



## RESEARCH LETTER

10.1002/2016GL071748

## Special Section:

The Arctic: An AGU Joint Special Collection

## Key Points:

- First data linking a gradient of sea ice extents to oceanic water vapor isotope values
- Initial sea ice loss leads to lower d-excess, then values increase with further ice loss
- Past rapid Greenland ice core d-excess drop potentially associated with gradual sea ice loss and not abrupt atmospheric circulation shifts

## Supporting Information:

- Supporting Information S1

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## Citation:

Klein, E. S., and J. M. Welker (2016), Influence of sea ice on ocean water vapor isotopes and Greenland ice core records, *Geophys. Res. Lett.*, *43*, doi:10.1002/2016GL071748.

Received 18 JUL 2016

Accepted 10 DEC 2016

Accepted article online 14 DEC 2017

## Influence of sea ice on ocean water vapor isotopes and Greenland ice core records

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**Abstract** A warming climate results in sea ice loss and impacts to the Arctic water cycle. The water isotope parameter deuterium excess, a moisture source proxy, can serve as a tracer to help understand hydrological changes due to sea ice loss. However, unlocking the sea ice change signal of isotopes from ice cores requires understanding how sea ice changes impact deuterium excess, which is unknown. Here we present the first isotope data linking a gradient of sea ice extents to oceanic water vapor deuterium excess values. Initial loss of sea ice extent leads to lower deuterium excess moisture sources, and then values progressively increase with further ice loss. Our new process-based interpretation suggests that past rapid (1–3 years) Greenland ice core changes in deuterium excess during warming might not be the result of abrupt atmospheric circulation shifts, but rather gradual loss of sea ice extent at northern latitude moisture sources.

## 1. Introduction

Changes to the Arctic hydrologic cycle are greatly influenced by a shifting balance between sea ice and open water. Therefore, reduced sea ice extent driven by rapid Arctic warming [Cavalieri and Parkinson, 2012; Parkinson and Comiso, 2013] has important hydroclimatic implications. Recent decreases in Arctic sea ice extent are likely leading to more Arctic sourced precipitation [Bintanja and Selten, 2014; Kim et al., 2014; Klein et al., 2016; Kopec et al., 2015; Puntsgag et al., 2016]. Water isotope ratios ( $\delta^{18}\text{O}$ ,  $\delta^2\text{H}$ , and deuterium excess) are important tools to help understand these Arctic hydroclimate changes [Klein et al., 2015; Steen-Larsen et al., 2013]. Moreover, water vapor isotope ratio measurements collected above the sea surface (i.e., at moisture sources) are critical for a process-based understanding of how sea ice changes are impacting the Arctic water cycle. The water isotope parameter deuterium excess (or d-excess,  $\delta^2\text{H} - 8 * \delta^{18}\text{O}$ ) is particularly important as it records disproportionate changes in  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  influenced by evaporation, which provides information about the environmental characteristics of precipitation moisture sources [Gat, 1996]. Previous work indicates that altered sea ice extent can influence moisture sources and d-excess values [Jouzel et al., 2007].

However, without a high temporal resolution, process-based understanding of how sea ice extent influences d-excess water vapor values at moisture sources, it is difficult to clearly interpret what d-excess shifts indicate about sea ice changes and Arctic moisture sources. For example, a study examining changes in Arctic precipitation suggests that recent shifts to lower d-excess values are correlated with less sea ice extent [Kopec et al., 2015], which is in contrast to earlier work that claims Arctic Ocean water vapor during ice growth has higher d-excess values [Kurita, 2011]. Similarly, there is uncertainty in the interpretation of what d-excess shifts in Greenland paleoclimate ice core records suggest about changes in sea ice extent and climate. More specifically, high temporal resolution data from the Northern Greenland Ice Core Project (NGRIP) reveal a substantial and rapid (1–3 years) decrease in d-excess values during shifts from cold to warm periods, such as the transition at the end of the Younger Dryas (YD) [Steffensen et al., 2008]. Due primarily to their rapid nature, these past d-excess changes have been interpreted to indicate an abrupt shift in atmospheric circulation to a warmer Greenland water vapor source region and not altered sea ice extent [Steffensen et al., 2008]. This interpretation relies on the assumption that low d-excess values are associated with ice free northern waters, and thus, the dramatically quick sea ice breakup required to produce these low values is not plausible. However, these interpretations were made without any observation-based data about how sea ice extent influences water vapor d-excess at oceanic moisture sources. This is understandable, as water vapor isotope data from oceanic moisture sources are difficult to collect and are thus quite limited. Additionally, there are currently no data exploring the influence of sea ice extent on d-excess values at oceanic moisture sources, which are necessary for clearer interpretation of the sea ice signal stored in paleoclimate ice core isotope d-excess records.

To help fill this critical data gap we present the first Arctic Ocean continuous water vapor isotope ratio measurements, which include unprecedented data across a broad spectrum of sea ice extents during a summer 2015 research cruise. The primary goals of this study are (1) understand how shifts in sea ice extent influence oceanic water vapor isotope ratios and (2) apply this process-based understanding to help interpret the potential influence of sea ice extent on the rapid changes in d-excess values recorded in NGRIP data during climate transitions [Steffensen *et al.*, 2008].

## 2. Approach and Methods

Continuous water vapor measurements were collected on a summer 2015 research cruise aboard the United States Coast Guard Cutter Healy from 2 to 21 July, which began in Kodiak and ended in Nome, Alaska (Figure S1 in the supporting information). A Picarro L2130-i analyzer (hereafter analyzer) measured vapor  $\delta^{18}\text{O}$ ,  $\delta^2\text{H}$ , and water concentration (g/kg). The L2130-i is a cavity ring down-spectroscopy analyzer, which is based on cavity-enhanced, near-infrared laser absorption spectroscopy procedures, tuned on a narrow spectral region [Brand *et al.*, 2009; Crosson *et al.*, 2002; Gupta *et al.*, 2009]. The instrument was set up below the bow of the ship, and samples were collected through a tube that connected to a PVC pipe that extended out 1 m away from the ship and ~11 m above the ocean surface. The ratios of water vapor isotopes were measured approximately every second by the analyzer, and 5 min average values were used for analysis. Twice a day (approximately every 12 h), standard waters (United States Geological Survey 45 and 46) were injected and analyzed to correct for potential instrument drift.

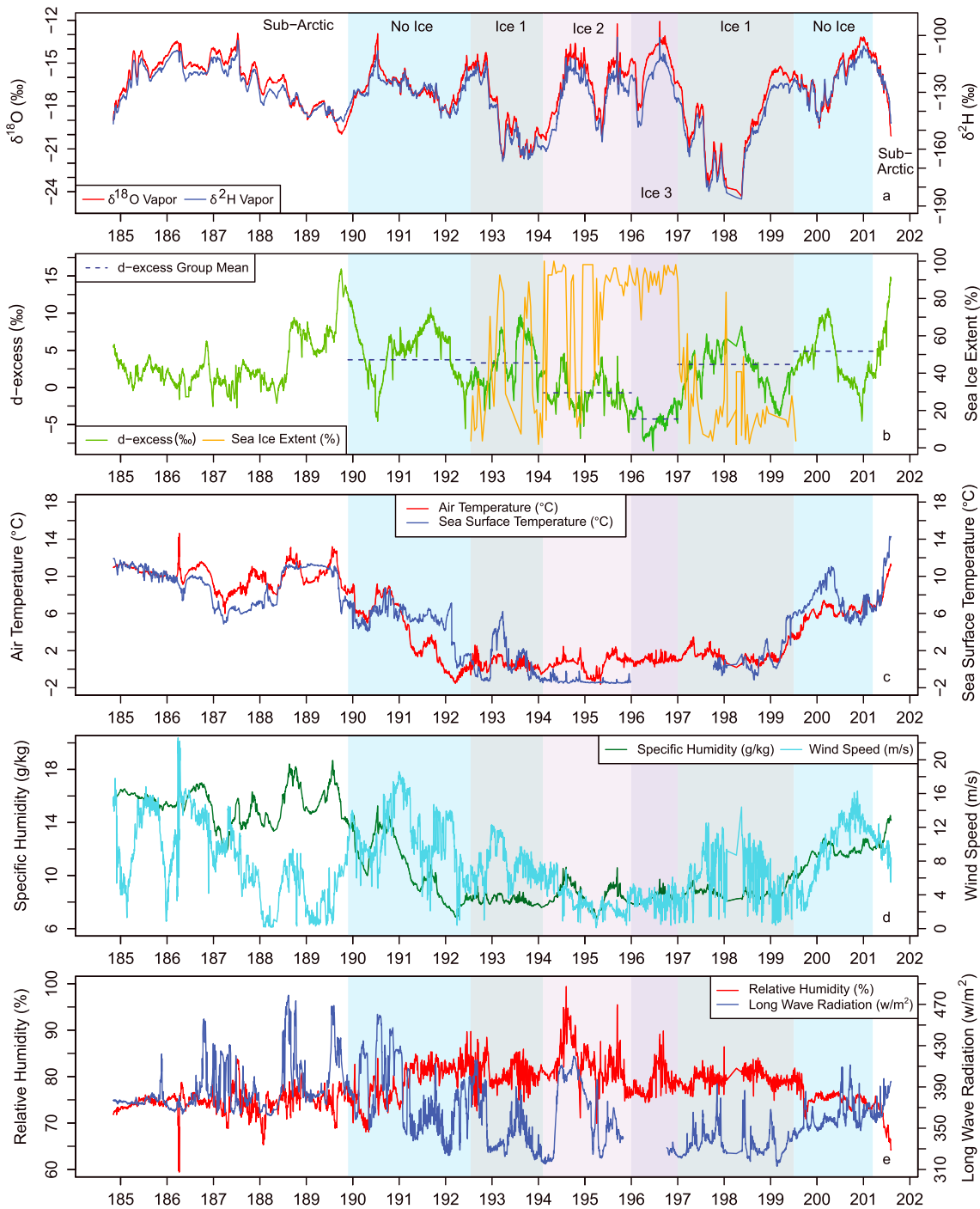
Meteorological measurements taken aboard the Healy and incorporated into analyses included location (Kongsberg Differential Position Sensor GPS); air temperature, wind speed, and direction (RM Young); sea surface temperature (Seabird SBE3S); relative humidity (RH) (Viasala HMP 110); and long wave radiation (Eppley PIR). Sea ice extent was estimated on an hourly basis from photographs taken from a camera mounted to the ship, which results in repeat images from the same location and direction (in the bow of the ship). Additional details about methods are in the supporting information.

## 3. Sea Ice Influence on Water Isotopes and Hydroclimate

### 3.1. Sea Ice, Weather, and d-Excess Values

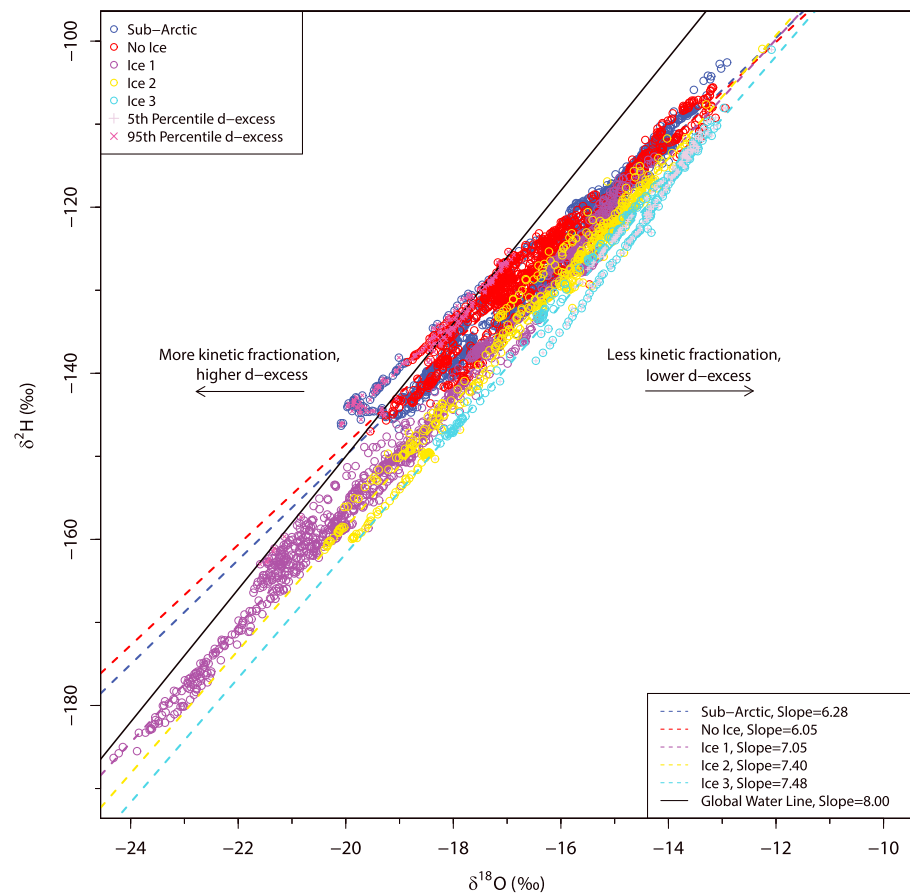
Our water vapor isotope ratios varied relative to mean percent sea ice extent (Figure 1 and Table S1 in the supporting information). Arctic Ocean water vapor d-excess values were inversely related to sea ice extent ( $p < 0.01$ ,  $r^2 = 0.25$ ) (Figure S2). For additional comparative analyses Arctic isotope and meteorological data were stratified into four groups. Hereafter, these four groups are named No ice, Ice 1 (29%), Ice 2 (79%), and Ice 3 (90%), respectfully, as determined by mean percent ice extent (Figure 1 and Table S1). There is also a Sub-Arctic group, which includes all data collected south of the Bering Strait (Figure S1). The Ice 3 group had the lowest mean d-excess value ( $-4.2\text{‰}$ ), while each of the progressively lower mean sea ice extent groups were associated with increasing mean d-excess values of  $-0.6$ ,  $2.6$ , and  $4.4\text{‰}$ , respectively (Figure 1b and Table S1). Additionally, the Ice 3 group with the lowest d-excess value also had the lowest sea ice extent variability (standard deviation (SD) = 6.4), while the other Ice 2 and Ice 1 groups had much greater variability in sea ice extent (SD = 28 and 25, respectively). The Ice 2 group explores an environment with both a large range and variability of sea ice extents (Figure 1b).

Sea ice extent was also associated with meteorological factors that influence d-excess. Sea ice had a negative relationship with wind speed (WS) ( $p < 0.01$ ,  $r^2 = 0.23$ ) and sea surface temperature (SST) ( $p < 0.01$ ,  $r^2 = 0.12$ ) (Figure 1 and Table S1). Overall, relative humidity (RH) was not significantly related to sea ice extent ( $p < 0.772$ ), but the greatest RH values occurred in the Ice 2 and Ice 3 groups (Figure 1e and Table S1). This is likely influenced by the combination of largely dominant sea ice coverage coupled with smaller leads that expose water with colder SST for evaporation. Consistent with this idea, SST and RH are negatively related ( $p < 0.01$ ,  $r^2 = 0.47$ ). Subsequently, SST ( $p < 0.01$ ,  $r^2 = 0.16$ ) and WS ( $p < 0.01$ ,  $r^2 = 0.09$ ) were positively related to d-excess, while RH was negatively related ( $p < 0.01$ ,  $r^2 = 0.03$ ) (Figure S4). These environmental data suggest that while d-excess is influenced by other factors such as SST and WS, these meteorological variables are initially governed by sea ice extent (Figure 1 and Table S1).



**Figure 1.** Research cruise water vapor and meteorological data. Five classification groups (Table S1) are represented with the following colors in each panel: Sub-Arctic (white), No Ice (blue), Ice 1 (gray), Ice 2 (light purple), and Ice 3 (dark purple). Time is presented on the x axis as day of year, same scale for each panel. (a)  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  water vapor isotope ratios, (b) d-excess and sea ice extent, (c) air temperature and sea surface temperature, (d) specific humidity and wind speed, and (e) relative humidity and long wave radiation. The data gaps in Figures 1c and 1e are due to instrument malfunction.

These water vapor isotope data indicate that lower d-excess values occur in Arctic Ocean waters with dominant, but not complete sea ice extent, and higher d-excess values occur under ice free conditions (Figure 1 and Table S1). Associated d-excess values along a gradient between these two end-members are defined by progressively decreasing and variable sea ice extent.



**Figure 2.** Water vapor isotope ratio data from each classification group (Table S1). Slopes for each of the groups, relative to the global mean water line, are also presented. Subsets in the 5th percentile (plus symbol) and 95th percentile (cross symbol) of all d-excess values are presented relative to the classification groups.

### 3.2. Sea Ice Influence on Water Isotope Fractionation

Of all the groups, water vapor isotopes in the Ice 3 group reveal the least influence from kinetic fractionation conditions. The  $^2\text{H}$  isotope is less sensitive to the effects of kinetic fractionation than the  $^{18}\text{O}$  isotope, as the proportional  $^2\text{H}$  change is minimal relative to the already large amount of fractionation (influenced by the different molecular diffusion of the lighter  $^2\text{H}$  isotope) experienced under equilibrium conditions [Gat, 1996]. Thus, a shift to more kinetic fractionation conditions results in greater depletion of  $\delta^{18}\text{O}$  isotope ratios, relative to  $\delta^2\text{H}$ . This relationship is evident in our data in the relative  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  shifts from the Ice 3 to No Ice groups (Table S1). The  $\delta^{18}\text{O}$  values depleted by nearly 1.5‰, while the  $\delta^2\text{H}$  values depleted by just over 2‰. Given the difference in scales, the  $\delta^{18}\text{O}$  shift is almost 5 times greater than the  $\delta^2\text{H}$  shift. This greater depletion of  $\delta^{18}\text{O}$ , relative to  $\delta^2\text{H}$ , results in an excess of deuterium ( $^2\text{H}$ ) and thus higher d-excess values in the No Ice group.

Comparing the relative changes of  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  ratios of the different sea ice groups on a water line provides information about how these fractionation differences impact d-excess values (Figure 2). First, the Sub-Arctic and No Ice groups have shallower slopes (6.28 and 6.05, respectively) than the Ice 1 through Ice 3 groups, suggesting greater evaporative influence [Gat, 1996], which could be expected as they are the only groups with completely open water evaporative sources. It is also apparent that the Ice 3 isotope values are the furthest offset to the right of all the groups. This largely horizontal right shift of the Ice 3 water vapor line reveals the disproportionate  $\delta^{18}\text{O}$  enrichment, relative to  $\delta^2\text{H}$  (Figures 2 and 1a and Table S1), which as previously described, leads to lower d-excess values (Figure 1b). The right shift of the Ice 3 water line also indicates a more humid moisture source [Clark and Fritz, 1997] and perhaps most importantly, that the conditions

associated with evaporation in the Ice 3 group are the least influenced by kinetic fractionation of all the groups. Similarly, the next two groups, Ice 2 and Ice 1, shift to the left (relative to Ice 3) with regard to their decreasing average sea ice extent (Figure 2). Additionally, the Ice 1 group has the most depleted isotope values and more kinetic fractionation than Ice 3, which is also supported by the left position of its water line, relative to Ice 3.

The conditions leading to reduced kinetic fractionation in the Ice 3 group result in the lowest d-excess values of the entire record (Figure 1b and Table S1). Of all the water vapor isotope data collected across Arctic and Sub-Arctic waters (Figure S1) during the research cruise (nearly 4500 5 min averages of over 1.3 million continuous data points), the Ice 3 group has the lowest absolute and mean d-excess values (Figure 1b). Moreover, the 5th percentile of d-excess values (i.e., the lowest) from the entire record is dominated by isotopes from the Ice 3 group (86%), with the remaining 14% completely within the Ice 2 group (Figure 2). Conversely, nearly two thirds of the 95th percentile of d-excess values (i.e., the highest) are from the Sub-Arctic group (64%), including the highest d-excess values (Figure 1b), with most of the rest from the No Ice group (33%) and a small contribution from the Ice 1 group (3%). When plotted relative to the global mean water line, it is apparent that the 5th percentile of d-excess values is the most offset to the right, indicating the most disproportionate  $\delta^{18}\text{O}$  enrichment (relative to  $\delta^2\text{H}$ ) and thus a lower d-excess value due to reduced kinetic fractionation (Figure 2). On the other end, the 95th percentile of d-excess values is the most offset to the left, indicating the most disproportionate  $\delta^{18}\text{O}$  depletion (relative to  $\delta^2\text{H}$ ), leading to more (or excess) deuterium and thus the higher d-excess value associated with more kinetic fractionation. Moreover, the fractionation-influenced differences between the sea ice groups we describe are supported by theoretical calculations of evaporative fractionation effects and d-excess values. Theoretical estimates of equilibrium [Majoube, 1971] and kinetic [Merlivat and Jouzel, 1979] fractionation effects based on meteorological conditions (e.g., RH) associated with each sea ice group support our findings (Figure 2) that kinetic fractionation effects are reduced and d-excess values are lower with more sea ice (see the supporting information for more details).

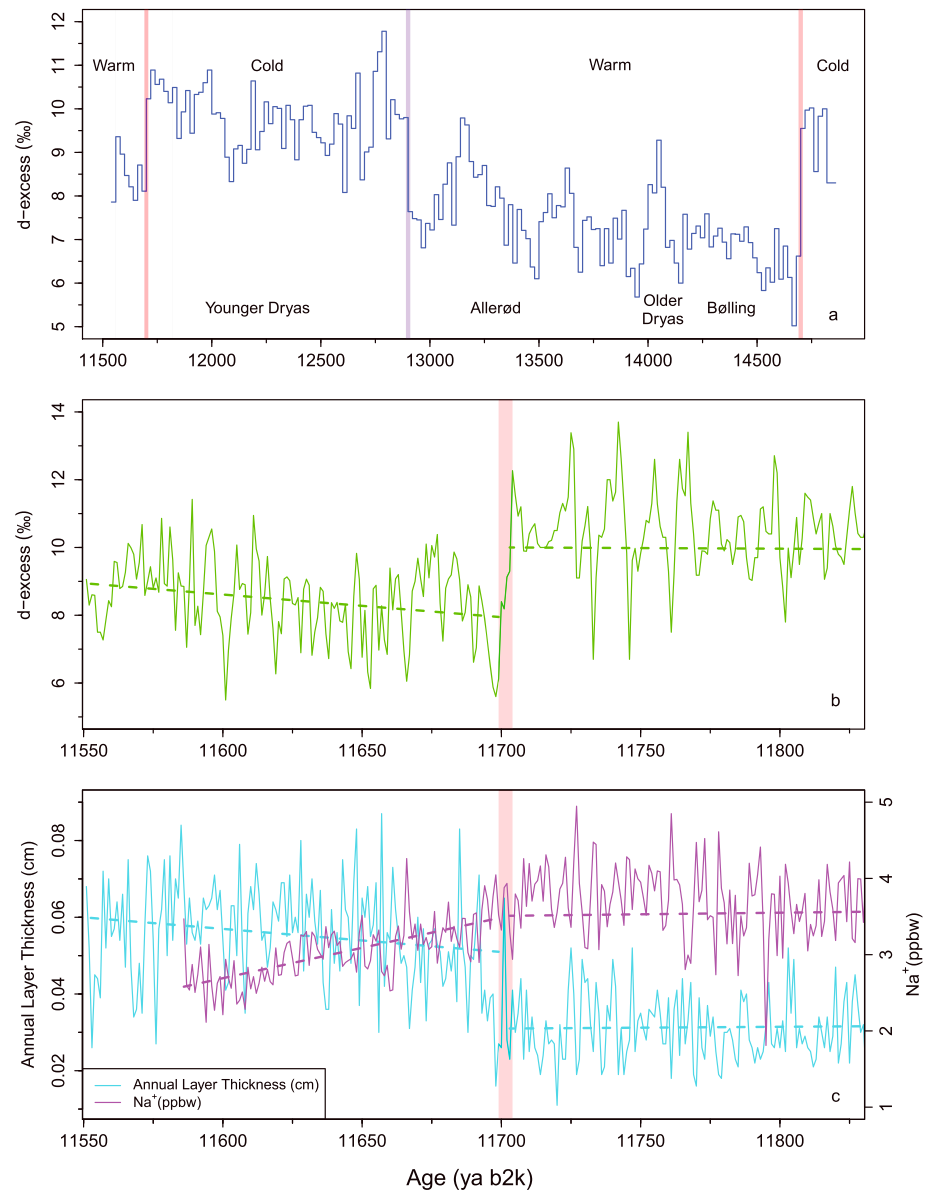
During oceanic transit, air parcels continually evaporate liquid ocean water moisture sources [Gat, 1996]. In our data, this evaporation of local oceanic water is apparent in the significant relationship between long wave radiation (i.e., energy emitted from the ocean surface) and specific humidity ( $p < 0.01$ ,  $r^2 = 0.35$ ) (Figures 1d and 1e). This is important, as it indicates that our water vapor samples above the ocean are dominated by local surface water evaporation and that the isotope values are not greatly influenced by vapor from other more distant locations. This is consistent with expectations, as evaporation of water, the first step in the hydrologic cycle, controls the isotope composition of water vapor [Craig and Gordon, 1965] and is further described in the supporting information.

Kinetic fractionation increases with greater wind speed above a water body [Gat, 1996], and the mean wind speed in the No Ice group (10.3 m/s) is more than 3 times greater than the mean wind speed in the Ice 3 group (3.3 m/s) (Table S1 and Figure 1d), which could be expected as more open water can lead to increased wind speeds [Long and Perrie, 2012]. So overall, small open water leads among dominant sea ice result in environmental conditions least influenced by kinetic fractionation (i.e., lower winds) during evaporation of cold SST waters, which results in lower d-excess values (Figure 1). As sea ice decreases, characteristics become more favorable for kinetic fractionation (i.e., higher winds) of the increasingly open and warmer SST water, until an open water Arctic Ocean environment results in the most kinetic fractionation, and thus the highest d-excess values (Figures 1b and 2 and Table S1).

Even though other factors like SST and WS influence d-excess, these variables are governed by sea ice extent. Consequently, our data suggest that d-excess is first controlled by sea ice extent. Therefore, Arctic moisture sources can have either high [Kurita, 2011] or low [Kopeck et al., 2015] d-excess values, depending on sea ice conditions. Establishment of this critical relationship between sea ice and d-excess values has important new implications for the interpretation of paleoclimate ice core records and changes in Arctic hydroclimate.

### 3.3. Sea Ice, d-Excess, and Greenland ice Cores

Understanding how d-excess can vary across Arctic Ocean moisture sources shows that values can be higher or lower as a function of sea ice conditions. These d-excess and sea ice relationship data provide important context to historic d-excess records recovered from ice cores, specifically the longer Arctic ice core records from Greenland. There is a sharp d-excess decrease in Greenland ice core records during multiple cold to



**Figure 3.** NGRIP ice core records from multiple parameters [Rasmussen *et al.*, 2006; Steffensen *et al.*, 2008]. (a) d-excess data at 20 year resolution from 11540 (years before A.D. 2000, ya b2k) to 14,860 (major climate oscillations, and transitions between them, are highlighted). (b) d-excess values from 11,550 to 11,850 (ya b2k, which corresponds to the period between the two gray lines in Figure 3a at higher temporal resolution (1–3 years). (c) Higher temporal resolution data for marine sea-salt ( $\text{Na}^+$ ) and annual layer thickness from 11,550 to 11,850 (ya b2k). In Figures 3b and 3c, slopes from before and after the  $\sim 3$  year YD transition (red rectangle) are presented with dashed lines.

warm transition periods [Jouzel *et al.*, 2007; Steffensen *et al.*, 2008]. The transition at the end of the YD period (Figure 3a) is a good example for evaluating the influence of sea ice on water isotopes. Across cores from multiple different Greenland sites, there is a sharp decrease in d-excess values at the end of the YD [Jouzel *et al.*, 2007; Steffensen *et al.*, 2008].

It is thought that this change represents a dramatic shift in the northern high-latitude water cycle, including a large rise in Greenland snow accumulation [Alley, 2000], but the magnitude of the water cycle change and the conditions that caused it remain uncertain [Jouzel *et al.*, 2007]. Previous work with the high temporal resolution NGRIP data suggests that the rapidity of these d-excess shifts (1–3 years) rules out the possibility that they were caused by changes in sea ice, as it was thought that ice conditions could not have degraded so



quickly [Steffensen *et al.*, 2008]. This d-excess shift is instead associated with abrupt changes in atmospheric circulation and the water vapor source regions of precipitation arriving at Greenland. Embedded in this interpretation is the assumption that the only sea ice change that could result in sharply reduced d-excess values is a dramatic decrease in northern sea ice extent, which does not account for the varying impacts on d-excess from a spectrum of sea ice extents.

Our sea ice and d-excess data reveal that a large and dramatic change in sea ice extent over a 1–3 year period might not be necessary to decrease d-excess values and that conversely, the lowest d-excess values are instead the result of a relatively small reduction in sea ice extent (Figures 2 and S1 and Table S1). We discovered that the lowest d-excess values were formed in environmental conditions of relatively stable, dominant sea ice with smaller open water leads (Figures 1 and S4 and Table S1). With these data in mind, it is now possible to understand how a relatively small loss in regional sea ice extent (e.g., ~10% or less) could influence local Greenland moisture source water vapor and its corresponding ice core d-excess values. As the ocean surface was largely covered by sea ice in our lowest d-excess data, this environment can be seen as a proxy for the sea ice conditions at the start of the warming transition at the end of the cold YD (Figure 3a). Sea ice extent fluctuates seasonally and a multiyear pattern can change in 1 year due to less sea ice formation over a single winter [Denton *et al.*, 2005]. It then follows that climate warming at the end of the YD in Greenland [Alley, 2000] could lead to a loss, but not complete disappearance, of sea ice extent over 1 to 3 years, which would have a disproportionately negative influence on d-excess values.

Moreover, this interpretation of Greenland ice core d-excess decreases does not require an abrupt change of the dominant Greenland moisture source, the subtropical North Atlantic [Drumond *et al.*, 2016], and alteration of atmospheric circulation [Steffensen *et al.*, 2008]. Instead, subtropical North Atlantic water vapor could pass north over degrading sea ice similar in character to the Ice 3 group (Figures 1b and S4 and Table S1) and incorporate the resultant locally derived lower d-excess vapor (which might retain its value during continental transit, see the supporting information) before condensing and precipitating on the Greenland Ice Sheet. This isotope imprinting mechanism could also help explain why the rapid d-excess decrease after the YD is relatively quickly followed by a d-excess increase in the NGRIP record (Figure 3b). It is possible that the sea ice extent near NGRIP decreased, potentially in conjunction with a northward shift of the southern ice edge, to the point that locally dominant moisture sources had less sea ice and subsequently were producing higher d-excess water vapor values (Figures 1b, 2, and S4). Similar processes are present in other climate periods, such as the warm Bølling-Allerød interstadial (Figure 3a). Like the YD transition, the start of the warmer Bølling oscillation also results in a rapid decrease in d-excess values, which our interpretation suggests is the start (and not end) of sea ice extent reduction. Again, this is followed by an increase and then gradual rise in d-excess values (i.e., a continued reduction of sea ice) before the brief colder Older Dryas (OD) period (about 14 kya), which also concludes with a sharp d-excess decline. It is also important to note the decreases in d-excess prior to the onset of the OD and YD warm to cold transitions (Figure 3a), which are consistent with an increase in sea ice extent at moisture sources before the d-excess rise expected with complete sea ice coverage. Overall, the negative relationship between moisture source sea ice extent and d-excess (Figures 2 and S4) might be repeated throughout various warm and cold transitions (Figure 3a), until (1) the local moisture source becomes open water (leading to relatively higher d-excess) or (2) the sea ice edge shifts so far south that there is no longer any local open water moisture source to evaporate from (leading to the highest d-excess). This pattern is consistent with the idea that as a result of temperatures much colder than anything during the Holocene, ice completely surrounded Greenland during the YD and thus very little moisture reached its interior [Alley, 2000], which is manifest in the period's high d-excess values (Figure 3a).

Our interpretation that a rapid drop in Greenland ice core d-excess is not associated with a dramatic reduction in sea ice extent and instead a much smaller decrease also explains the disconnect with the slower rate of changes in the Greenland air temperature and marine sea-salt proxies [Steffensen *et al.*, 2008]. Air temperatures near NGRIP are estimated to have changed over ~50 years during the YD transition, much slower than the 1–3 year d-excess decline [Steffensen *et al.*, 2008]. A more gradual air temperature increase is consistent with the slower rate of sea ice extent change we propose. Additionally, greater sea ice extent can result in large increases of sea-salt preserved in ice cores [Levine *et al.*, 2014]. So the change from generally stable YD sea-salt values to a more gradual, relative to the sharp d-excess shift, decrease after the YD transition (Figures 3b and 3c) is cited as evidence supporting the interpretation that sea ice changes did not influence the d-excess drop [Steffensen *et al.*, 2008].

However, our interpretation of Greenland Ice Sheet d-excess variation suggests a reason for this disconnect: the change in sea-salt values after the d-excess shift was more gradual because the associated decrease in sea ice extent was also more gradual. This increase in open water and atmospheric humidity associated with the d-excess decline (relative to the completely ice covered and higher d-excess YD) could also be expected to result in more precipitation. Accordingly, there is a greater than 50% increase in mean annual layer thickness after the d-excess decrease (Figures 3b and 3c), which represents the annual precipitation rate [Steffensen *et al.*, 2008] and is positively influenced by reduced sea ice extent [Li *et al.*, 2005]. Moreover, this representation of annual precipitation rate gradually increasing after the YD transition (relative to the generally stable values during the YD) (Figure 3c) is consistent with our interpretation of a slower reduction in sea ice extent progressively opening more water to serve as local moisture sources for the Greenland Ice Sheet.

#### 4. Conclusions

While subtropical North Atlantic moisture source characteristics are important for Greenland Ice Sheet precipitation [Drumond *et al.*, 2016], sea ice dynamics (e.g., high-latitude North Atlantic) can also influence precipitation patterns [Li *et al.*, 2005]. We recognize that there are spatial and temporal differences between our modern moisture source data and the ice core data, as the Greenland ice core data represent an average of d-excess values from larger oceanic moisture sources over a longer period of time. However, the fundamental physical processes we present connecting sea ice to d-excess values at oceanic moisture sources can be logically scaled up in both space and time. Additionally, our continuous water vapor provide high temporal resolution data that demonstrate the influence of sea ice conditions on oceanic moisture source d-excess values. Therefore, as we have shown that comparatively small shifts in sea ice extent can change the direction of d-excess water vapor values at moisture sources from positive to negative, it is possible that the large decreases in d-excess in Greenland ice core records are the result of changes in sea ice extent and not the previously suggested abrupt change of water vapor source regions and atmospheric circulation [Steffensen *et al.*, 2008]. Furthermore, our data suggest that a rapid and large loss in sea ice might have instead resulted in a shallower decrease in d-excess values, not the sharp decrease in the ice core record. Additional studies are needed to determine if the influence of local moisture source water isotopes (impacted by changing sea ice extents) is large enough to cause the observed changes in Greenland Ice Sheet d-excess values, but our process-based interpretation of the relationship between d-excess and sea ice changes provides a new framework for thinking about how sea ice fluctuations could impact ice core isotope values during various climate oscillations. The data and ideas presented here also offer a new contextual understanding to the isotope characteristics of modern precipitation in an Arctic hydrologic cycle in which sea ice extent is decreasing under a progressively warming climate [Cavalieri and Parkinson, 2012; Comiso *et al.*, 2008].

#### Acknowledgments

This material is based upon work supported by the National Science Foundation Division of Polar Programs under grant award 1504141 and the U.S. Department of Homeland Security under grant award DHS-14-ST-061-COE-001A-02. We thank the United States Coast Guard Healy crew for help with field logistics. We thank J. Ferguson and M. Franklin for laboratory assistance and B. Vaughn and T. Jones for constructive feedback that improved the manuscript. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Department of Homeland Security. Data are available from the NSF Arctic Data Center: <https://arctic-data.io/>

#### References

- Alley, R. B. (2000), The Younger Dryas cold interval as viewed from central Greenland, *Quat. Sci. Rev.*, 19(1), 213–226.
- Bintanja, R., and F. Selten (2014), Future increases in Arctic precipitation linked to local evaporation and sea-ice retreat, *Nature*, 509(7501), 479–482.
- Brand, W. A., H. Geilmann, E. R. Crosson, and C. W. Rella (2009), Cavity ring-down spectroscopy versus high-temperature conversion isotope ratio mass spectrometry: A case study on  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  of pure water samples and alcohol/water mixtures, *Rapid Commun. Mass Spectrom.*, 23(12), 1879–1884.
- Cavalieri, D., and C. Parkinson (2012), Arctic sea ice variability and trends, 1979–2010, *Cryosphere*, 6(4), 881–889.
- Clark, I. D., and P. Fritz (1997), *Environmental Isotopes in Hydrogeology*, CRC Press, London.
- Comiso, J. C., C. L. Parkinson, R. Gersten, and L. Stock (2008), Accelerated decline in the Arctic sea ice cover, *Geophys. Res. Lett.*, 35, L01703, doi:10.1029/2007GL031972.
- Craig, H., and L. I. Gordon (1965), *Deuterium and Oxygen 18 Variations in the Ocean and the Marine Atmosphere*, Lab. Geol. Nucl. Pisa, Italy.
- Crosson, E. R., K. N. Ricci, B. A. Richman, F. C. Chilese, T. G. Owano, R. A. Provencal, M. W. Todd, J. Glasser, A. A. Kachanov, and B. A. Paldus (2002), Stable isotope ratios using cavity ring-down spectroscopy: Determination of  $^{13}\text{C}/^{12}\text{C}$  for carbon dioxide in human breath, *Anal. Chem.*, 74(9), 2003–2007.
- Denton, G. H., R. B. Alley, G. C. Comer, and W. S. Broecker (2005), The role of seasonality in abrupt climate change, *Quat. Sci. Rev.*, 24(10), 1159–1182.
- Drumond, A., E. Taboada, R. Nieto, L. Gimeno, S. Vicente-Serrano, and J. López-Moreno (2016), A Lagrangian analysis of the present-day sources of moisture for major ice-core sites, *Earth Syst. Dyn.*, 7, 549–558.
- Gat, J. R. (1996), Oxygen and hydrogen isotopes in the hydrologic cycle, *Annu. Rev. Earth Planet. Sci.*, 24(1), 225–262.
- Gupta, P., D. Noone, J. Galewsky, C. Sweeney, and B. H. Vaughn (2009), Demonstration of high-precision continuous measurements of water vapor isotopologues in laboratory and remote field deployments using wavelength-scanned cavity ring-down spectroscopy (WS-CRDS) technology, *Rapid Commun. Mass Spectrom.*, 23(16), 2534–2542.



- Jouzel, J., M. Stievenard, S. J. Johnsen, A. Landais, V. Masson-Delmotte, A. Sveinbjornsdottir, F. Vimeux, U. Von Grafenstein, and J. W. White (2007), The GRIP deuterium-excess record, *Quat. Sci. Rev.*, *26*(1), 1–17.
- Kim, B.-M., S.-W. Son, S.-K. Min, J.-H. Jeong, S.-J. Kim, X. Zhang, T. Shim, and J.-H. Yoon (2014), Weakening of the stratospheric polar vortex by Arctic sea-ice loss, *Nat. Commun.*, *5*, 4646, doi:10.1038/ncomms5646.
- Klein, E., J. Cherry, J. Young, D. Noone, A. Leffler, and J. Welker (2015), Arctic cyclone water vapor isotopes support past sea ice retreat recorded in Greenland ice, *Sci. Rep.*, *5*, 10295, doi:10.1038/srep10295.
- Klein, E., M. Nolan, J. McConnell, M. Sigl, J. Cherry, J. Young, and J. Welker (2016), McCall Glacier record of Arctic climate change: Interpreting a northern Alaska ice core with regional water isotopes, *Quat. Sci. Rev.*, *131*, 274–284.
- Kopeck, B. G., X. Feng, F. A. Michel, and E. S. Posmentier (2015), Influence of sea ice on Arctic precipitation, *Proc. Natl. Acad. Sci. U.S.A.*, *113*(1), 46–51.
- Kurita, N. (2011), Origin of Arctic water vapor during the ice-growth season, *Geophys. Res. Lett.*, *38*, L02709, doi:10.1029/2010GL046064.
- Levine, J., X. Yang, A. Jones, and E. Wolff (2014), Sea salt as an ice core proxy for past sea ice extent: A process-based model study, *J. Geophys. Res. Atmos.*, *119*, 5737–5756, doi:10.1002/2013JD020925.
- Li, C., D. S. Battisti, D. P. Schrag, and E. Tziperman (2005), Abrupt climate shifts in Greenland due to displacements of the sea ice edge, *Geophys. Res. Lett.*, *32*, L19702, doi:10.1029/2005GL023492.
- Long, Z., and W. Perrie (2012), Air-sea interactions during an Arctic storm, *J. Geophys. Res.*, *117*, D15103, doi:10.1029/2011JD016985.
- Majoube, M. (1971), Fractionnement en oxygene-18 et en deuterium entre l'eau et sa vapeur, *J. Chem. Phys.*, *197*, 1423–1436.
- Merlivat, L., and J. Jouzel (1979), Global climatic interpretation of the deuterium-oxygen 18 relationship for precipitation, *J. Geophys. Res.*, *84*(C8), 5029–5033, doi:10.1029/JC084iC08p05029.
- Parkinson, C. L., and J. C. Comiso (2013), On the 2012 record low Arctic sea ice cover: Combined impact of preconditioning and an August storm, *Geophys. Res. Lett.*, *40*, 1356–1361, doi:10.1002/grl.50349.
- Puntsag, T., M. J. Mitchell, J. L. Campbell, E. S. Klein, G. E. Likens, and J. M. Welker (2016), Arctic vortex changes alter the sources and isotopic values of precipitation in northeastern US, *Sci. Rep.*, *6*, 22647, doi:10.1038/srep22647.
- Rasmussen, S. O., K. K. Andersen, A. Svensson, J. P. Steffensen, B. M. Vinther, H. B. Clausen, M. L. Siggaard-Andersen, S. J. Johnsen, L. B. Larsen, and D. Dahl-Jensen (2006), A new Greenland ice core chronology for the last glacial termination, *J. Geophys. Res.*, *111*, D06102, doi:10.1029/2005JD006079.
- Steen-Larsen, H. C., S. J. Johnsen, V. Masson-Delmotte, B. Stenni, C. Risi, H. Sodemann, D. Balslev-Clausen, T. Blunier, D. Dahl-Jensen, and M. Ellehøj (2013), Continuous monitoring of summer surface water vapor isotopic composition above the Greenland Ice Sheet, *Atmos. Chem. Phys.*, *13*(9), 4815–4828.
- Steffensen, J. P., K. K. Andersen, M. Bigler, H. B. Clausen, D. Dahl-Jensen, H. Fischer, K. Goto-Azuma, M. Hansson, S. J. Johnsen, and J. Jouzel (2008), High-resolution Greenland ice core data show abrupt climate change happens in few years, *Science*, *321*(5889), 680–684.