosphere to nitrate (NO_x), increasing nitrate concentration. The authors use a two-dimensional atmospheric model to simulate the nitrate and ozone changes associated with the A.D. 1908 Tunguska event where a bolide airburst occurred over Siberia, Russia. The model performs well for the Tunguska event, accurately simulating the nitrate increase of ~160 ppb observed in the Greenland Ice Sheet Project 2 (GISP2) ice core record from Summit Greenland. Scaling the predicted nitrate changes upward by six orders of magnitude to the suggested Younger Dryas–size bolide implies a very large increase in nitrate concentration (i.e., 10^6 times larger than the Tunguska increase) that should be recorded in Greenland ice at the start of the Younger Dryas (Fig. 1A).

Greenland ice cores also show ammonium (NH_4^+) increases during the Tunguska event and the Younger Dryas (Fig. 1B). While biomass burning is implicated for the Younger Dryas increase (e.g., Firestone et al., 2007), the amount of burning during the Tunguska event is too small to account for the ammonium increase of >200 ppb (Melott et al., 2010). Another alternative, involving direct ammonium deposition from the bolide, still fails to account for the observed Tunguska increase. The authors thus suggest a third mechanism called the Haber process that could account for both the Younger Dryas and Tunguska increases, in which, under high pressure, nitrogen and hydrogen can form ammonia. For the Tunguska increase, a potential impact with permafrost could provide the hydrogen, whereas the Laurentide Ice Sheet itself might be the hydrogen source for the Younger Dryas impact.

The Melott et al. study thus lays out a test for the occurrence of a Younger Dryas bolide impact, constrained by observations of the recent Tunguska impact. Their estimates, however, for the increases in nitrate and ammonium associated with a Younger Dryas–size comet are orders of magnitude larger than observed in the Summit Greenland ice core records; the Younger Dryas nitrate and ammonium increases are at most just half of the Tunguska increase. Likewise, the anomalies noted at the start of the Younger Dryas appear to be non-unique in the highest-resolution records (Figs. 1A and 1B). This may be due to the ice core sample resolution. The GISP2 ~3.5 yr sample resolution could potentially under-sample a nitrate or ammonium increase (Mayewski et al., 1997) because both compounds have atmospheric residence times of a few years. As Melott et al. note, higher-resolution sampling from the Greenland ice cores could determine if large (i.e., orders of magnitude larger than the Tunguska event) increases in nitrate and ammonium occurred at the start of the Younger Dryas.

Several other issues still remain with the bolide-forcing hypothesis for the Younger Dryas. For instance, the original Firestone et al. (2007) impact-marker records have not proven reproducible in a subsequent study (Surovell et al., 2009). Similarly, a compilation of charcoal records do not indicate large-scale burning of ice-free North America at the onset of the Younger Dryas (Marlon et al., 2009) as put forward by Firestone et al. (2007). Another recent study showed that late Pleistocene megafauna extinctions, potentially attributable to a Younger Dryas impact (Firestone et al., 2007), significantly preceded the Younger Dryas (Gill et al., 2009). Furthermore, it has yet to be demonstrated how a short-lived event, such as a bolide impact (or abrupt Arctic meltwater discharge, i.e., Tarasov and Peltier, 2005), can force a millennia-long cold event when state-of-the-art climate models require a continuous freshwater forcing for the duration of the AMOC reduction (e.g., Liu et al., 2009). If the bolide impacted the southern Laurentide margin near the Great

Lakes, it could have opened the eastern outlet of Lake Agassiz, but Great Lake till sequences are not disturbed (e.g., Mickelson et al., 1983).

Ultimately, the bolide-forcing hypothesis predicts that the Younger Dryas is a unique deglacial event, as suggested by Broecker (2006). However, high-resolution proxy records sensitive to AMOC strength (Chinese speleothem $\delta^{18}O$ and atmospheric methane) document a Younger Dryas–like event during termination III (the third to the last deglaciation) (Figs. 2B and 2C; Carlson, 2008; Cheng et al., 2009). The boreal summer insolation increase during termination III is similar to the last deglaciation, as is the timing of the event relative to the peak in insolation (Fig. 2D). While not as well constrained, both events occurred at approximately the same sea level (Fig. 2A), suggesting there may be a common forcing related to the size of the Laurentide Ice Sheet (Carlson, 2008). During terminations II and IV (Fig. 2), greater increases in boreal summer insolation driving faster ice retreat and attendant continuous reduction in AMOC strength can explain the lack of Younger Dryas–like events in these cases (e.g., Ruddiman et al., 1980; Carlson, 2008). Alternatively, a bolide could have forced the termination III event as well. The direct (if there was a bolide, then there will be a very large nitrate spike) approach presented by Melott et al. is testable through sub-annual sampling of the Greenland ice cores, providing a step forward in resolving the forcing of the Younger Dryas and our understanding of abrupt climate events.

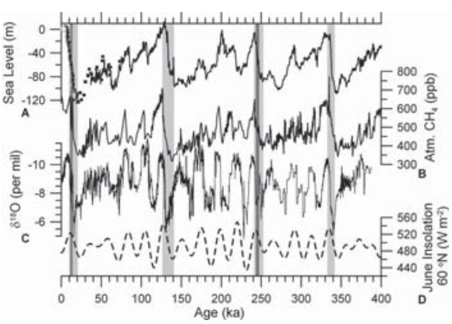

Figure 2. A: Sea level (symbols from Clark et al., 2009; line from Rohling et al., 2009). B: Atmospheric methane (CH_4) (Petit et al., 1999). C: Chinese speleothem $\delta^{18}O$ records of East Asian Monsoon (Cheng et al., 2009, and references therein). D: Boreal summer insolation (Berger and Loutre, 1991). Light gray bars denote deglaciations (terminations), while the two dark gray bars denote the Younger Dryas and the Younger Dryas–like event during termination III (i.e., decreased atmospheric methane and East Asian Monsoon (higher $\delta^{18}O$).

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