AGU ADVANCING EARTH AND SPACE SCIENCES

Geophysical Research Letters

RESEARCH LETTER
10.1029/2023GL104249

Snow-Atmosphere Humidity Exchange at the Ice Sheet Surface Alters Annual Mean Climate Signals in Ice Core Records

Laura J. Dietrich[1], Hans Christian Steen-Larsen[1], Sonja Wahl[2], Tyler R. Jones[3], Michael S. Town[1], and Martin Werner[4]

[1]Geophysical Institute, University of Bergen and Bjerknes Center for Climate Research, Bergen, Norway, [2]School of Architecture, CRYOS, Civil and Environmental Engineering, EPFL, Lausanne, Switzerland, [3]INSTAAR, University of Boulder, Boulder, CO, USA, [4]Alfred Wegener Institute, AWI, Bremerhaven, Germany

Abstract Surface processes alter the water stable isotope signal of the surface snow after deposition. However, it remains an open question to which extent surface post-depositional processes should be considered when inferring past climate information from ice core records. Here, we present simulations for the Greenland Ice Sheet, combining outputs from two climate models with an isotope-enabled snowpack model. We show that surface vapor exchange and associated fractionation imprint a climate signal into the firn, resulting in an increase in the annual mean value of δ^{18}O by +2.3‰ and a reduction in d-excess by −6.3‰. Further, implementing isotopic fractionation during surface vapor exchange improves the representation of the observed seasonal amplitude in δ^{18}O from 65.0% to 100.2%. Our results stress that surface vapor exchange is important in the climate proxy signal formation and needs consideration when interpreting ice core climate records.

Plain Language Summary The climate information contained in falling snow is modified by exchange processes with the atmosphere after the snow has fallen to the surface. It is important to understand how this modification affects the interpretation of past climate information from ice core isotope records. In this study, we combined outputs from two climate models to simulate the climate signal in a snow core on the Greenland Ice Sheet. We evaluate the snow core model using snow observations from the Greenland Ice Sheet. By simulating snow cores with and without the modification at the surface, we find a considerable impact of the surface modification on the climate signal in the snow core. Further, considering the surface modification causes an improved representation of the seasonal changes compared to observations. Our findings highlight the importance of surface processes in forming climate information contained in ice cores and underscore the need to include these processes in the ice core interpretation.

Key Points:

- Water isotopic fractionation during vapor exchange significantly affects the simulated annual and seasonal isotope climate signal in ice cores
- The simulated seasonal amplitude of the δ^{18}O signal in the snowpack improves when including surface vapor exchange induced fractionation
- A phase shift in the simulated seasonal maximum in d-excess toward early autumn is induced by vapor exchange, consistent with observations

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

L. J. Dietrich and H. C. Steen-Larsen, Laura.Dietrich@uib.no; Hans.Christian.Steen.Larsen@uib.no

Citation:

Dietrich, L. J., Steen-Larsen, H. C., Wahl, S., Jones, T. R., Town, M. S., & Werner, M. (2023). Snow-atmosphere humidity exchange at the ice sheet surface alters annual mean climate signals in ice core records. *Geophysical Research Letters*, *50*, e2023GL104249. https://doi.org/10.1029/2023GL104249

Received 15 MAY 2023
Accepted 24 AUG 2023

Author Contributions:

Conceptualization: Laura J. Dietrich, Hans Christian Steen-Larsen
Data curation: Laura J. Dietrich, Michael S. Town, Martin Werner
Formal analysis: Laura J. Dietrich
Funding acquisition: Hans Christian Steen-Larsen
Investigation: Laura J. Dietrich, Hans Christian Steen-Larsen, Tyler R. Jones
Methodology: Laura J. Dietrich, Hans Christian Steen-Larsen, Sonja Wahl, Tyler R. Jones, Michael S. Town

1. Introduction

Ice core records are invaluable climate archives and provide estimates of past climate temperatures more than 800,000 years back in time, with the potential to unravel climate information of more than 1.5 million years (EPICA community members, 2004; Jouzel et al., 2007; Lilien et al., 2021). Additionally, the difference in abundance of heavier oxygen molecules (δ^{18}O, see Text S1 in Supporting Information S1 for a description of the δ-notation) to the abundance of heavier hydrogen (deuterium) molecules (δD), the d-excess ($\delta D - 8{*}\delta^{18}O$, Dansgaard (1964)), is commonly used to infer moisture source region information (Johnsen et al., 1989; Landais et al., 2021). The traditional interpretation of this climate signal is that when snow forms, it captures an integrated snapshot of the state of the atmosphere from source region to deposition site (Dansgaard et al., 1969; Jouzel, 2013). The recorded climate signal is superimposed by noise that can be induced by wind-driven erosion and redistribution, the irregularities in the temporal and spatial distribution of precipitation events, and signal loss due to post-depositional diffusion (Casado et al., 2020; Persson et al., 2011; Zuhr et al., 2021, 2023). Moreover, recent observations documented that while the snow is exposed to the atmosphere, phase-changing processes affect the isotopic composition of the surface snow (Casado et al., 2021; Ritter et al., 2016; Wahl et al., 2022). The term post-depositional processes includes snow metamorphism, surface sublimation and deposition of atmospheric water vapor, sublimation of blowing snow, surface melt and evaporation, refreezing, and recrystallization (Casado et al., 2018). However, current research regarding the post-depositional impact on the isotopic composition of the snow is inconclusive and provides only limited quantification on whether these post-depositional changes appear as noise in the isotope climate records or if they are part of the formation process of the climate signal in ice core proxy records.

Project Administration: Hans Christian Steen-Larsen
Software: Laura J. Dietrich, Sonja Wahl
Visualization: Laura J. Dietrich, Hans Christian Steen-Larsen, Tyler R. Jones
Writing – original draft: Laura J. Dietrich
Writing – review & editing: Laura J. Dietrich, Hans Christian Steen-Larsen, Sonja Wahl, Tyler R. Jones, Michael S. Town, Martin Werner

To date, the required tools to answer this open question do not yet exist. An isotope-enabled atmospheric climate model is required that is coupled to a snowpack and surface exchange model that sufficiently captures the relevant post-depositional phase-changing processes (Madsen et al., 2019; Wahl et al., 2021). We approach this issue by combining simulations from the isotope-enabled global climate model ECHAM6-wiso (Cauquoin & Werner, 2021; Werner et al., 2011) with accurate surface vapor exchange simulations from the polar regional climate model MAR (Fettweis et al., 2013), as input for an updated version of the isotope-enabled SNOWISO surface-exchange and snowpack model (Wahl et al., 2022).

2. EGRIP Drilling Site

All observations are obtained in the Greenland accumulation zone, at the East Greenland Ice-core Project (EGRIP, Figure S1 in Supporting Information S1) deep ice core drilling site. The EGRIP site is located at 75° 38'N and 36° 00'W at the onset of the Northeast Greenland Ice Stream (NEGIS) at a height of ∼2,700 m above sea level (Hvidberg et al., 2020). EGRIP is a low accumulation site with 13.8–14.9 cm yr^{-1} water equivalent compared to other Greenland deep core drilling sites (Nakazawa et al., 2021).

3. SNOWISO Surface-Exchange and Snowpack Model

We use an updated version (v2) of the SNOWISO model (Wahl et al., 2022). The SNOWISO model is a one-dimensional isotope-enabled surface-exchange and snowpack model. It requires input information on precipitation, near-surface atmospheric variables, and the isotopic composition ($\delta^{18}O$, δD) of precipitation and near-surface atmospheric vapor. Output variables are the isotopic composition of the simulated snow core on depth and time scale and the isotopic composition of the surface humidity flux.

The SNOWISO model is divided into two parts (Figure 1), a surface cell with a variable height z_{SC} and the snowpack below with grid cells of constant spacing dz. At each time step, (a) precipitation mass and isotopic input are added and mixed into the surface cell, (b) isotopic fractionation during water vapor exchange with the atmosphere is applied to a layer within the surface cell with the constant thickness z_{EX}, the model depth up to which the snow is in direct exchange with the atmosphere, and mixed into the surface cell, (c) isotopic diffusion is applied between all grid cells, and (d) in case the height of the surface cell exceeds the combined height of a grid cell and the surface vapor exchange layer ($z_{SC} > dz + z_{EX}$), the surface cell releases a new snowpack cell.

Isotopic fractionation during sublimation as observed directly over the snow surface in Greenland (Wahl et al., 2022) is implemented in the snow-atmosphere exchange parameterization scheme. As in the original version of the SNOWISO model in Wahl et al. (2022), the water isoptic composition of the sublimation flux is calculated with a Craig and Gordon (1965) isotope evaporation model parameterized by Merlivat and Jouzel (1979). In the modified version (v2) of the SNOWISO model used in this study, the isotopic composition of the flux during the vapor deposition is calculated following Jouzel and Merlivat (1984). The resulting isotopic fraction during vapor exchange is applied to the surface layer of the SNOWISO model (Figure 1).

For small humidity gradients and, thus, small fluxes ($h - 1 < 0.02$, where h is the air relative humidity with respect to the surface temperature), the isotopic composition of the surface snow in the model is unchanged. The kinetic fractionation coefficients for ^{18}O $k_{18O} = 6‰$ and for deuterium $k_D = 0.88 \cdot k_{18O}$ are chosen following Merlivat and Jouzel (1979). No effect of wind speed on the kinetic fractionation is applied as this effect has not been observed over a snow surface, and the original parameterization in Merlivat and Jouzel (1979) has been questioned (Bonne et al., 2019; Zannoni et al., 2022). Diffusion within the snowpack is applied following Johnsen et al. (2000).

The simulations in this study are run with a vertical resolution of $dz = 1$ cm. Decreasing the vertical resolution below 1 cm does not change the simulation significantly (Figure S6 in Supporting Information S1). We set the model time step to 30 min to guarantee numerical stability. The depth of the exchange layer z_{EX} that is influenced by the atmosphere is set to 5 mm (Wahl et al., 2022). Input data (Table S1 in Supporting Information S1) for precipitation amount and isotopes, and the near-surface vapor isotopes are taken from a global ECHAM6-wiso reanalysis (Cauquoin & Werner, 2021) on a T127 grid, corresponding to ∼28 × 111 km horizontal resolution at the EGRIP site. The snowpack is initialized with a constant profile of the mean precipitation isotopic composition in the simulation period. Meteorological and snowpack temperature and density input are taken from regional MAR simulations (Dietrich, Steen-Larsen, et al., 2023) over Greenland on a 30 × 30 km horizontal resolution,

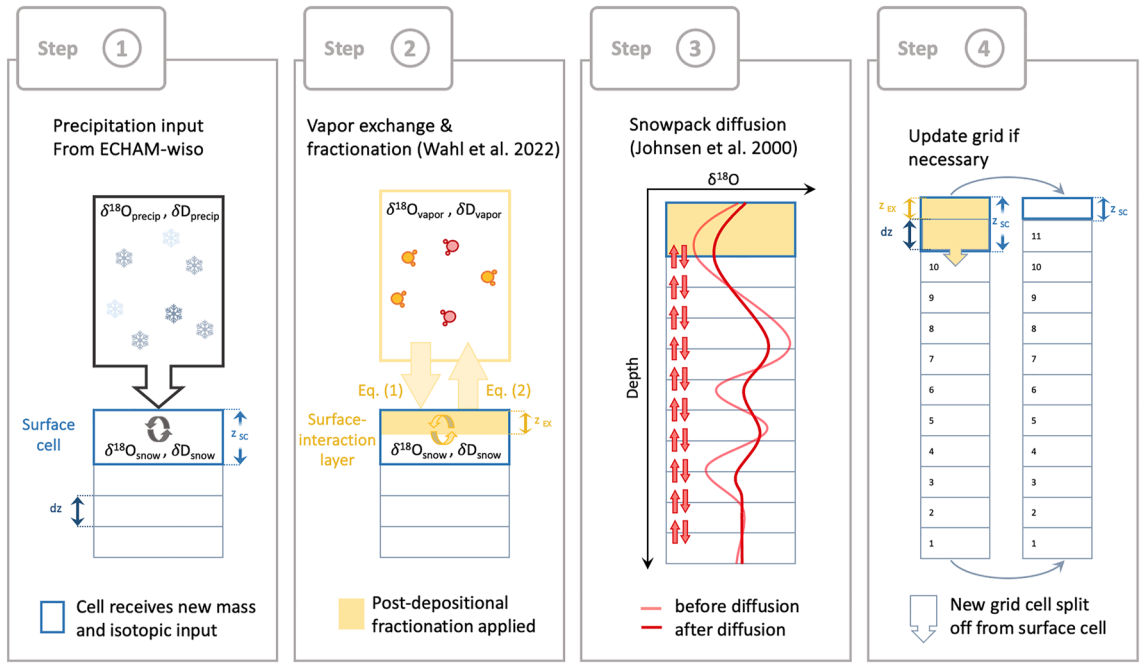

Figure 1. Illustration of the calculations in the SNOWISO model at each time step. The depth of each grid cell is dz, and the depth of the layer that is affected by vapor exchange induced fractionation is z_{EX}. The surface cell is marked by a blue outline, and its height z_{SC} is variable between $z_{EX} < z_{SC} < dz + z_{EX}$. Yellow fill indicates the layer that is affected by vapor exchange induced fractionation. Red arrows indicate diffusion in the snow column.

driven by the ERA-5 reanalysis product (Hersbach et al., 2020). The surface vapor exchange from MAR is corrected following Dietrich, Steen-Larsen, et al. (2023).

4. Observational Data

4.1. Snowpack Cores at EGRIP

The performance of the SNOWISO model is evaluated against averaged isotopic profiles of the upper 1 m of the snowpack across several years at the EGRIP site (original dataset: Behrens et al., 2023, processed data used in this study: Town et al., 2023). In 2017, 24 snowpack cores were obtained at four independent sites on eight sample days. In 2018, 35 snow cores were obtained at five sites on seven sample days. In 2019, 25 cores were obtained at five sites on five sample days. For each year, all individual 1-m snowpack isotopic profiles were aligned using the on-site temperature record and averaged (Town et al., 2023), providing three average isotopic records for 2017, 2018, and 2019.

We align the average of observed snow profiles to the simulations for better direct comparison. We use the seasonal extrema of $\delta^{18}O$ as tie points and linearly stretch the vertical coordinate in between. The snow profiles are aligned to the simulation in which vapor exchange induced fractionation is applied. The alignment allows us to quantify the changes to the d-excess seasonal cycle on the modeled time scale. For comparability, we show the simulated snow profiles aligned to the provided temperature-constrained age-depth relationship (Figures S2c, S2d, and S3 in Supporting Information S1), and for no alignment between the simulated and observed snow profiles (Figures S2e, S2f in Supporting Information S1). We acknowledge that aligning the observational $\delta^{18}O$ record of the snowpack to either local temperature or to simulations from the SNOWISO model both comes with caveats since neither model is an exact representation of all processes. However, we note that the choice of alignment has only a limited impact on the results. With this study, we move toward using isotope-enabled general circulation models (GCMs) to infer past climate information from ice core isotope records. We, therefore, decided to focus on the case where the average observed snow profiles are aligned with the simulations.

4.2. NEGIS Firn Core

For the evaluation of the entire simulated snow core, we use data from a firn core drilled in the NEGIS in 2012 (Vallelonga et al., 2014). The provided age-depth relationship for this core shows a misalignment on the

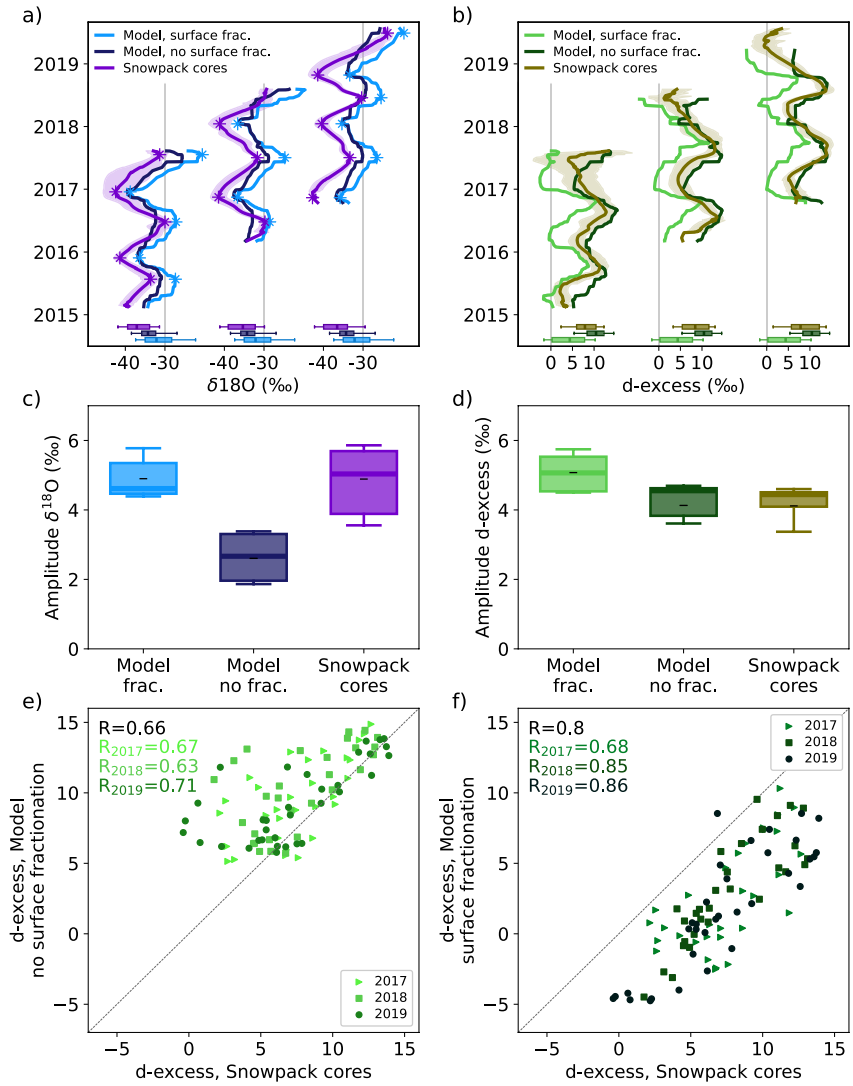

Figure 2. (a–d): Comparison of simulated δ^{18}O (a), d-excess values (b), and their seasonal amplitudes (δ^{18}O: c; d-excess: d) for vapor exchange induced fractionation in the model applied (light blue/green) and suppressed (dark blue/green) to observations (violet/khaki) at the EGRIP drilling site. The observations consist of three averages of all snowpack cores drilled in 2017, 2018, and 2019, respectively. (e), (f): Comparison of monthly binned averages of d-excess from the observations to monthly binned averages in the snow core simulation with vapor exchange induced fractionation turned off (e) and on (f) to the observed averages of d-excess in the snow cores drilled in 2017 (dots), 2018 (squares), and 2019 (triangles).

seasonal scale, likely because the lack of volcanic strata in the upper 3 m affected the annual layer counting (Kjær et al., 2013; Vallelonga et al., 2014). Consistent with the alignment of the snow profiles, we align the seasonal extrema of δ^{18}O in the firn core data with the seasonal extrema of δ^{18}O in the precipitation input from the model simulations with ECHAM6-wiso.

5. Results

5.1. Evaluation of the Isotopic Simulations

We evaluate the model performance using three average snowpack isotope profiles obtained in 2017, 2018, and 2019 (Town et al., 2023) in Figure 2. In the control simulation with no fractionation of the surface snow, δ^{18}O has a positive bias of 3.0 [2.3–3.7] ‰(square brackets show the bias range for the three individual snow profiles in 2017, 2018, and 2019, Figure 2a). Including fractionation induced by surface vapor exchange leads to an increase of the positive bias in δ^{18}O to 5.1 [4.5–5.7] ‰. The simulated bias is consistent with the positive bias of +2.7

‰ that Steen-Larsen et al. (2017) found in their evaluation of ECHAM5-wiso water vapor isotope simulations compared to observations, and the positive bias of +4.4 ‰ reported by Masson-Delmotte et al. (2015) in their evaluation of ECHAM5-wiso precipitation isotope simulations against shallow core observations. Both studies were carried out at the North Greenland Eemian Ice Drilling (NEEM) site in North Greenland.

The d-excess is overestimated in the control simulation by 1.7 [1.0–2.5] ‰ compared to the snow profiles (Figure 2b). Including vapor exchange induced fractionation shifts the d-excess toward negative values, and the simulated d-excess is underestimated by −4.25 [−3.54 – −4.96] ‰ compared to the snow profiles. We note, however, that the supersaturation function (Jouzel & Merlivat, 1984) in the parameterization of the isotopic fractionation during snow crystal formation in the cloud-scheme of the ECHAM-wiso model (Cauquoin & Werner, 2021; Werner et al., 2011) is tuned to align the simulated precipitation d-excess with the d-excess observations in the surface snow from across the Antarctic Ice Sheet (Masson-Delmotte et al., 2008). By doing so, post-depositional effects on the surface snow d-excess are implicitly included in the simulated precipitation d-excess. This hypothesis is supported by Steen-Larsen et al. (2017), who found that the simulated water vapor d-excess in ECHAM5-wiso was too low compared to vapor isotope measurements at the NEEM site, with a negative bias of −9 ‰, but only a limited bias in the simulated precipitation isotopes compared to snow samples (Masson-Delmotte et al., 2015). Therefore, an increased negative bias in the simulated d-excess when including vapor exchange effects is expected as post-depositional effects are implicitly applied twice. Furthermore, the supersaturation is tuned to the d-excess of Antarctic snow samples, not Greenland snow samples. Moisture sources for the snow being deposited at the EGRIP site might originate from a large spatial range of sources in the North Atlantic in which the simulated d-excess of the boundary layer has been documented as being too low in isotope-enabled GCMs (Steen-Larsen et al., 2017). The positive bias in δ^{18}O, as reported above, would however not be explained by the choice of supersaturation, but be a result of too little distillation during transport from the moisture source (Steen-Larsen et al., 2017).

In recent years, high-resolution water isotope records obtained from continuous measurements of ice core records have raised the possibility of investigating seasonal signals (Gkinis et al., 2021; Jones et al., 2023). To investigate the role that surface vapor exchange induced fractionation might play when simulating the isotope seasonality in ice core records, we define the seasonal amplitude as the difference between two extrema divided by two in both δ^{18}O and d-excess, and consider diffusion as insignificant for the seasonal amplitude in the top 1 m. In the control simulation, the seasonal amplitude of δ^{18}O is underestimated, reaching on average 65.0% (3.2 ‰) of the observed seasonal amplitude (4.9 ‰). Including vapor exchange induced fractionation in the model improves the representation of the seasonal amplitude in δ^{18}O to 100.2% (4.9%0, Figures 2a and 2c) of the observed seasonal amplitude.

The simulated seasonal amplitude of d-excess in the control simulation (4.1 ‰) matches the observed seasonal amplitude (4.1 ‰, Figures 2b and 2d). Including vapor exchange effects, increases the simulated amplitude in d-excess to 123.3% (5.1 ‰) of the observed amplitude. More importantly, including vapor exchange effects does not cause a phase shift in the seasonal cycle of δ^{18}O but causes a phase shift in the d-excess moving the maxima toward early boreal autumn (Figures 2a and 2b, Figure S4 in Supporting Information S1). The simulated d-excess maxima in early boreal autumn are consistent with observations from back-diffused records of ice core isotope records and snowpit samples (Johnsen et al., 1989; Landais et al., 2012). The seasonality of the d-excess profile changes, and the correlation with the d-excess observed in the snowpack improves from 0.66 to 0.8 when applying vapor exchange induced fractionation in the model (Figures 2e and 2f).

5.2. Impact of Vapor Exchange on the Isotopic Signal in a Firn Core

Two simulations were performed, a control simulation and a simulation with applied vapor exchange induced fractionation (Figure 3). Due to isotopic fractionation during sublimation (Madsen et al., 2019; Wahl et al., 2022) including the effects of vapor exchange causes an enrichment in δ^{18}O at the snow surface, in particular in summer, when sublimation dominates the vapor exchange. The effect of vapor exchange on the isotopic signal increases the annual mean δ^{18}O in the 30-year-long simulation (1990–2020) by 2.3 [1.6–2.8] ‰ (square brackets show the range of annual mean increase). Despite this relatively strong impact on the annual mean value, the inter-annual variability (standard deviation of the annual mean) only increases by 9% from 1.3 ‰ in the control simulation to 1.4 ‰ when vapor exchange induced fractionation is included. The simulated inter-annual variability of δ^{18}O in both simulations is, however, lower than the observed 1.9 ‰ for the period 1990–2011 in a firn core record

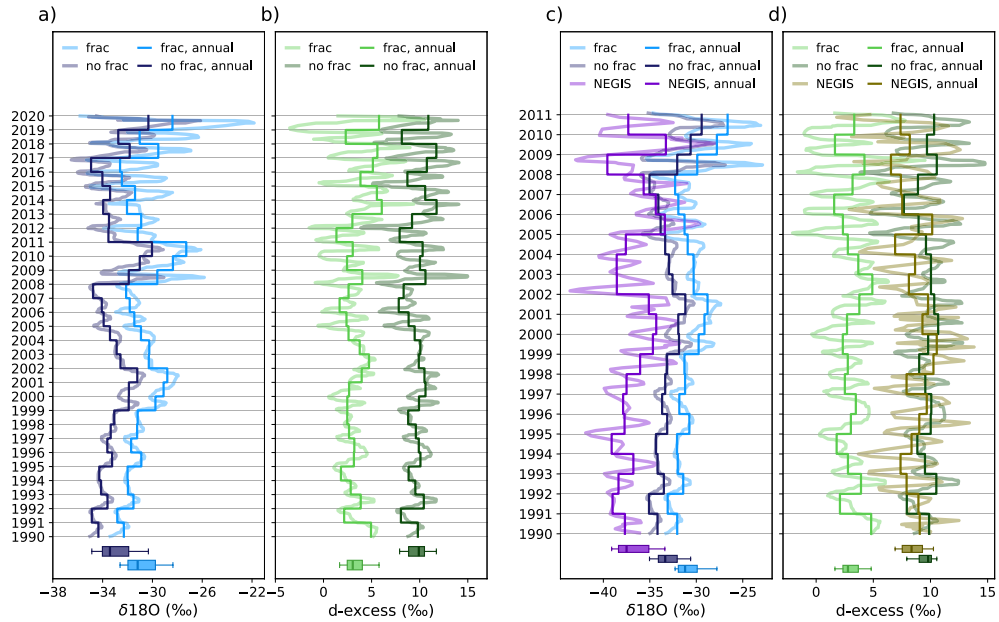

Figure 3. (a, b): Simulation of a 30-year-long snow core (1990–2020). (c, d): Comparison of a 21-year-long snow core simulation (1990–2011) to firn core observations (Vallelonga et al., 2014, Northeast Greenland Ice Stream). The simulated values of δ^{18}O (a, c blue) and d-excess (b, d green) are shown in the control simulation in dark colors (no frac) and when post-depositional fractionation included in light colors (frac). The observed isotopic records of δ^{18}O and shown in violet and for d-excess in brown. Step lines (dark lines) show the annual mean values of the snowpack core simulations (transparent lines). Boxplots show the distribution of the annual means, where the boxes indicate the 25th–75th percentile and whiskers indicate the 5th–95th percentile.

(Vallelonga et al. (2014), NEGIS, Figure 3c). For comparison, the simulated inter-annual variability of δ^{18}O in the time period covering the firn core (1990–2011) increased by 11% from 1.4 ‰ in the control to 1.6 ‰ when vapor exchange effects are included (Figure 3c).

Due to the different kinetic fractionation coefficients for δ^{18}O and δD, the HD^{16}O molecules are preferentially sublimated compared to $H_2^{18}O$ molecules, leading to a reduction in the d-excess of the surface snow. In the simulation, the d-excess decreases by −6.3 [−4.9−−7.9] ‰ due to vapor exchange (Figure 3b). The inter-annual variability of the d-excess is increased by 18% with a standard deviation of 0.79 ‰ in the control simulation to 0.9 ‰ when including vapor exchange effects. The observed d-excess annual standard deviation in the firn core is 1.1 ‰. For comparison, the simulated inter-annual variability of the d-excess in the time period covering the core (1990–2011) increased by 24% from 1.04 ‰ in the control to 1.29 ‰ when vapor exchange effects are included (Figure 3d).

6. Discussion

In a sensitivity analysis, the inputs of vapor and precipitation isotopes (δ^{18}O and δD), precipitation rate, and vapor exchange rate are randomly and independently varied within a range of ±20%. We find our results to be very robust for the simulation of δ^{18}O (Figures S7a and S7b in Supporting Information S1). As expected, the sensitivity of the d-excess to independent variations of δ^{18}O and δD is higher than their individual sensitivity (Figures S7e and S7g in Supporting Information S1). Both δ^{18}O and d-excess show only a small sensitivity to variations in the snowpack temperature and density (Figures S7b, S7d, S7f, S7h in Supporting Information S1). The choice of vertical resolution has no significant impact on the snow and firn core simulations for resolutions 0.5 cm < dz < 2 cm (Figure S6a in Supporting Information S1).

Independent of the SNOWISO model's capabilities to simulate the surface fractionation during vapor exchange and diffusion, the simulation depends largely on the accumulation, and the isotopes in precipitation and vapor, provided by MAR and ECHAM6-wiso. Using the uncorrected vapor exchange from MAR in our simulations considerably shifts the simulated firn core d-excess signal to higher values (Figure S6b in Supporting

Information S1) as a result of underestimated summer sublimation and overestimated winter deposition (see Dietrich, Steen-Larsen, et al. (2023) for details). In many paleoclimate simulations, the output of vapor exchange is in daily or monthly resolution. However, averaging the relatively large sub-diurnal variations causes an underestimation of the effect of vapor exchange induced fractionation on the firn core simulation (Figure S6c in Supporting Information S1). We conclude that an accurate representation and sub-diurnal temporal resolution of the vapor exchange in isotope-enabled models is essential when simulating the isotopic fluxes in atmosphere-snow interactions on ice sheets.

The comparison of a firn core simulation at the EGRIP site to the NEGIS firn core (Vallelonga et al., 2014, Section 4) highlights the caveats that we are still facing in modeling isotopes in GCMs. Despite the diffusion length in the simulation being comparable to observed values (Figures S8 in Supporting Information S1), the seasonal and, to a lesser degree, inter-annual variability in the simulations is underestimated (Figures 3c and 3d). This is a well-known issue in isotope-enabled GCMs (Goursaud et al., 2018; Sodemann et al., 2008; Werner & Heimann, 2002) and can be partly explained by the coarse horizontal resolution, which does not resolve stratigraphic variations (Breil et al., 2021), and an incorrect representation of the precipitation intermittency (Laepple et al., 2011, "drizzling-problem") or moisture pathways (Masson-Delmotte et al., 2008).

The validity of our results depends on how accurately the model captures the post-depositional impact of vapor exchange on the surface snow. Wahl et al. (2022) used an earlier version of the SNOWISO model to simulate day-to-day changes in the surface snow isotopes. They found an overestimation of the impact that vapor exchange had on the isotopes in a comparison of the top 0.5 cm with surface snow samples. In an evaluation (Text S4 in Supporting Information S1) of the SNOWISO model, using the latest model version and the simulation setup from this study, we only found a bias in the isotopic composition of the top 2 cm surface snow (Figure S5 in Supporting Information S1), which is likely induced by the input data (Section 5.1). Moreover, the correlation of $\delta^{18}O$ between simulation and snow samples improves slightly from $R = 0.73$ to $R = 0.84$ when including vapor exchange induced fractionation in the model (Figures S5a and 5Sb in Supporting Information S1). A new vertical grid in the current SNOWISO model version and a different choice of vertical resolution could explain the improved agreement. Additionally, Wahl et al. (2022) use the observed snow temperature at 10 cm depth in the diffusion scheme, while a depth variable snow temperature profile from MAR is used in this study.

We find a strong dependence of the simulated d-excess on vapor exchange at the deposition site. This questions how much of the d-excess source region signal is conserved in ice core proxy records. The simulations show a shift of the seasonal maxima in d-excess from boreal summer to early autumn (Figures 2a and 2b, Figure S4 in Supporting Information S1). The maximum values of d-excess during early boreal autumn, as observed in ice core isotope records, have led to conclusions that the source region sea surface temperature is imprinted in the ice core isotope records. However, based on the simulations in this study, we argue that the maximum d-excess in early boreal autumn is a result of snow-air exchange.

Recent research on post-depositional climate signal formation in the surface snow opens up new perspectives, such as the possibility of reconstructing surface humidity fluxes of past climates. Casado et al. (2020) were able to constrain the timescales at which climate variability can be reconstructed by modeling the impact of precipitation intermittency and the accumulation rate on isotopic simulations of the snowpack, assuming that surface vapor exchange does not fractionate the snow. Our study now provides, to our knowledge, the first model-based estimate of how surface vapor exchange induced fractionation impacts the isotopic record on annual time scales. Other post-depositional processes are not included in the simulation yet, such as the vapor exchange through snow metamorphism or wind pumping along with snow redistribution at the surface. The entire extent of the post-depositional impact on the climate signal in ice core proxy records and their spatial and temporal variability needs to be further studied.

7. Conclusions

Vapor exchange at the surface impacts the water isotopes in the snow after deposition. We estimated the impact of this surface fractionation on the seasonal to annual climate signal recorded in ice cores using the SNOWISO surface exchange and snowpack model. Precipitation and vapor isotopic composition were provided by the global circulation model ECHAM6-wiso, and surface humidity fluxes by the regional climate model MAR. The SNOWISO model simulates the fractionation in the surface snow layer and diffusion in the snowpack. Our results

outline the particular importance of post-depositional processes in the climate signal formation in ice cores and fundamentally question our current proxy interpretation.

Due to vapor exchange induced fractionation, we found a shift of the mean annual values by +2.3 ‰ for $\delta^{18}O$ and by −6.3 ‰ for d-excess in a firn-core simulation for the period 1990–2020. These results suggest that post-depositional fractionation of the surface snow affects the climate signal imprinted in ice cores, an important caveat to current paleoclimate interpretations that do not consider the potential role of changes in vapor exchange for different climates.

In simulations of snow cores excluding surface vapor exchange impacts, the modeled seasonal isotopic amplitude is too small compared to observations. Implementing vapor exchange into simulations improves the representation of the seasonal amplitude in $\delta^{18}O$ from 65% to 100.2% of the observed seasonal cycle. This may explain a known conundrum in the interpretation of the water isotopes, that the diffusion-corrected seasonal amplitude is often substantially reduced compared to expectations of isotope-temperature scaling based on the seasonal temperature cycle (Jones et al., 2023). Our results thus suggest that additional isotopic corrections are needed to convert a high-frequency, seasonally resolved water-isotope signal in a deep ice core back to a climate signal. In addition to the classic back-diffusion described in Johnsen et al. (2000), we suggest a correction based on the surface fractionation due to vapor exchange. The quantification of the correction for vapor exchange should be the topic of future studies based on the analysis of simulated climatologies. Since vapor exchange has a pronounced seasonal cycle, its effect needs to be considered in the interpretation of seasonal variations in water isotope records.

Due to the tight relation between temperature and humidity, it appears likely that the impact of vapor exchange varies in different climates and for different ice core drilling sites. We see an urgent need to quantify the role of vapor exchange in the interpretation of climate variability. The evaluations in this study show that the SNOWISO model provides a tool to more reliably model the climate imprint that surface processes leave in the surface snow.

Data Availability Statement

Snow core data are available on PANGEA (Town et al., 2023). The firn core data are available in Vallelonga (2014). ECHAM6-wiso outputs are available on Zenodo (Cauquoin & Werner, 2023). MAR outputs are available on Zenodo (Dietrich, 2023). SNOWISO model data are available on Zenodo (Dietrich, Wahl, & Steen-Larsen, 2023).

Acknowledgments
This paper has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program: Starting Grant SNOWISO (Grant agreement no. 759526). The simulations were performed on resources provided by Sigma2 - the National Infrastructure for High Performance Computing and Data Storage in Norway. EGRIP is directed and organized by the Centre for Ice and Climate at the Niels Bohr Institute, University of Copenhagen. It is supported by funding agencies and institutions in Denmark (A. P. Møller Foundation, University of Copenhagen), USA (US National Science Foundation, Office of Polar Programs), Germany (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research), Japan (National Institute of Polar Research and Arctic Challenge for Sustainability), Norway (University of Bergen and Trond Mohn Foundation), Switzerland (Swiss National Science Foundation), France (French Polar Institute Paul-Emile Victor, Institute for Geosciences and Environmental research), Canada (University of Manitoba) and China (Chinese Academy of Sciences and Beijing Normal University).

References

Behrens, M., Hörhold, M., Town, M. S., Zuhr, A., Hoffmann, A., Faber, A.-K., et al. (2023). Snow Profiles of stable water isotopes at the EastGRIP deep drilling site, summer seasons 2016 - 2019 [Dataset]. PANGEA. https://doi.org/10.1594/PANGAEA.957431

Bonne, J.-L., Behrens, M., Meyer, H., Kipfstuhl, S., Rabe, B., Schönicke, L., et al. (2019). Resolving the controls of water vapour isotopes in the Atlantic sector. *Nature Communications*, *10*(1), 1632. https://doi.org/10.1038/s41467-019-09242-6

Breil, M., Christner, E., Cauquoin, A., Werner, M., Karremann, M., & Schädler, G. (2021). Applying an isotope-enabled regional climate model over the Greenland ice sheet: Effect of spatial resolution on model bias. *Climate of the Past*, *17*(4), 1685–1699. https://doi.org/10.5194/cp-17-1685-2021

Casado, M., Landais, A., Picard, G., Arnaud, L., Dreossi, G., Stenni, B., & Prié, F. (2021). Water isotopic signature of surface snow metamorphism in Antarctica. *Geophysical Research Letters*, *48*(17), e2021GL093382. https://doi.org/10.1029/2021gl093382

Casado, M., Landais, A., Picard, G., Münch, T., Laepple, T., Stenni, B., et al. (2018). Archival processes of the water stable isotope signal in east Antarctic ice cores. *The Cryosphere*, *12*(5), 1745–1766. https://doi.org/10.5194/tc-12-1745-2018

Casado, M., Münch, T., & Laepple, T. (2020). Climatic information archived in ice cores: Impact of intermittency and diffusion on the recorded isotopic signal in Antarctica. *Climate of the Past*, *16*(4), 1581–1598. https://doi.org/10.5194/cp-16-1581-2020

Cauquoin, A., & Werner, M. (2021). High-resolution nudged isotope modeling with ECHAM6-WISO: Impacts of updated model physics and ERA5 reanalysis data. *Journal of Advances in Modeling Earth Systems*, *13*(11), e2021MS002532. https://doi.org/10.1029/2021ms002532

Cauquoin, A., & Werner, M. (2023). ECHAM6-WISO nudged simulation water isotopes and precipitation for the period 1990-2020 [Dataset]. Zenodo. https://doi.org/10.5281/zenodo.8341390

Craig, H., & Gordon, L. I. (1965). Deuterium and oxygen 18 variations in the ocean and the marine atmosphere.

Dansgaard, W. (1964). Stable isotopes in precipitation. *Tellus*, *16*(4), 436–468. https://doi.org/10.3402/tellusa.v16i4.8993

Dansgaard, W., Johnsen, S. J., Møller, J., & Langway, C. C., Jr. (1969). One thousand centuries of climatic record from camp century on the Greenland ice sheet. *Science*, *166*(3903), 377–381. https://doi.org/10.1126/science.166.3903.377

Dietrich, L., Steen-Larsen, H. C., Wahl, S., Faber, A.-K., & Fettweis, X. (2023). On the importance of the humidity flux for the surface mass balance in the accumulation zone of the Greenland ice sheet. *The Cryosphere Discussions*, 1–25.

Dietrich, L. J. (2023). MAR model simulations 1990-2020 for the EastGRIP drilling site in Greenland [Dataset]. Zenodo. https://doi.org/10.5281/zenodo.8335402

Dietrich, L. J., Wahl, S., & Steen-Larsen, H. C. (2023). SNOWISO model snow- and firn core simulations for the EastGRIP drilling site in Greenland [Dataset]. Zenodo. https://doi.org/10.5281/zenodo.8430274

EPICA community members. (2004). Eight glacial cycles from an Antarctic ice core. *Nature*, *429*(6992), 623–628. https://doi.org/10.1038/nature02599

Fettweis, X., Franco, B., Tedesco, M., Van Angelen, J., Lenaerts, J. T., van den Broeke, M. R., & Gallée, H. (2013). Estimating the Greenland ice sheet surface mass balance contribution to future sea level rise using the regional atmospheric climate model MAR. *The Cryosphere*, *7*(2), 469–489. https://doi.org/10.5194/tc-7-469-2013

Gkinis, V., Vinther, B. M., Popp, T. J., Quistgaard, T., Faber, A.-K., Holme, C. T., et al. (2021). A 120,000-year long climate record from a nw-Greenland deep ice core at ultra-high resolution. *Scientific Data*, *8*(1), 141. https://doi.org/10.1038/s41597-021-00916-9

Goursaud, S., Masson-Delmotte, V., Favier, V., Orsi, A., & Werner, M. (2018). Water stable isotope spatio-temporal variability in Antarctica in 1960–2013: Observations and simulations from the ECHAM5-WISO atmospheric general circulation model. *Climate of the Past*, *14*(6), 923–946. https://doi.org/10.5194/cp-14-923-2018

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049. https://doi.org/10.1002/qj.3803

Hvidberg, C. S., Grinsted, A., Dahl-Jensen, D., Khan, S. A., Kusk, A., Andersen, J. K., et al. (2020). Surface velocity of the Northeast Greenland ice stream (NEGIS): Assessment of interior velocities derived from satellite data by GPS. *The Cryosphere*, *14*(10), 3487–3502. https://doi.org/10.5194/tc-14-3487-2020

Johnsen, S., Clausen, H., Cuffey, K. M., Hoffmann, G., Schwander, J., & Creyts, T. (2000). Diffusion of stable isotopes in polar firn and ice: The isotope effect in firn diffusion. *Physics of Ice Core Records*, *121–140*, 121–140. Retrieved from https://eprints.lib.hokudai.ac.jp/dspace/bitstream/2115/32465/1/P121-140.pdf

Johnsen, S., Dansgaard, W., & White, J. (1989). The origin of arctic precipitation under present and glacial conditions. *Tellus B: Chemical and Physical Meteorology*, *41*(4), 452–468. https://doi.org/10.3402/tellusb.v41i4.15100

Jones, T. R., Cuffey, K. M., Roberts, W. H., Markle, B. R., Steig, E. J., Stevens, C. M., et al. (2023). Seasonal temperatures in west Antarctica during the Holocene. *Nature*, *613*(7943), 292–297. https://doi.org/10.1038/s41586-022-05411-8

Jouzel, J. (2013). A brief history of ice core science over the last 50 yr. *Climate of the Past*, *9*(6), 2525–2547. https://doi.org/10.5194/cp-9-2525-2013

Jouzel, J., Masson-Delmotte, V., Cattani, O., Dreyfus, G., Falourd, S., Hoffmann, G., et al. (2007). Orbital and millennial Antarctic climate variability over the past 800,000 years. *Science*, *317*(5839), 793–796. https://doi.org/10.1126/science.1141038

Jouzel, J., & Merlivat, L. (1984). Deuterium and oxygen 18 in precipitation: Modeling of the isotopic effects during snow formation. *Journal of Geophysical Research*, *89*(D7), 11749–11757. https://doi.org/10.1029/jd089id07p11749

Kjær, H. A., Vallelonga, P., Svensson, A., Kristensen, M. E. L., Tibuleac, C., & Bigler, M. (2013). Continuous flow analysis method for determination of dissolved reactive phosphorus in ice cores. *Environmental Science & Technology*, *47*(21), 12325–12332. https://doi.org/10.1021/es402274z

Laepple, T., Werner, M., & Lohmann, G. (2011). Synchronicity of Antarctic temperatures and local solar insolation on orbital timescales. *Nature*, *471*(7336), 91–94. https://doi.org/10.1038/nature09825

Landais, A., Steen-Larsen, H., Guillevic, M., Masson-Delmotte, V., Vinther, B., & Winkler, R. (2012). Triple isotopic composition of oxygen in surface snow and water vapor at neem (Greenland). *Geochimica et Cosmochimica Acta*, *77*, 304–316. https://doi.org/10.1016/j.gca.2011.11.022

Landais, A., Stenni, B., Masson-Delmotte, V., Jouzel, J., Cauquoin, A., Fourré, E., et al. (2021). Interglacial Antarctic–southern ocean climate decoupling due to moisture source area shifts. *Nature Geoscience*, *14*(12), 918–923. https://doi.org/10.1038/s41561-021-00856-4

Lilien, D. A., Steinhage, D., Taylor, D., Parrenin, F., Ritz, C., Mulvaney, R., et al. (2021). Brief communication: New radar constraints support presence of ice older than 1.5 myr at little dome c. *The Cryosphere*, *15*(4), 1881–1888. https://doi.org/10.5194/tc-15-1881-2021

Madsen, M. V., Steen-Larsen, H. C., Hörhold, M., Box, J., Berben, S. M. P., Capron, E., et al. (2019). Evidence of isotopic fractionation during vapor exchange between the atmosphere and the snow surface in Greenland. *Journal of Geophysical Research: Atmospheres*, *124*(6), 2932–2945. https://doi.org/10.1029/2018jd029619

Masson-Delmotte, V., Hou, S., Ekaykin, A., Jouzel, J., Aristarain, A., Bernardo, R., et al. (2008). A review of Antarctic surface snow isotopic composition: Observations, atmospheric circulation, and isotopic modeling. *Journal of Climate*, *21*(13), 3359–3387. https://doi.org/10.1175/2007jcli2139.1

Masson-Delmotte, V., Steen-Larsen, H. C., Ortega, P., Swingedouw, D., Popp, T., Vinther, B., et al. (2015). Recent changes in north-west Greenland climate documented by neem shallow ice core data and simulations, and implications for past-temperature reconstructions. *The Cryosphere*, *9*(4), 1481–1504. https://doi.org/10.5194/tc-9-1481-2015

Merlivat, L., & Jouzel, J. (1979). Global climatic interpretation of the deuterium-oxygen 18 relationship for precipitation. *Journal of Geophysical Research*, *84*(C8), 5029–5033. https://doi.org/10.1029/jc084ic08p05029

Nakazawa, F., Nagatsuka, N., Hirabayashi, M., Goto-Azuma, K., Steffensen, J. P., & Dahl-Jensen, D. (2021). Variation in recent annual snow deposition and seasonality of snow chemistry at the east Greenland ice core project (EGRIP) camp, Greenland. *Polar Science*, *27*, 100597. https://doi.org/10.1016/j.polar.2020.100597

Persson, A., Langen, P., Ditlevsen, P., & Vinther, B. (2011). The influence of precipitation weighting on interannual variability of stable water isotopes in Greenland. *Journal of Geophysical Research*, *116*(D20), D20120. https://doi.org/10.1029/2010jd015517

Ritter, F., Steen-Larsen, H. C., Werner, M., Masson-Delmotte, V., Orsi, A., Behrens, M., et al. (2016). Isotopic exchange on the diurnal scale between near-surface snow and lower atmospheric water vapor at Kohnen station, east Antarctica. *The Cryosphere*, *10*(4), 1647–1663. https://doi.org/10.5194/tc-10-1647-2016

Sodemann, H., Masson-Delmotte, V., Schwierz, C., Vinther, B., & Wernli, H. (2008). Interannual variability of Greenland winter precipitation sources: 2. Effects of North Atlantic oscillation variability on stable isotopes in precipitation. *Journal of Geophysical Research*, *113*(D12), D12111. https://doi.org/10.1029/2007jd009416

Steen-Larsen, H., Risi, C., Werner, M., Yoshimura, K., & Masson-Delmotte, V. (2017). Evaluating the skills of isotope-enabled general circulation models against in situ atmospheric water vapor isotope observations. *Journal of Geophysical Research: Atmospheres*, *122*(1), 246–263. https://doi.org/10.1002/2016jd025443

Town, M. S., Steen-Larsen, H. C., Wahl, S., & Faber, A.-K. (2023). Water isotopologues of near-surface polar snow from short (1-m) snow cores, extracted from the EastGRIP site on Greenland Ice Sheet during summers 2017-2019 with age-depth model [Dataset]. PANGAEA. https://doi.org/10.1594/PANGAEA.958540

Vallelonga, P. (2014). NOAA/WDS paleoclimatology—Northeast Greenland Ice Stream (NEGIS) 2012 Ice Core Chemistry and Density. https://doi.org/10.25921/PWGG-J247

Vallelonga, P., Christianson, K., Alley, R., Anandakrishnan, S., Christian, J., Dahl-Jensen, D., et al. (2014). Initial results from geophysical surveys and shallow coring of the northeast Greenland ice stream (NEGIS). *The Cryosphere*, *8*(4), 1275–1287. https://doi.org/10.5194/tc-8-1275-2014

Wahl, S., Steen-Larsen, H. C., Hughes, A., Dietrich, L. J., Zuhr, A., Behrens, M., et al. (2022). Atmosphere-snow exchange explains surface snow isotope variability. *Geophysical Research Letters*, *49*(20), e2022GL099529. https://doi.org/10.1029/2022GL099529

Wahl, S., Steen-Larsen, H. C., Reuder, J., & Hörhold, M. (2021). Quantifying the stable water isotopologue exchange between the snow surface and lower atmosphere by direct flux measurements. *Journal of Geophysical Research: Atmospheres*, *126*(13), e2020JD034400. https://doi.org/10.1029/2020jd034400

Werner, M., & Heimann, M. (2002). Modeling interannual variability of water isotopes in Greenland and Antarctica. *Journal of Geophysical Research*, *107*(D1), ACL–1.

Werner, M., Langebroek, P. M., Carlsen, T., Herold, M., & Lohmann, G. (2011). Stable water isotopes in the ECHAM5 general circulation model: Toward high-resolution isotope modeling on a global scale. *Journal of Geophysical Research*, *116*(D15), D15109. https://doi.org/10.1029/2011jd015681

Zannoni, D., Steen-Larsen, H. C., Peters, A., Wahl, S., Sodemann, H., & Sveinbjörnsdóttir, A. (2022). Non-equilibrium fractionation factors for d/h and 18o/16o during oceanic evaporation in the north-west Atlantic region. *Journal of Geophysical Research: Atmospheres*, *127*(21), e2022JD037076. https://doi.org/10.1029/2022jd037076

Zuhr, A. M., Münch, T., Steen-Larsen, H. C., Hörhold, M., & Laepple, T. (2021). Local-scale deposition of surface snow on the Greenland ice sheet. *The Cryosphere*, *15*(10), 4873–4900. https://doi.org/10.5194/tc-15-4873-2021

Zuhr, A. M., Wahl, S., Steen-Larsen, H. C., Hörhold, M., Meyer, H., & Laepple, T. (2023). A snapshot on the buildup of the stable water isotopic signal in the upper snowpack at EastGRIP on the Greenland ice sheet. *Journal of Geophysical Research: Earth Surface*, *128*(2), e2022JF006767. https://doi.org/10.1029/2022jf006767

References From the Supporting Information

Craig, H. (1961). Standard for reporting concentrations of deuterium and oxygen-18 in natural waters. *Science*, *133*(3467), 1833–1834. https://doi.org/10.1126/science.133.3467.1833

Hörhold, M., Behrens, M., Wahl, S., Faber, A.-K., Zuhr, A., Meyer, H., & Steen-Larsen, H. C. (2022). Snow stable water isotopes of a surface transect at the EastGRIP deep drilling site, summer season 2019 [Dataset]. PANGAEA. https://doi.org/10.1594/PANGAEA.945563

Hörhold, M., Behrens, M., Wahl, S., Faber, A.-K., Zuhr, A., Zolles, T., & Steen-Larsen, H. C. (2022). Snow stable water isotopes of a surface transect at the EastGRIP deep drilling site, summer season 2018 [Dataset]. PANGAEA. https://doi.org/10.1594/PANGAEA.945544

Johnsen, S., & Andersen, N. (1978). On power estimation in maximum entropy spectral analysis. *Geophysics*, *43*(4), 681–690. https://doi.org/10.1190/1.1440846