Younger Dryas cooling and the Greenland climate response to CO_2

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Greenland ice-core δ^{18}O-temperature reconstructions suggest a dramatic cooling during the Younger Dryas (YD; 12.9–11.7 ka), with temperatures being as cold as the earlier Oldest Dryas (OD; 18.0–14.6 ka) despite an approximately 50 ppm rise in atmospheric CO_2. Such YD cooling implies a muted Greenland climate response to atmospheric CO_2, contrary to physical predictions of an enhanced high-latitude response to future increases in CO_2. Here we show that North Atlantic sea surface temperature reconstructions as well as transient climate model simulations suggest that the YD over Greenland should be substantially warmer than the OD by approximately 5 °C in response to increased atmospheric CO_2. Additional experiments with an isotope-enabled model suggest that the apparent YD temperature reconstruction derived from the ice-core δ^{18}O record is likely an artifact of an altered temperature-δ^{18}O relationship due to changing deglacial atmospheric circulation. Our results thus suggest that Greenland climate was warmer during the YD relative to the OD in response to rising atmospheric CO_2, consistent with sea surface temperature reconstructions and physical predictions, and has a sensitivity approximately twice that found in climate models for current climate due to an enhanced albedo feedback during the last deglaciation.

oxygen isotope | arctic climate | global warming

Greenland ice cores provide key records of gradual and abrupt climate changes in the high-northern latitudes, with the Younger Dryas (YD) being the most recent abrupt cold event of the last glaciation. Based on ice-core δ^{18}O temperature reconstructions derived from borehole temperature calibrations (1, 2), the YD was at least as cold as the earlier Oldest Dryas (OD) cold event over Greenland (Figs. 1*D* and 2*A*). The apparent similarity in temperature during these two cold events is surprising, given that atmospheric CO_2 increased by approximately 50 ppm between the two events (3) (Fig. 1*A*) and that the reduction in Atlantic meridional overturning circulation (AMOC) during the YD was no greater than the OD, and likely less (4, 5) (Fig. 1*C*). A YD as cold as the OD thus implies an apparent conundrum: Greenland climate has a muted response to increased atmospheric CO_2, contrary to the enhanced impact of anthropogenic greenhouse gases on high-latitude climate predicted by all state-of-art climate models (6).

Here we propose that Greenland climate during the YD should be substantially warmer than the OD. Our hypothesis is motivated by the basic physical principle that an increase in atmospheric CO_2 should lead to an increase in surface temperature, especially at high latitudes because of polar amplification (6). Our hypothesis is further supported by North Atlantic sea surface temperature (SST) records that provide an independent estimate of the temperature changes near Greenland, and indicate that the YD was warmer than the OD (Figs. 1*E* and 2*B*). We use a state-of-the-art climate model to evaluate additional controls on the ice-core δ^{18}O record that may have obscured the temperature signal.

Analysis

In Fig. 2*B* we show four SST proxy records from the North Atlantic and their leading principal component (7–10). Although these SSTs are based on two different proxies [alkenones (7, 9) versus *Globigerina bulloides* Mg/Ca (8, 10)], they are consistent in recording a YD that is warmer than the OD. In contrast, all Greenland ice-core δ^{18}O records except for one (Northern Greenland Ice core Project) (Fig. 2*A*) and their leading principal component suggest a YD that is colder than or equivalent to the OD when a constant δ^{18}O-temperature relationship is applied (1, 3, 11).

Model

We use a transient deglacial experiment with the National Center for Atmospheric Research (NCAR) Community Climate System Model 3 (CCSM3) climate model forced by realistic insolation, atmospheric CO_2, continental ice sheets, and meltwater discharge (12) (Fig. 1, red line; *Methods 1*) to test our hypothesis that the YD was warmer than the OD. The model replicates Northern Hemisphere cooling from the Last Glacial Maximum (LGM, approximately 21 ka) into the OD, abrupt warming into the Bølling–Allerød (BA) warm periods (14.6–12.9 ka), the cooling into the YD, and the subsequent recovery to the warm climate into the Holocene, mainly in response to the rising CO_2 and meltwater forcing of the AMOC (Fig. 1 *B–E*). Overall, our transient simulation reproduces many major features of the deglacial surface temperature evolution consistent with the reconstruction from various proxy records over the globe (12–15). One notable feature in both the reconstructions and simulations is that globally, the YD interval is warmer than the OD interval (13–15), which is also reflected in the North Atlantic region (Fig. 1*E*). The agreement between model simulations and observations is best demonstrated between the leading principal component of the SST reconstructions and their corresponding model-simulated SST principal component (Fig. 2*B*). The consistency between simulated and reconstructed SSTs provides confidence in the model's ability to simulate global and regional temperature responses, particularly around the North Atlantic region.

Over Greenland, the model simulates a cooling during the OD followed by an abrupt BA warming (Fig. 1*D*) in response to melt-

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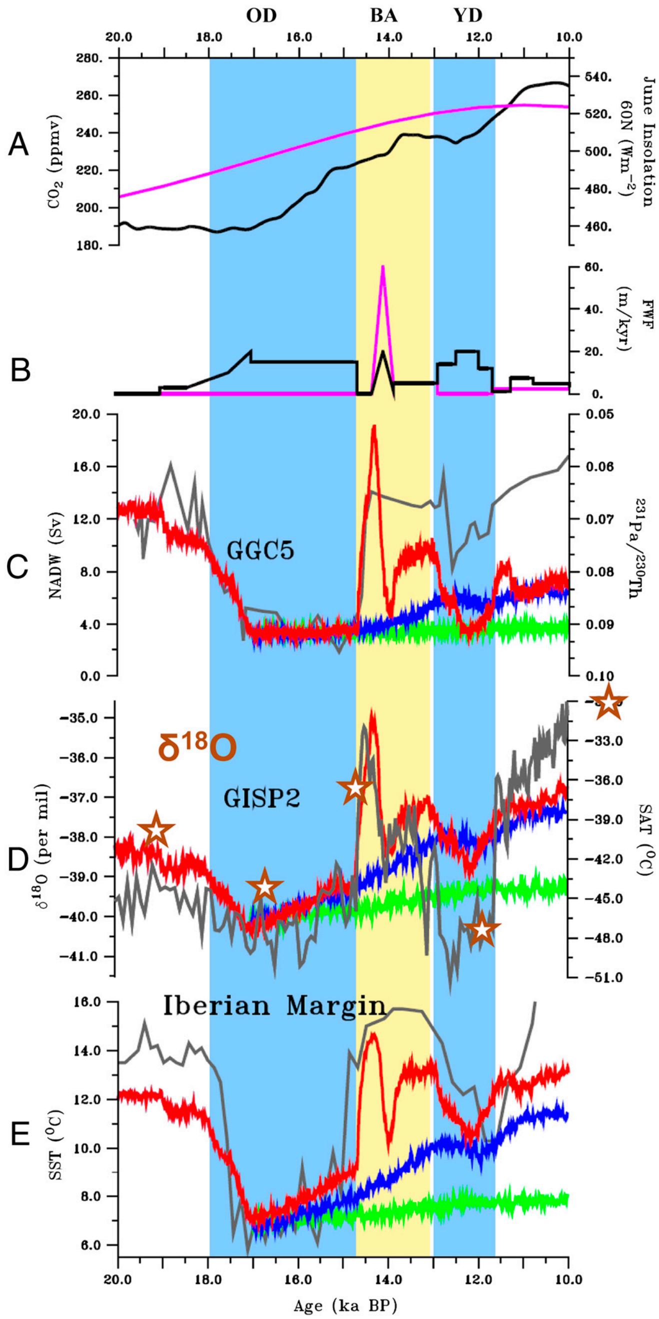

Fig. 1. Model forcings: (*A*) 60 °N June insolation (purple) (31) and atmospheric CO_2 concentration (black) (3); (*B*) meltwater fluxes into the North Atlantic (black) and Southern Ocean (purple). (*C*) AMOC for the model (red) and reconstructed (gray) (4). (*D*) Greenland Ice Sheet Project 2 (GISP2) $\delta^{18}O$ and surface temperature reconstruction (gray) (1) and model (red; model offset by −3 °C), and isoCAM3 precipitation $\delta^{18}O_p$ (stars) [PI plotted at approximately 10 ka (*Methods 2*)]. (*E*) Iberian Margin SST (gray) (7) (Fig. 2) and model (red). The CO_2 (blue) and orbital forcing (green) sensitivity experiments are also shown. All model variables are decadal means.

water-driven changes in the AMOC (Fig. 1 *B* and *C*). When forced by North Atlantic meltwater discharge at 12.9 ka, the model simulates >7 °C of YD cooling relative to the Holocene. Despite similar reductions in AMOC, however, the YD is approximately 5 °C warmer than the OD. A CO_2-alone sensitivity experiment indicates that approximately 70% of this warming is caused by the approximately 50 ppm increase in atmospheric CO_2 (Fig. 1, blue line, *Methods 1*). The remaining excess warmth relative to the OD is explained by increased boreal summer insolation and a nonlinear rectification associated with the sea-ice albedo feedback, demonstrated by an insolation-alone sensitivity experiment (Fig. 1, green line, *Methods 1*). The model Greenland temperature is therefore consistent with our basic physical understanding but inconsistent with the $\delta^{18}O$-borehole temperature reconstructions (1, 2).

We suggest that the origin of the Greenland $\delta^{18}O$-temperature data-model inconsistency lies in the Greenland $\delta^{18}O$-borehole temperature calibration. Indeed, this $\delta^{18}O$-borehole temperature calibration was developed originally for gradual glacial-interglacial changes rather than abrupt climate change (1, 16), and therefore the borehole temperature calibration cannot constrain such an abrupt event like the YD. Temperatures derived from Greenland ice-core gas measurements suggest a YD climate that was approximately 15 °C colder than present and that temperature warmed by 10 ± 4 °C at the end of the YD (17), which overlaps with the model simulated warming at the lower bound (approximately 6 °C) and the $\delta^{18}O$-temperature estimate at the upper bound (approximately 14 °C). These independent temperature estimates from gas measurements, however, relate to the abrupt warming at the end of the YD and temperature relative to present, instead of the degree of cooling into the YD and YD temperature relative to the OD.

In an attempt to better understand the relationship between Greenland temperature and ice-core $\delta^{18}O$ during the last deglaciation, we performed experiments with an isotope-enabled atmospheric model forced by the SSTs from the transient simulation at the LGM, OD, BA, YD, and preindustrial (PI) (*Methods 2*). The simulated Greenland precipitation $\delta^{18}O_p$ is consistent with the ice-core records and shows a decrease from the LGM to the OD, an increase during the BA, a decrease during the YD, and another increase into the Holocene (Fig. 1*D*, stars). In particular, the YD $\delta^{18}O_p$ is slightly lower than the OD despite an approximately 5 °C mean annual warming (*SI Text*). The spatial distribution of the change in mean annual surface air temperature and $\delta^{18}O_p$ between the YD and OD generally shows a positive correlation at high latitudes, with warmer temperatures corresponding to increased $\delta^{18}O$ (Fig. 3*A* and *B*), as suggested originally by Dansgaard (11). The region near Greenland, however, is an exception because surface warming corresponds to decreased $\delta^{18}O_p$. The lower $\delta^{18}O_p$ over Greenland during the YD relative to the OD is likely caused by increased delivery of moisture sourced from the North Pacific (18, 19). The lowering of the Laurentide Ice Sheet by up to 2 km between the OD and YD (20) induced a northward migration of the storm track over the North Atlantic region (21), with an intensified low-level westerly jet (Fig. 3 *C* and *D*) that increased moisture delivery to Greenland from the North Pacific and North America. This remote moisture delivery depleted precipitation $\delta^{18}O$ relative to a North Atlantic source, overwhelming the warmer YD and causing to the lower $\delta^{18}O$ over Greenland during the YD relative to the OD.

The large $\delta^{18}O$ and inferred temperature decrease during the YD of similar magnitude to the OD could also have arisen from extreme seasonality, with winter cooling of approximately 24 °C and summer cooling of approximately 6 °C from the present (2). The model simulation, however, produces similar increases in seasonality during both the YD and OD (*SI Text*), indicating that the comparable $\delta^{18}O$ minima during both events attributed to the seasonality hypothesis are not supported by this climate model.

Conclusions

Our study suggests that rising deglacial CO_2 had a significant impact on Greenland temperature during the YD despite a decrease in the AMOC. About 70% of the approximately 5 °C of warming between the YD and OD is caused by the concurrent approximately 50 ppm increase in atmospheric CO_2 (Fig. 1*D*). This temperature-CO_2 relationship implies a glacial climate sensitivity of approximately 10 °C over Greenland for a doubling of

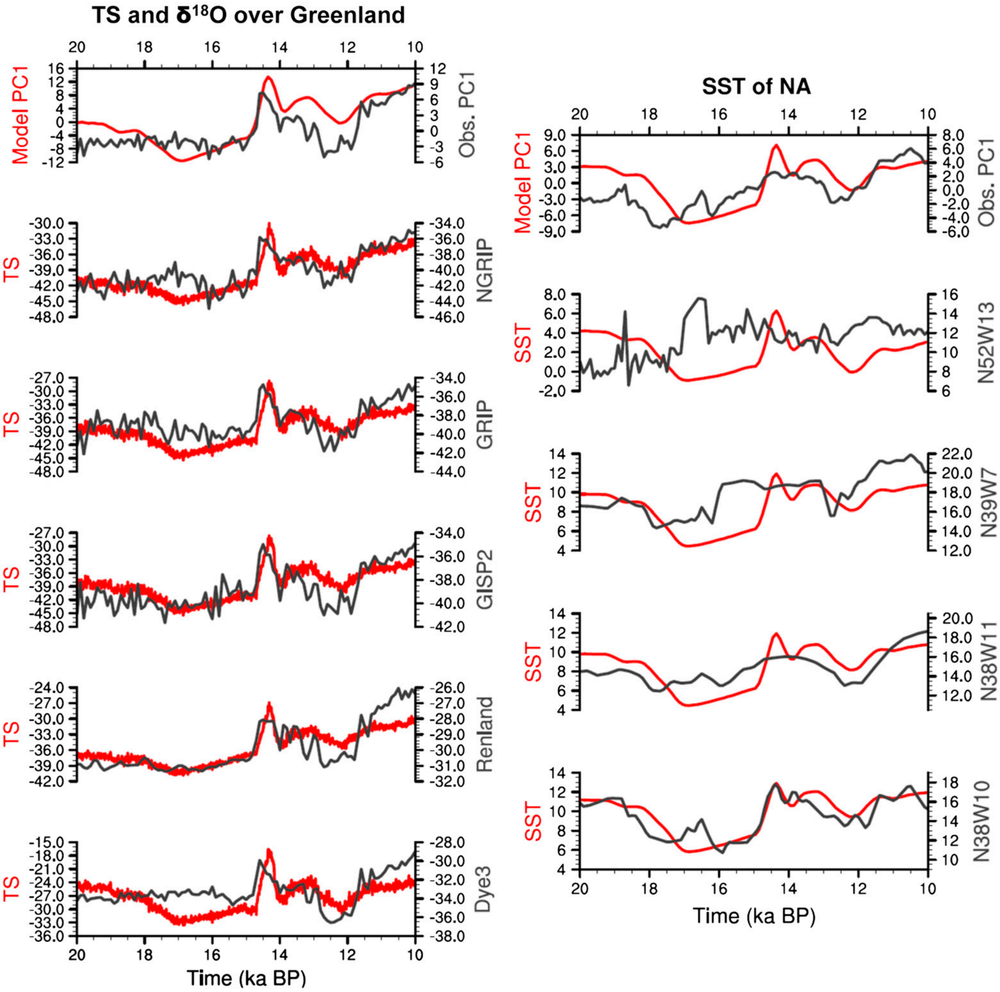

Fig. 2. (*A*) Greenland ice core $\delta^{18}O$ records (black) and the corresponding decadal mean model annual temperatures (red). (*B*) Four SSTs in the northern North Atlantic from the proxy (black) and model (red). The time coefficients of the Empirical Orthogonal Function mode 1 (EOF1) for the proxy (black) and model (red) are also plotted on the top in each panel. It is seen that the GISP2 record is typical of the Greenland ice cores, and its evolution is almost identical to that of the EOF1 coefficient. The northern North Atlantic SSTs and their EOF are also largely consistent in the proxy and the model, both exhibiting a warmer YD than OD. N52W12(8), N39W7(9), N38W11(7), N38W10(10).

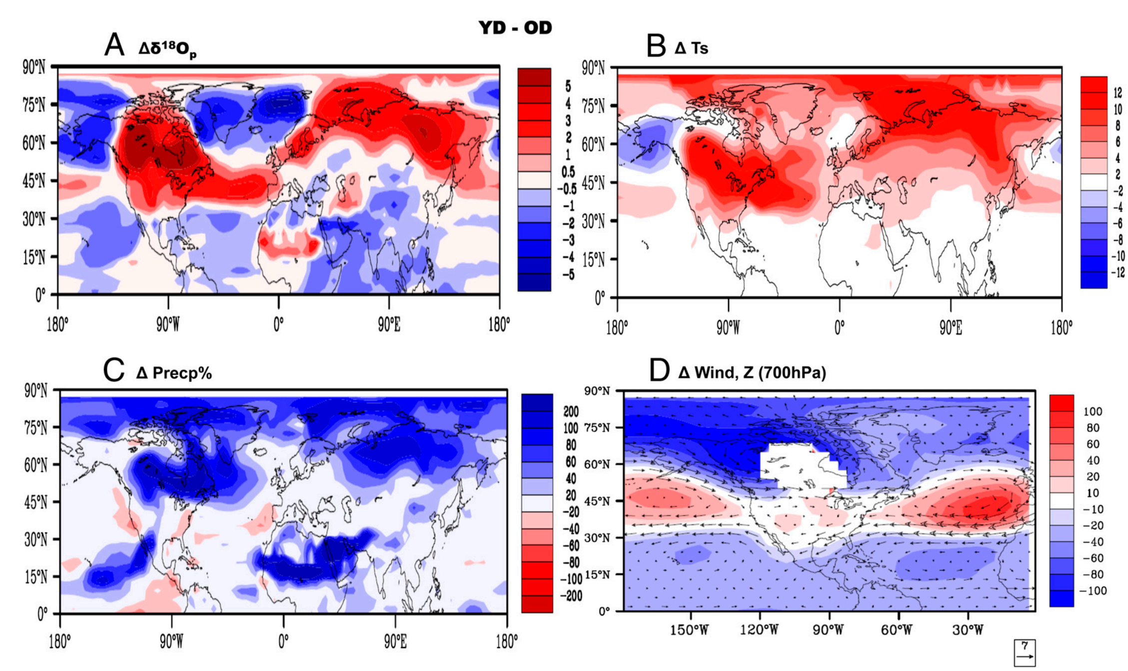

Fig. 3. Difference between the YD and OD experiments in isoCAM3 for annual (*A*) precipitation-weighted $\delta^{18}O_p$ ($\Delta^{18}O$), (*B*) surface temperature (°C), (*C*) precipitation anomaly normalized by the climatology in the Northern Hemisphere, and (*D*) precipitation-weighted wind (vector, in m/s) and geopotential height (shading, in m) at 700 hPa around Greenland. The comparison between $\delta^{18}O$ and temperature shows generally a positive spatial correlation in the polar region, except over Greenland, where the negative $\delta^{18}O_p$ appears to be associated with an increased precipitation and source water from the remote North Pacific.

CO_2 due to polar amplification, which is about twice the modern polar sensitivity in current climate models (6). The enhanced deglacial Greenland climate response to increased CO_2 relative to present is likely in response to the greatly expanded sea ice and snow cover that increased the albedo feedback. We test this inference with CO_2 doubling sensitivity experiments in CCSM3 (*Methods 3*) that support a doubled deglacial Greenland CO_2-sensitivity relative to modern from these attendant cryospheric feedbacks.

In conclusion, our study suggests a significant response of Greenland temperature to rising atmospheric CO_2 between the OD and YD, despite at least similar reductions in AMOC strength. This warming was, however, masked by an evolving deglacial relationship between atmospheric temperature and water vapor $\delta^{18}O$. Our study therefore suggests that climate sensitivity as assessed from ice core records may underestimate the severity of rapid regional warming over Greenland in response to present and future anthropogenic greenhouse gas emissions.

Methods

1. Our model is the NCAR CCSM3 version T31x3 (22) with a dynamic global vegetation module. Our deglaciation experiment prior to 14.5 ka is the DGL-A simulation of Liu et al. (12), which we refer to for more details of the model setup and integration. The experiment was continued until 10 ka, with two major periods of freshwater forcing: 14.4–13.9 ka to the North Atlantic and Southern Ocean (23–25) and 12.9–11.7 ka to the North Atlantic (26) (Fig. 1*B*). The warmer YD than OD is a robust result in many sensitivity experiments with various freshwater scenarios. Here, we show the deglaciation experiment using an upper bound of freshwater flux during the YD to the North Atlantic as strong as that during the OD (Fig. 1*C*). The sensitivity experiments forced by CO_2-alone and insolation alone started from 17 ka are integrated forward the same as the deglaciation experiment except being forced only by the CO_2 and insolation, respectively. Details of these deglaciation experiments can be found in He (27).
2. The isotope-enabled isoCAM3 incorporates stable water isotopes into the NCAR atmospheric general circulation model CAM3 (T31) with fractionation associated with surface evaporation and cloud processes (28). Five isotope sensitivity experiments are carried out using CAM3 setup the same as in the deglaciation experiment at 19 ka (LGM), 17 ka (OD), 14.5 ka (BA), 12.1 ka (YD), and preindustrial age (PI) (fixed topography, orbital forcing, and greenhouse gases). Each experiment is forced by a 50-y history of monthly SST and sea ice from the deglaciation experiment, with the mean of the last 30 y used for analysis. The mean climate of these snapshot experiments is very similar to that of the transient simulation, a validation of this approach. Surface ocean $\delta^{18}O$ values are prescribed as $\delta^{18}O = 1.7‰$ (LGM) based on ref. 29, and is extrapolated onto other periods as 1.57‰ (OD), 1.25‰ (BA), 0.84‰ (YD), and 0.5‰ (PI). The spatial slope is derived over the Greenland region as $\delta^{18}O = 0.86\ T - 7.8‰$ ($r = 0.95$) (PI); $0.92\ T + 2.6‰$ ($r = 0.97$) (YD); $0.61\ T - 8.4‰$ ($r = 0.86$) (BA); $0.79\ T + 3.7‰$ ($r = 0.98$) (OD); and $0.66\ T - 3.7‰$ ($r = 0.98$) (LGM). Model $\delta^{18}O$ over Greenland in Fig. 1*D* is corrected with an altitude effect associated with the lower topography (by approximately 1,150 m in PI) in the model as follows: The model temperature over Greenland is first decreased by approximately 7.5 °C using the lapse rate of −6.5 °C/km, and the model $\delta^{18}O$ is then decreased by −6.4‰ using the spatial slope in the model.
3. We performed two CO_2 doubling sensitivity experiments in CCSM3. The experiments are initiated with the climate states and climate forcing at YD and PI taken from the transient deglaciation experiment (12). In both cases after doubling atmospheric CO_2, the model is integrated for 90 y. The average temperature of the last 20 y increases by 6.75 °C and 3.49 °C over Greenland in the YD and PI sensitivity experiments, demonstrating an enhanced CO_2 response at YD than PI, due to the expanded sea ice coverage and in turn the associated albedo positive feedback around Greenland. These transient CO_2 sensitivities are 20–30% smaller than the equilibrium sensitivity, as simulated at YD (approximately 10 °C) and for the present in Intergovernmental Panel for Climate Change coupled atmosphere-slab ocean models (approximately 5 °C) (4) because of the slow adjustment of the deep ocean (30).

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