

RC2

General comments:

This paper examined the role of sublimation as a driver of isotope climate signal preserved in ice cores. This study conducted two experiments in laboratory and field (Greenland) and a modelling for lab experiment. Each of the three major topics, experiment, modeling, and field experiments, are interesting and the data will be valuable. However, I think that each topic ends up with insufficient discussion/interpretation. In addition, because of the three topics, it is difficult to understand the main findings of this study. Please see my comments for details. Overall, substantial revision is needed for this MS.

Major comments

(1) L310 "This contradicts the traditional theory of sublimation, which states that sublimation occurs layer-by-layer and does not alter the snow isotopic composition...(Dansgaard et al., 1973)".

>This is one of major arguments of this paper. Please explain why the traditional theory is wrong. During sublimation, the remaining ice is not mixed. Thus, the isotope ratio is not controlled by typical Rayleigh distillation. This basic concept sounds very reasonable and therefore many people believe it.

The traditional theory postulates that the ice core water isotope signal is governed by the precipitation isotope effect. However due to the practical difficulties of sampling the snow fall on top of the Greenland and Antarctic Ice Sheets and the time scales involved in creating the ice core signal in the real world it has not been possible to establish the physical processes linking the snowfall water isotope and ice core isotope climate signal. However, previous work (Ritter et al., 2016, Casado et al., 2018, Steen-Larsen et al., 2014) has documented both for Antarctica and Greenland that the water stable isotope signal of the snow is influenced by post-depositional processes taking place between precipitation events. Thus, while the isotope signal of precipitation may be controlled by Rayleigh distillation, the recorded signal in the ice sheet reflects a combination of Rayleigh distillation and post-depositional processes.

Furthermore, previous laboratory experiments (i.e. Ebner et al., 2017; Sokratov and Golubev, 2009) have established that sublimation does influence the isotopic composition of remaining snow, and sublimation does not occur layer-by-layer as was traditionally thought. These previous laboratory and field experiments show that there are deficiencies in the traditional theory. Our manuscript aims to address these issues and work towards determining the extent to which the isotope signal in the ice core reflects precipitation (i.e. Rayleigh distillation), sublimation, and condensation.

(2) The model used in this paper is based on a mass balance, in which input data is the observed vapor isotope ratio. Thus, it is not surprising that the model result agrees with the observation. I think different approach is needed to understand the physical process behind this experiment. For example, Figure 4 shows significant decrease of relative humidity. This should affect kinetic fractionation during sublimation. Thus, the net isotope fractionation factor had changed during the experiment. How much this affects your observation? The impact of changing fractionation factor may be evaluated (i.e., Craig-Gordon model). This is important because the snow/vapor isotope composition changed because of changing fractionation factors.

The decreasing relative humidity does likely cause the fractionation factor to change; however, this is not the reason that the snow/vapor composition is changing. As lighter isotopes preferentially sublime, the remaining fraction of snow becomes isotopically heavier. Subsequently, continuous sublimation causes both the remaining fraction of snow and the sublimated vapor to become isotopically heavier with time. While the changing fractionation factor may cause the relationship between the snow and sublimated vapor to vary slightly over the course of the experiment, the primary cause of changing snow and vapor composition is the removal of relatively more light isotopes than heavy isotopes from the system.

Because the removal of light isotopes drives the changing snow surface composition, it is reasonable to use a mass balance model to describe this physical process. Rather than calculating the vapor isotopic composition with a parameterization that was developed for water bodies (i.e. Craig-Gordon model), we therefore make use of the actual, measured vapor isotopic composition. The development of a full parameterization for the sublimation fractionation is beyond the scope of this paper, but could be developed in future modeling studies.

Furthermore, it is important to note that while we use a mass balance model to estimate changes in the snow surface (and a future full parameterization could do the same), only by including the Johnsen diffusion model are we able to simulate the full snow column. Thus, our model demonstrates not only that the isotopic composition of the snow surface changes due to sublimation, but that these changes can rapidly propagate deeper below the surface layer.

Additionally, we had explored utilizing the Craig-Gordon model to describe our experimental results, but found that we were not able to fit the model to our observations. This indicates that either the Craig-Gordon model for evaporation is not applicable to sublimation, or that it is not applicable to the rate of sublimation flux observed in the laboratory experiments. Thus, the mass balance model is more effective in describing our observations. That being said, we will note that fitting the values for k , n , or θ (as used in the Craig-Gordon model) would only be valid for the very specific environmental conditions used in the experiment, and a calculated kinetic fractionation factor would not be applicable to a real-world scenario. Thus, providing this number as a result may only introduce confusion to the reader.

(3) Please state clearly what is new compared to previous studies in Introduction. Sampling depths appear to be finer for this study? What new for the laboratory experiment?

The key novelty of these laboratory experiments compared to previous studies is the combination of continuous water vapor isotope measurements of the sublimated snow along with high resolution sampling of the snow pack for both $d_{18}O$ and dD measurements. The continuous water vapor isotope measurements allow us the possibility to directly measure the isotopic composition of the sublimate flux from the snow surface.

Previous laboratory studies only measured $d_{18}O$ (i.e. Ebner et al., 2017), or only measured snow (i.e. Sokratov and Golubev, 2009). Previous field studies had lower sampling resolution (i.e. Steen-Larsen et al., 2014), or only measured surface snow (i.e. Casado et al., 2018, Ritter et al., 2016). Building off of these previous studies, our laboratory experiment is the first to measure $d_{18}O$ and dD at finer resolution of snow samples with continuous vapor measurements of $d_{18}O$ and dD . Our field experiments are the first to measure snow $d_{18}O$ and dD at multiple depths at hourly resolution for multiple multi-day experimental periods, with simultaneous continuous vapor measurements of $d_{18}O$ and dD .

To clarify this in the manuscript, we have added the following in L70: “Thus, these laboratory and field experiments are the first to measure both d18O and dD at fine vertical and temporal resolution for multiple depths across several multi-day experimental periods under differing environmental conditions, with simultaneous continuous measurements of atmospheric vapor d18O and dD. In case of the laboratory experiments presented, the vapor isotopic composition can directly be interpreted as the isotopic composition of the flux, since the experimental set-up fulfills the closure assumption and therefore allows a direct comparison of flux and snow isotopic composition.”

(4) Maybe the originality of this study is that the combination of the tree topics (lab, field, and model). If so, what did you “learn” from the combination? As the authors themselves noted, the laboratory experiment is difficult to compare the field result because of extreme condition of the lab experiment.

The benefit of utilizing multiple experiment types is that we are able to better interpret field observations. By isolating the process of sublimation in the laboratory experiments, we can determine the effect of sublimation on the snowpack. Thus, in the field experiments, we can differentiate between sublimation and other processes (such as condensation) that are occurring throughout the experimental period. While the effect of sublimation in the field is dampened compared to the laboratory conditions, we are able to identify time periods when it may be occurring (as discussed in Section 4).

(5) Reproducibility is the crucial for such experiment. Thus, please describe the setting of the experiment strictly (please refer to specific comments).

See responses to specific comments.

(6) I do not understand the exact purpose of the FB experiment because the condition (the box and cloth cover) is too far from nature. Maybe this is designed as an intermediate between laboratory and field?

Yes, the FB experiment is intended to be an intermediate between the laboratory and field. The FS samples, taken directly from the snow surface, are subject to variability in the snow surface isotopic composition due to wind blown snow, dunes, etc. For this reason we have three FS sample sites and report the average values, but it is also useful to include observations from FB snow samples that are subject to similar atmospheric conditions but are homogeneous at the start of the experiment.

(7) Please add the raw data and modelling code you used in supplementary material so that the readers can reproduce the figures.

The raw data is currently under revision for publication through PANGAEA and a DOI will be added when available. The reader would be able to reproduce figures using the model equations described in Appendix C.

Specific comments

L6 “how vapor-snow exchange and sublimation processes....”

>I think that the physical mechanism behind the vapor-snow exchange process is sublimation and deposition. Why did you say “the vapor-snow exchange and sublimation”? In fact, the two terms appeared several times throughout the paper.

To simplify this we have changed the following instances:

L6 from “vapor-snow exchange and sublimation” to “vapor-snow exchange”

L369 from “sublimation and snow-vapor exchange” to “sublimation and vapor deposition”

L371 from “sublimation and snow-vapor isotope exchange” to “sublimation and vapor deposition”

L.18 “our results demonstrate that post-depositional processes such as sublimation play a role...”

>Please clarify the difference from the previous findings.

L18-19 has been modified: “...our results demonstrate that post-depositional processes such as sublimation play a role in creating the climate signal recorded in the water isotopes in surface snow, both in laboratory and field settings.” to clarify that we use findings from both laboratory and field experiments, which differs from previous studies.

L92 “Plywood box” > Add thickness.

L92 has been revised: “outer plywood box (2.7 cm thick)”

L.93 “PID-controlled heater” > Add details (e.g., what kind of heater (cable or panel)? Wattage?). Please also illustrate the location of the heater in Fig.1a.

L93 has been revised to “PID-controlled (Omega CN7800; 50 W) cable heater wrapped around the inside of the plywood box.”

L.93 “with a generator” > Add details (product name, manufacture name etc.).

L93 has been revised to “with a generator (Puregas CDA-10)”

L94 “mass flow controller” > Add details (product name, manufacture name etc.). Please also illustrate this in Fig. 1a.

“...mass flow controller...” has been changed to “...HORIBA SEC-4400 mass flow controller...”. To maintain simplicity in the diagram we have not changed the illustration, but the caption has been changed: “...dry air was pumped into the inner box...” has been changed to “...dry air regulated by a mass flow controller was pumped into the inner box...”.

L95. “continuously-running fans” > Add details (wind speed, product name, manufacture name etc.). How many fans exactly did you install?

“...continuously-running fans maintained mixed air in the chamber” has been changed to “...two continuously-running computer fans at the top of the chamber maintained mixed air”

L.96 “small boxes” > Please add material used for this box. Please also add thickness of the boxes.

“...small boxes...” has been changed to “...small plastic boxes...”. The thickness of the boxes is not relevant; the size described “(5.7x5.7x7.6 cm)” are the inner measurements of the box.

L.115 “experiments used snow” → Please add details (type of snow, density etc.)

Detail added to L97: “...well-mixed and sifted so that snow grain size (1-2 mm) and isotope value was homogeneous...”

L.137 “partially buried” > How deep exactly?

L137 has been clarified: “Sampling boxes were partially buried in the snow surface, with the top of the sample box 1-2 cm above the surrounding snow surface to minimize any risk of contamination from wind-blown snow. Samples were also protected from direct overhead...”

L.137 “a cloth covering” > Please add details (material used, thickness, color). I do not understand why you used the cloth. Maybe the melting occurred because the boxes only “partially” buried?

L137 has been clarified: “...overhead sunlight using a light-colored thin cloth covering.” The cloth is also visible in the photos in Fig. 1. Having the boxes partially buried may have contributed to melt, but it would have been very difficult to fully bury the boxes without risking contamination from the surrounding snow.

L.161 “KNF pump” > please add details (product name).

L161 has been revised: “...diaphragm pump (KNF model DC-B 12V UNMP850)...”

L.304 “.a strong decrease in the d-excess. This indicates that the HD16O water isotopes are preferentially removed compared to H218O”

> A decrease in the d-excess does not necessarily indicate that the HD16O is preferentially removed compared to H218O (i.e., HD16O are almost always preferentially removed compared to H218O because of larger isotope effect). The change of d-excess depends on changes in dD and d18O relative to slope of 8.

L303-305 have been revised: “In addition we observe a strong decrease in the snow surface d-excess. Decreasing d-excess driven by kinetic fractionation is also observed when a body of water evaporates into a sub-saturated atmosphere (Benson and White 1994, Merlivat and Jouzel 1979). As a similar effect is observed during sublimation in laboratory experiments, we draw the analogy that this is due to kinetic fractionation .”

L.304 “this indicates that the HD16O water isotopes are preferentially removed compared to H218O” > Precisely, the HD16O is an isotopologue of water. Furthermore, there is NO water isotopes, only oxygen (or hydrogen) isotope exists. But I know that many people used this term, “water isotope”. Thus, it is not necessarily to revise “water isotope” throughout this manuscript. But this sentence is a bit strange.

In the instance of L304 “isotopes” is changed to “isotopologues” as we are specifically referencing HD16O. In other cases we prefer to use “water isotopes” which is commonly used throughout ice core literature.

L355 “A site such as Renland (east-central Greenland), which receives 45 cm per year ...will be less affected.... ”

> The SE-Dome core is a more suitable example of a high-accumulation site, which receives 102 cm per year. Furthermore, the ice-core d18O record is remarkably similar to the isotope-GCM outputs, suggesting negligible influence of post-depositional effect (Furukawa et al., 2017).

The example in L355 has been changed: “A site such as SE-Dome (southeast Greenland), which receives 102 cm per year ice equivalent precipitation (Furukawa et al., 2017) (i.e. several meters of snowfall), will be less affected...”

Reference: Furukawa, R., Uemura, R., Fujita, K., Sjolte, J., Yoshimura, K., Matoba, S., & Iizuka Y. (2017). Seasonal-scale dating of a shallow ice core from Greenland using oxygen isotope matching between data and simulation. *Journal of Geophysical Research: Atmospheres*, 122, 10,873 – 10,887. <https://doi.org/10.1002/2017JD026716>

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