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Is the Noble Gas-Based Rate of Ocean Warming During the Younger Dryas Overestimated?

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Key Points:
- A new Younger Dryas mean ocean temperature record shows significantly slower ocean heat uptake, compared to a previous reconstruction
- Noble gases are subject to fractionation during clathrate formation in glacial ice and thus errors in reconstructed mean ocean temperature
- Mean ocean temperature and Antarctic temperature covary through the entirety of the last deglaciation

Supporting Information:
- Supporting Information S1

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Is the Noble Gas-Based Rate of Ocean Warming During the Younger Dryas Overestimated?

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Abstract Noble gases in ice cores enable reconstructions of past mean ocean temperature. A recent result from the clathrate-containing WAIS Divide Ice Core showed tight covariation between ocean and Antarctic temperatures throughout the last deglaciation, except for the Younger Dryas interval. In the beginning of this interval, oceans warmed at 2.5 °C/kyr—three times greater than estimates of modern warming. If valid, this challenges our understanding of the mechanisms controlling ocean heat uptake. Here we reconstruct mean ocean temperature with clathrate-free ice samples from Taylor Glacier to test these findings. The two records agree in net temperature change over the Younger Dryas, but the Taylor Glacier record suggests sustained warming at the more modest rate of 1.1 ± 0.2°C/kyr. We explore mechanisms to explain differences between records and suggest that the noble gas content for the Younger Dryas interval of WAIS Divide may have been altered by a decimeter-scale fractionation during bubble-clathrate transformation.

Plain Language Summary Oceans have taken up most of the additional heat trapped by greenhouse gases, mitigating the current rate of surface warming. In order to understand changes in ocean heat uptake over time, we use atmospheric noble gases measured in ice cores to estimate past ocean temperature change. This method works because the amount of noble gases dissolved in seawater changes with temperature. A recent ocean temperature reconstruction identified a 700-year interval during the transition from the last ice age to the current warm period when oceans warmed three times faster than they are currently warming. This result challenged our understanding of how oceans warm as an ice age ends. We tested this finding with a new ice core record and found that ocean warming during this interval occurred at a rate that is comparable to today, which is more consistent with our understanding of ocean heat uptake. We suggest that the noble gas record in the original ice core was altered by a process that affects how atmospheric gases are distributed in ice and is unrelated to ocean temperature change. From these findings we suggest caution in interpreting noble gas records in ice cores where this process may occur.

1. Introduction

Ocean heat uptake plays a crucial role in regulating the rate of planetary warming. To understand mechanisms controlling ocean warming on centennial-millennial timescales, it is necessary to consult paleoclimate archives. Reconstructions of atmospheric noble gas ratios (Kr/N_2, Xe/N_2, and Xe/Kr) from trapped air in ice cores reflect past mean ocean temperature (MOT) due to the temperature-dependent changes of gas solubilities in seawater and thus the relative partitioning of noble gases between the ocean and atmosphere (Headly & Severinghaus, 2007; Ritz et al., 2011). The MOT proxies reflect volume-averaged ocean temperature change; the rate of MOT change (or ocean heat uptake) depends on both the magnitude of the surface forcing and on ocean mixing/circulation. A recent MOT study covering the last deglaciation from the Antarctic WAIS Divide (WD) ice core showed features in MOT change that were not apparent in traditional ocean temperature reconstructions from marine sediment cores, including covariation between MOT and Antarctic temperature (Bereiter, Shackleton, et al., 2018). The exceptional resolution and age control of this record enabled strong constraints on rates of ocean temperature change. The most surprising feature of this record was a 1.6 °C MOT warming in the first 700 years of the Younger Dryas (referred to as YD1), which is

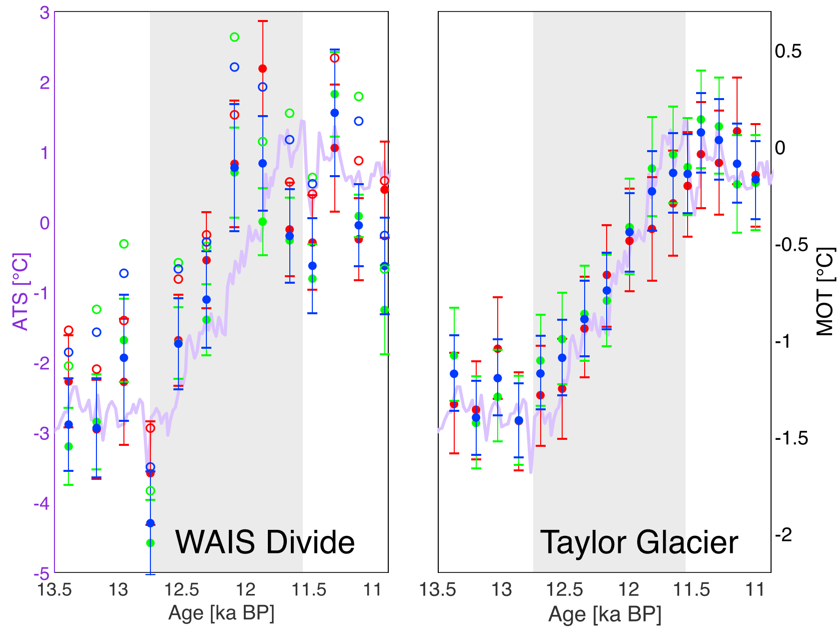

Figure 1. Mean ocean temperature (MOT) records for published WAIS Divide (WD; left; Bereiter, Shackleton, et al., 2018) and Taylor Glacier (right) derived from Kr/N_2 (red), Xe/N_2 (blue), and Xe/Kr (green) with 1σ uncertainties (scale on right). Open circles in left panel show WD data corrected with the least squares method applied in this study. Antarctic temperature stack (ATS; Parrenin et al., 2013) is shown in purple (scale on left). MOT and ATS data are displayed as anomalies relative to modern. Gray bars highlight the Younger Dryas.

roughly triple the rate of modern ocean warming. This interval represents the only significant deviation of the MOT trend from that of Antarctic temperature during the last deglaciation (Figure 1).

The Younger Dryas (12.75–11.55 ka BP) was marked by abrupt cooling of Greenland and the North Atlantic (Broecker et al., 1988) and gradual warming in Antarctica (Blunier et al., 1997), as a result of reduction in Atlantic Meridional Overturning Circulation (AMOC; Broecker et al., 1989). The Younger Dryas ended with abrupt recovery of the AMOC (McManus et al., 2004). Modeling studies suggest that MOT and ocean heat content should increase through the duration of AMOC reduction at a rate roughly one quarter of that found at WD for YD1 (Galbraith et al., 2016; Pedro et al., 2018). As of yet, no evidence for major changes in climate or ocean circulation have been found that shed light on the YD1 warming.

Because of the important implications of the rapid YD1 MOT warming, we sought to replicate this MOT change with another ice core record. We analyzed samples from Taylor Glacier, Antarctica, a blue ice area where ice from the last glacial cycle can be found in abundance (Baggenstos et al., 2017). Importantly, the air in Taylor Glacier ice is enclosed entirely in the form of bubbles and lacks clathrates due to the relatively shallow depth of the glacier, while WD is a deep ice core in which the Younger Dryas is within fully clathrated ice, approximately 400 to 500 m below the bubble-clathrate transition zone (BCTZ; Fitzpatrick et al., 2014).

2. Methods and Site Description

Sixteen ice core samples from Taylor Glacier covering 13.4–11.0 ka BP were collected along a previously established sampling line, which contains a well-dated, high-resolution record of the last deglaciation (Baggenstos et al., 2017). Samples were analyzed for isotopes of nitrogen, argon, and krypton and Kr/N_2, Xe/N_2, and Xe/Kr following Bereiter, Kawamura, et al. (2018). Results are reported in delta notation, relative to the modern atmosphere.

Ice core Kr/N_2, Xe/N_2, and Xe/Kr are influenced by gravitational (Schwander, 1989; Craig et al., 1988) and thermal (Severinghaus et al., 1998) fractionation. Because the effects of gravitational and thermal fractionation are well understood for the measured gases, the isotope ratios can be used to correct Kr/N_2, Xe/N_2, and

Xe/Kr to derive their original atmospheric compositions. We solve for fractionations using all measured isotope ratios in a linear least squares system of equations (Baggenstos, 2015; and supporting information).

To derive MOT, Kr/N_2, Xe/N_2, and Xe/Kr were input into the four-box ocean-atmosphere model of Bereiter, Shackleton, et al. (2018). To estimate uncertainty in the rate and magnitude of MOT change in the Taylor Glacier record, we run 10,000 Monte Carlo simulations of the data, propagating analytical uncertainties, sample age uncertainties, and uncertainties in the sea level record used in the box model (Lambeck et al., 2014) through the full evaluation routine.

3. Results/Discussion

Figure 1 shows the MOT results for Taylor Glacier compared to WD. The Taylor Glacier record shows sustained warming over the whole Younger Dryas interval at 1.1 ± 0.2 °C/kyr (1σ) for a total warming of 1.3 °C over 1,200 years. Overall, trends for Taylor Glacier are consistent with those of Antarctic temperature. While the WD record suggests similar net warming of 1.4 °C during the Younger Dryas, MOT change occurs in two phases. There is a rapid (2.5 ± 0.5 °C/kyr) warming in the first 700 years (YD1), followed by ~0.8 °C/kyr cooling in the final 500 years of the Younger Dryas. The Taylor Glacier and WD MOT records agree (within uncertainty) for much of the Younger Dryas, but they differ significantly in the warming rate during YD1 (supporting information). These rates are tightly constrained for each record, due to the high sampling resolution within this interval. Potential explanations for the differences between the records are explored below.

3.1. Lab Artifacts and Data Processing

Because the WD and Taylor Glacier records were measured using the same analytical method, we can rule out laboratory artifacts as the source of disagreement between the two records. However, for Taylor Glacier we applied a different method to correct for firn fractionations and slightly different parameterizations to the box model compared to the WD study. If we apply the same firn corrections and box model parameters to WD as we used for Taylor Glacier (open circles, Figure 1), we find that the whole record shifts to warmer MOT by ~0.4 °C, but the record structure remains essentially unchanged, and there is no significant change to the rate of warming during YD1. This suggests that the differences between records are likely a result of some unaccounted-for physical process within the firn or ice.

3.2. Smoothing of the Taylor Glacier MOT Record

An important consideration when comparing the WD and Taylor Glacier records is the effect of signal smoothing in the firn column (Spahni et al., 2003). Compared to the atmosphere, fast variations in gas records in ice cores are low-pass filtered because (1) gases within firn mix slowly with the atmosphere through molecular diffusive transport and (2) bubble enclosure occurs gradually over a depth range of ~15 m (Schwander et al., 1988). In effect, gases within an ice layer do not have a single age, but a distribution of ages. This smoothing process has greatest impact on gases that undergo fast atmospheric changes (e.g., CH_4), but if bubble close-off occurs gradually enough, it may also affect slower atmospheric changes such as the noble gas trends observed during YD1.

The degree of smoothing depends on site conditions; cold, low accumulation sites tend to have the widest gas age distributions and thus experience the most smoothing (Spahni et al., 2003). Because of its high accumulation and relatively moderate temperature, WD has an exceptionally narrow gas age distribution width (20 to 60 years; Rhodes et al., 2017); the noble gas MOT record should be virtually unaltered by smoothing at this site. In contrast, the Taylor Glacier deposition site has lower accumulation and colder temperatures, so a wider gas age distribution is expected. The YD1 MOT warming suggested by WD is quite rapid; one possible explanation for the differences between the two records is that the noble gas record is smoothed at Taylor Glacier.

In order to quantify the differences between the two MOT records due to smoothing, we compare abrupt CH_4 transitions at the onset and termination of the Younger Dryas between Taylor Glacier (Bauska et al., 2016) and WD (Rhodes et al., 2015). Because these atmospheric CH_4 changes are rapid (several hundred ppb over a few hundred years), they should be more affected by smoothing than the MOT record. From the degree of smoothing of the Taylor Glacier CH_4 record compared to WD, it is possible to predict the degree of smoothing of the Taylor Glacier MOT record.

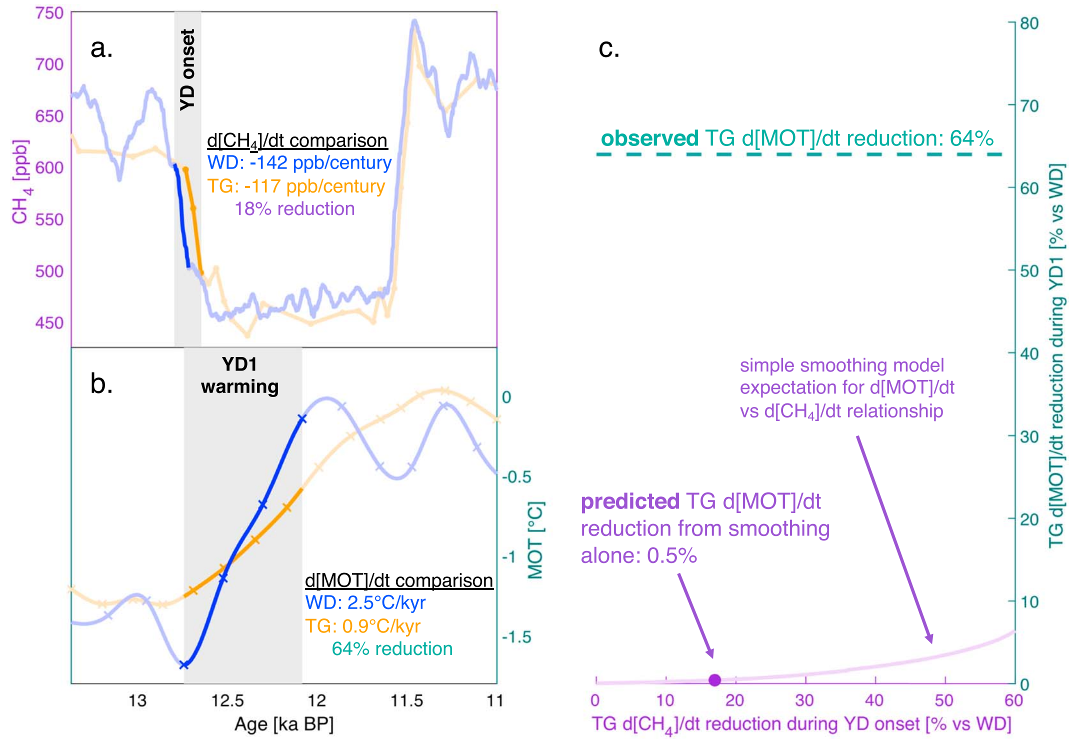

Figure 2. Comparison in rates of CH_4 and mean ocean temperature (MOT) change at Taylor Glacier (TG) compared to WAIS Divide (WD). (a) CH_4 records from TG (discrete, orange; Bauska et al., 2016) and WD (continuous, blue; Rhodes et al., 2015). Gray bar highlights CH_4 data used to estimate smoothing at TG. (b) Splined MOT records for TG (orange) and WD (blue; Bereiter, Shackleton, et al., 2018). Crosses indicate location of MOT data used to produce spline. Reported TG d[MOT]/d*t* is for the YD1 interval, which differs slightly (but agrees within uncertainty) with the d[MOT]/d*t* reported for the full Younger Dryas interval. Gray bar highlights YD1. (c) Modeled reduction of d[MOT]/d*t* versus d[CH_4]/d*t* at TG (relative to WD) due to smoothing. Purple dot shows observed reduction of TG d[CH_4]/d*t* and the expected reduction of d[MOT]/d*t*. Dashed teal line indicates the observed reduction of d[MOT]/d*t* for TG compared to WD.

The Taylor Glacier age scale was developed through gas synchronization between Taylor Glacier and WD from measurements of CH_4, CO_2, and $\delta^{18}O_{atm}$ (Baggenstos et al., 2017). A dynamic programming algorithm (Lisiecki & Lisiecki, 2002) was employed to optimize the fit of the Taylor Glacier gas records to those of WD on the WD2014 chronology (Buizert et al., 2015; Sigl et al., 2016), while maintaining a physically realistic (i.e., smooth) distance-age relationship. Because CH_4 data are used to constrain the age model, it is somewhat circular to compare rates of CH_4 transitions between WD and Taylor Glacier on the published Taylor Glacier age scale. To circumvent this issue, we reran the dynamic algorithm with $\delta^{18}O_{atm}$ alone. While the age model is still tied to WD2014, $\delta^{18}O_{atm}$ variations are several orders of magnitude slower than those of CH_4, so the effect of smoothing on $\delta^{18}O_{atm}$ is negligible.

On the new Taylor Glacier timescale, rates of CH_4 change (d[CH_4]/d*t*) at the transitions are comparable to those of WD, suggesting no substantial smoothing of the Taylor Glacier record relative to WD (Figure 2). In fact, the Younger Dryas termination d[CH_4]/d*t* is actually greater at Taylor Glacier than at WD. This is the more abrupt of the CH_4 transitions, so we would expect it to be more sensitive to smoothing. Comparing CH_4 transitions between Taylor Glacier and WD, it is important to note that the Taylor Glacier CH_4 data are in much lower resolution than for WD, so there is greater uncertainty in Taylor Glacier d[CH_4]/d*t*. However, high-resolution field measurements of CH_4 at Taylor Glacier confirm the d[CH_4]/d*t* of the lower resolution lab-based measurements (supporting information), and uncertainties in d[CH_4]/dt have little impact on smoothing estimates.

We convolved the WD CH_4 and MOT records with a log-logistic function to predict the degree of smoothing of the MOT record at Taylor Glacier from the observed CH_4 smoothing at Taylor Glacier relative to WD. A log-logistic function was chosen to approximate the gas age distribution at Taylor Glacier and realistically

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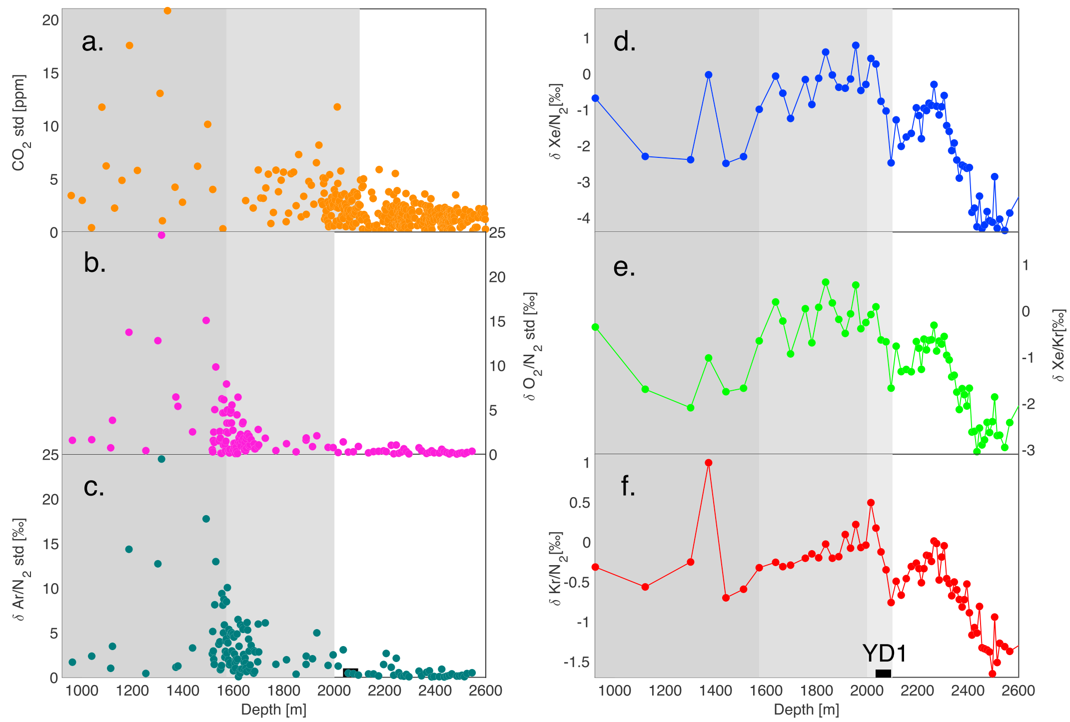

Figure 3. Evidence for spatial fractionation of noble gas ratios in and below the bubble-clathrate transition zone (BCTZ) at WAIS Divide. Standard deviations for replicate measurements of (a) CO_2 (this study and Marcott et al., 2014), (b) O_2/N_2, and (c) Ar/N_2 (Seltzer et al., 2017) versus depth. Dark gray paneling indicates the depth range of the BCTZ, and medium gray paneling marks the depth intervals below the BCTZ for which standard deviations are significantly elevated compared to the deepest (2,500–2,600 m) depth interval. Gravitationally and thermally corrected (d) Xe/N_2, (e) Xe/Kr, and (f) Kr/N_2 within and below BCTZ (Bereiter, Kawamura, et al., 2018; Bereiter, Shackleton, et al., 2018). Dark gray paneling indicates the depth range of the BCTZ, medium gray paneling marks the depth intervals where standard deviations for all three indicator gases are elevated, and light gray paneling marks where only standard deviations of CO_2 show significant elevation. Black bar indicates the YD1 depth interval.

simulate smoothing (supporting information). However, results are insensitive to the shape of the smoothing function; a simple boxcar function yields a similar relationship between the degree of smoothing of the CH_4 record and the MOT record.

As expected, the CH_4 record is significantly more sensitive to smoothing than the MOT record. The observed 18% reduction of $d[CH_4]/dt$ at Taylor Glacier (compared to WD) at the Younger Dryas onset gives an expected reduction in the YD1 MOT rate of 0.5% at Taylor Glacier relative to WD. Accounting for uncertainties in Taylor Glacier $d[CH_4]/dt$, an upper bound on smoothing of the CH_4 record (59%) predicts an upper estimate on MOT smoothing of 6% in the Taylor Glacier record. However, the observed rate of MOT warming at Taylor Glacier is 64% reduced compared to WD during YD1. From these results, we can confidently reject the hypothesis that the difference between the Taylor Glacier and WD MOT records is the result of smoothing.

3.3. Outliers in the WD Record Due to Clathrate Layering

In addition to higher rates of MOT warming during YD1, the WD record also has more high frequency variability than Taylor Glacier during and just after the Younger Dryas (Figure 3). Here we consider the possibility that high frequency variations in the WD noble gas record during the Younger Dryas and Early Holocene are not atmospheric and are instead related to fractionation of noble gases due to layering during bubble-clathrate transformation. Taylor Glacier samples are entirely in bubbly ice and therefore free of any such effect.

The proposed mechanism was originally invoked to explain centimeter-scale variations in CO_2 and O_2/N_2 measurements within and just below the BCTZ (Lüthi et al., 2010). The effect is summarized as follows: the fractionation of gases in the BCTZ is due to the differential permeation of gases from bubbles to growing clathrates. Clathrate formation does not occur gradually with increasing depth but in layers. Layers in which clathrates first form are more enriched in gases with higher bubble-to-clathrate permeation rates, even after all surrounding bubbles have transformed to clathrates. Below the BCTZ, gas content slowly rehomogenizes via molecular diffusion through the ice lattice, which can take tens of thousands of years (Bereiter et al., 2009). The proposed mechanism would introduce systematic error within the BCTZ and random error to samples below the BCTZ that decreases with depth, as gases have more time to rehomogenize and thinning of layers enhances diffusion.

In the BCTZ (where bubbles and clathrates coexist), we observe systematic error in gases influenced by clathrate layering. For CO_2, this is due to the preferential sampling of bubbles over clathrates during gas extraction (Stauffer & Tschumi, 2000). For O_2/N_2 and Ar/N_2 (and likely Kr/N_2, Xe/N_2, and Xe/Kr), there is preferential sampling of clathrates, because of gas loss from bubbles from core cracking during drilling due to the brittle nature of ice in the BCTZ (Bender & Sowers, 1995; Kobashi et al., 2008). In contrast, for samples just below the BCTZ (in fully clathrated ice), we expect random error associated with this clathrate layering process, depending on whether the depth interval preferentially contains earlier or later-formed clathrates. Bereiter, Kawamura, et al. (2018) showed that Kr/N_2, Xe/N_2, and Xe/Kr are systematically fractionated in the BCTZ at WD, and noble gas samples in this region were rejected from the MOT record. However, spatial fractionation of Kr/N_2, Xe/N_2, and Xe/Kr beyond the BCTZ (and the associated random error) was not considered, because samples were averaged over a length (~30 cm) that earlier studies suggest should have homogenized the spatial variability caused by clathrate layering.

Lüthi et al. (2010) suggested that samples averaged over more than 10 cm provide reliable gas measurements. However, the estimate of averaging length of Lüthi et al. (2010) came from a single ice core (EDML) from high-resolution CO_2 measurements. Unfortunately, we do not have high resolution gas data to estimate the required averaging length at WD, but it is possible that the length scale of clathrate layering varies between sites. It is important to note that the processes driving clathrate layering are not fully understood but that the limiting step in bubble-clathrate transformation is clathrate nucleation. Factors including grain size (Faria et al., 2010), bubble size (Lipenkov, 2000), and ice chemistry (Ohno et al., 2010; Shimada & Hondoh, 2004) may influence clathrate nucleation. While a consensus has yet to be reached on the relative importance of these factors, they are all either directly or indirectly related to ice impurity content. Ice chemistry data from the Younger Dryas depth interval at WD suggest layering of impurities on the order of tens of centimeters (Sigl et al., 2016, and supporting information), so we find it plausible that the 30-cm MOT samples may still be affected by this process.

Because little is known about the permeation rates of gases from bubbles to clathrates, we look to empirical evidence to estimate the range of gas rehomogenization below the BCTZ. One indication that clathrates at a given depth below the BCTZ have not fully rehomogenized is the elevation of CO_2 pair differences with respect to deeper/older samples for which rehomogenization has already occurred (Lüthi et al., 2010). In addition to CO_2, we consider pair differences in O_2/N_2 and Ar/N_2 to identify the depth range of clathrate rehomogenization. In order to identify the influenced depth range, we bin data of standard deviations for replicate samples of WD CO_2 (Marcott et al., 2014), O_2/N_2, and Ar/N_2 (Seltzer et al., 2017) into 100-m depth intervals and use a Student t test to determine if the standard deviations within a given depth interval are greater (at the 95% confidence level) than the deepest (2,500–2,600 m) bin. The standard deviations for all three gases are clearly elevated within and just below the BCTZ (Figure 3). O_2/N_2 and Ar/N_2 standard deviations show statistically significant elevated values down to 2,000 m, while CO_2 standard deviations are significantly higher down to 2,100 m. The WD Early Holocene data are within the depth range identified from all three gas measurements, and the YD1 interval (2,034–2,094 m) is within the range identified by CO_2. If a larger bin size is used to identify the range of affected data (e.g., 200 m) so that there are more data per bin, the range extends even deeper (2,200 m for O_2/N_2 and Ar/N_2 and 2,400 m for CO_2). From these observations, we find it plausible that the noble gas ratios have still not fully homogenized at WD for the YD1 interval, and the spatial fractionation may still be in effect for deeper MOT samples. This spatial fractionation may have randomly altered a few WD data points within the Younger Dryas to create the observed two-phase pattern of MOT.

If we compare the standard deviation of the CO_2, O_2/N_2, and Ar/N_2 replicate data within the YD1 depth interval to that of the deepest bin (2,500–2,600 meters), we find that the standard deviations are on average 37%, 49%, and 53% elevated for CO_2, O_2/N_2, and Ar/N_2, respectively, within YD1, compared to the deepest samples. To estimate the magnitude of the error in MOT associated with clathrate layering, we artificially increase the reported WD MOT error within YD1 and run Monte Carlo simulations of the data to determine the increase in WD MOT error required so that the difference between the Taylor Glacier and WD YD1 warming rates is no longer statistically significant at the 95% confidence level (supporting information). We estimate a 35% increase in error due to clathrate layering within YD1. Note that we expect the error associated with clathrate layering to increase closer to the BCTZ, where clathrates have had less time to rehomogenize, so uncertainties in the early Holocene MOT data may be even larger than those estimated for the YD1 interval.

3.4. Reliability of WD Versus Taylor Glacier MOT Records

While we posit that clathrate layering in the WD record is the most likely cause for the disagreement between the WD and Taylor Glacier records, there is not enough evidence to conclusively reject the Younger Dryas in WD. However, there are several reasons that suggest the Taylor Glacier record is more plausible than that of WD. The first is the agreement between MOT proxies. MOT records derived from Kr/N_2, Xe/N_2, and Xe/Kr at Taylor Glacier show excellent agreement in overall trends and absolute MOT. While WD Kr/N_2, Xe/N_2, and Xe/Kr MOT records are in general agreement, they show more spread in absolute MOT, and the duration and magnitude of the YD1 MOT change differ slightly between the three proxies (Figure 1).

In addition, the Taylor Glacier record is more physically consistent with the expected response of MOT to ocean circulation changes during the Younger Dryas inferred from models. Proxy evidence for ocean circulation (McManus et al., 2004; Stieglitz et al., 2011) suggests that AMOC strength within the Younger Dryas was weakened, but relatively stable. Model simulations under weakened (and stable) AMOC conditions show sustained MOT warming (Galbraith et al., 2016; Pedro et al., 2018), which is consistent with the Taylor Glacier record. The modeled rates of MOT warming are about 40% lower than the Taylor Glacier record; however, these simulations were run under conditions that are more consistent with Heinrich Stadial 1 and are consistent with MOT warming rates found for Heinrich Stadial 1 (Bereiter, Shackleton, et al., 2018).

Interestingly, proxy evidence would suggest that the rate of MOT warming during Heinrich Stadial 1 may exceed that of the Younger Dryas, because the relative magnitude of AMOC reduction is greater during the former (McManus et al., 2004). However, the scaling between the AMOC reduction and rate of ocean warming has not (to our knowledge) been rigorously explored. In addition, the higher obliquity during the Younger Dryas (relative to Heinrich Stadial 1) results in higher annually averaged insolation at high latitudes, where deep-water formation occurs (Bereiter, Shackleton, et al., 2018). The increased insolation at these sites during the Younger Dryas may help to explain the higher rate of MOT warming found compared to Heinrich Stadial 1.

4. Conclusions

We suggest that a previously identified form of fractionation of CO_2 in ice cores may also affect Kr/N_2, Xe/N_2, and Xe/Kr measurements in ice samples below the BCTZ, adding random noise to the derived atmospheric noble gas ratios. While sample rejection within the BCTZ has been previously recommended for MOT records, we caution in interpreting high-frequency variations in samples several hundred meters below the BCTZ and suggest that the uncertainty in MOT within this depth region may be significantly larger than the analytical uncertainty of the method. Future work must be done to find more direct evidence of this mechanism and to better understand its effect on Kr/N_2, Xe/N_2, and Xe/Kr.

Considering these findings, we posit that the Taylor Glacier record shows a more plausible scenario of MOT warming over the Younger Dryas than that of WD and that MOT and Antarctic temperature covaried through the entirety of the last deglaciation. The rate of MOT warming (1.1 ± 0.2 °C/kyr) from the Taylor Glacier record is significantly smaller than that from WD, but the Younger Dryas MOT warming rate found for this study is still about 70% greater than that of Heinrich Stadial 1 and 40% greater than estimates of ocean heat uptake from 1955 to 2010 (Levitus et al., 2012). The differing rates of ocean heat uptake between the Younger Dryas and Heinrich Stadial 1 are not fully understood, though models have successfully captured the rate of ocean warming during Heinrich Stadial 1. Future simulations of the Younger Dryas may serve as a valuable opportunity to distinguish between internal (ocean circulation) and external (greenhouse gas and insolation) controls on ocean heat uptake.

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