Response to Review 1:

We thank the reviewer for their time and effort to evaluate and develop our study. We acknowledge the constructive criticism and comments from the reviewer and propose the following revisions. We appreciate the comments by the reviewer which have resulted in a significantly strengthened manuscript.

The original comments from the reviewer are in black and in blue are the author's responses, with blue italics to show the in-text changes. We want to point out that due to many useful comments and suggestions, the major revisions have been implemented resulting in significant changes to the manuscript, as can be seen in the document attached below.

Introduction

In my opinion, the introduction needs a more stringent train of thought to lead readers into the topic more smoothly. At the start, a broader introduction to the importance of proper ice core proxy use, and especially the relevance of this study in this wider context, would help to gain the readers' attention for this work. In this regard, L28-29, L46-50, L58-61, L67-69 are already interesting hooks, on which you could expand, so that the importance of your work is explicitly stated. I would further recommend a broader climate description of the study site, because this is something the authors rely on later during the interpretation of results (e.g. L375).

We take onboard this comment by adding an additional explanation of the interpretation of d-excess in ice cores (linked to a later comment starting L22). To expand the context and the importance of this study we propose to add the following text, which creates a stronger coherence between the introduction and the discussion on isotopic fractionation.

Introduction: *"... Decreasing SSA is predominantly the result of Ostwald Ripening, where large grains grow at the cost of smaller grains (Lifshitz and Slyozov,1961; Wagner 1961; Legegneux et al., 2004), and vapour diffusion driven by sublimation from convex surfaces, and deposition onto low energy regions (Pinzer et al., 2012; Flin and Brzoska, 2008; Sokratov and Golubev, 2009). The latter is dependent on temperature (Cabanes et al., 2002), temperature gradients between the air (Ebner et al.,2017), surface and subsurface, and wind conditions (Neumann et al., 2004; Town et at., 2008). Under natural conditions SSA decrease is driven by a combination of these processes (Pinzer and Schneebeli, 2009), each potentially modifying the isotopic composition of the snow (Ebner et al., 2017)."*

Regarding the study site, we have added some additional information about the accumulation rate and synoptic conditions at EastGRIP, while an extensive description of the meteorological conditions over the three sampling seasons has been added to the results. An overview of the results section restructuring can be found in the responses in the results section of the reviewer's comments.

"The accumulation rate is approximately 14 cm w.eq. yr^{-1} (Schaller et al., 2017).

Westerly winds prevail during 2017 and 2018 with a wind direction of 227◦N, while 2019 had a prevailing south westerly wind (239◦N), corresponding to opposing phases of the North Atlantic Oscillation (NAO).

Significant weather conditions such as ground fog, drifting snow and snowfall, were documented each day."

L5: The phrase 'after precipitation/deposition events' used here gives me the opportunity to point out the unclear use of either term in this manuscript. Given that you refer to surface snow, which stayed at the surface for an unknown period (L38-39), I would prefer the term 'deposition' event defined more clearly somewhere in the introduction/method section and used consistently throughout the manuscript, replacing 'precipitation'.

The term 'deposition event' is now used throughout the manuscript unless specifically referring to a precipitation. We propose to add the text below to define deposition events. We also take this opportunity to add an explanation of the influence of surface hoar and or sublimation crystal formation on the surface snow, based on SSA measurements of these deposition features from previous studies.

"The term deposition events is used to describe rapid increases in SSA, expected to be from precipitation or drifted snow. It does not explicitly include surface hoar and sublimation crystal-like grain growth at the surface, given that previous studies indicate these depositional features have an SSA value around 54 $m^2\ kg^{-1}$ using SSA of hoar frost (Dominé et al., 2009)."

To account for the possibility of deposition via surface hoar we use field observations, latent heat flux measurements and temperature gradient data when analysing the isotopic change.

L22: Since the interpretation of deuterium excess as a proxy of moisture source conditions is a key background for this study, I suggest expanding on this point of the introduction. What kind of conditions were thought to be reflected by d-excess

We have expanded on the interpretation of d-excess in ice cores and what environmental conditions control d-excess.

"The second-order parameter deuterium excess (d-excess) is defined by the deviation from the near-linear relationship between δ18O and δD due to non-equilibrium (kinetic) fractionation (d-excess = δD - 8 · δ18O), and is understood to reflect moisture source conditions (Dansgaard, 1964; Merlivat and Jouzel, 1979; Johnsen et al., 1989), snow crystal formation in clouds (Ciais and Jouzel, 1994; Sodemann et al., 2008), and changes in moisture source (Masson-Delmotte et al., 2005). …

Post-depositional processes at the surface involve additional kinetic effects adding complexity to the interpretation of d-excess (Casado et al., 2016; Hughes et al., 2021; Casado et al., 2021)."

This is followed by recent studies evidencing kinetic fractionation during sublimation, as well as the supersaturated conditions leading to hoar frost which would cause large increases in d-excess (Stenni et al., Feher et al., 2021, Hughes et al., 2021; Casado et al., 2021). The revised discussion more stringently links the results from our study to previous work.

L34: As far as I can see, this is the first time, you use SSA as an abbreviation, so that an explanation of the full term and a slightly more detailed definition would be appropriate here.

We apologise for this mistake; this sentence has now been modified to the following:

*"Snow metamorphism works to reduce the snow-air interface, which can be quantified using the parameter snow specific surface area (SSA) (Legagneux et al., 2005). SSA of a snow sample is dependent on optical grain radius and density of ice (SSA=6/rhoice*dopt) (Gallet et al., 2009)".*

L43: You use the term snow 'crystals' here. I suggest replacing it with snow 'grains', here and throughout the manuscript, because you are not specifically talking about the crystallographic term but rather the ice matrix, which is mostly composed of multi- crystal ice grains.

We agree, now 'snow crystals' has been changed to 'snow grains' throughout the text.

Methods

In section 2.5.1., the definition of a decay event is not entirely clear to me.

We add the following text to improve clarity:

"To systematically identify rapid decreases in SSA, which we use as a proxy for events of snow metamorphism after deposition (identified based on the high mean SSA values), a threshold is set using the bottom 10th percentile of SSA decreases over a two-day period. This was found to result in the most equal number of events from each sampling year compared to 1- and 3-day changes. SA decay events are defined as by the initial peak, identified by the threshold, through to the next increase in SSA (rather than decrease)."

L94-96: When did you take the samples exactly? How many were afternoon samples, and does this affect the results discussed here?

The samples were all done in the daytime, and primarily done in the morning. In the submitted paper we resampled the meteorological data to the SSA sampling time-periods to ensure consistent comparison. Moreover, the decay model and model intercomparison are now based on the exact sampling time, given that the existing models are hourly resolution.

It is slightly more complicated to include the exact sampling time when assessing the relationship between change in SSA and the absolute SSA values (Fig. 1), given that we do not want to interpolate SSA as we understand that the change will not be linear throughout the day. Instead, we propose to keep the "daily" change, and clearly state the different sampling times as limitation to the model. The corresponding description has been changed to:

"*The samples were all taken in the daytime, primarily in the morning. The meteorological data is re-sampled to the SSA sampling time-periods to ensure consistent comparison.* "

L97-98: I suggest amending the title of this section, because you are not strictly talking about the calibration of the Ice Cube device but the SSA measurements using the Ice Cube.

The section title has been changed to "*SSA measurement protocol*".

L101: is 294 kg m-3 the density averaged over all three seasons, or do the seasons differ significantly in value?

This is an average over all seasons. Annual means and standard deviations have also been added "(2017 = 307±40 kg m^{-3}, 2018 =278±47 kg m^{-3}, 2019 = 294±50 kg m^{-3})".

L108: Did you use the identical sample for SSA and stable water isotopic measurements or neighbouring material? Depending on this, the sentence in L110 needs amending: 'sealed in a polyethylene bag' or are several bags used for one sample?

The SSA samples were subsequently measured for water isotopes composition, we apologise that this was unclear. To clarify this sentence has been added to the text:

"Individual SSA samples were put in separate bags and subsequently sampled for water isotopic composition. Thus, every day the 10 SSA samples have a corresponding isotopic composition. The resultant isotope value is the average composition over the top 2.5 cm of snow."

L135: Why did you choose the threshold 6 m s-1? If I am not mistaken, blowing snow is already an issue at 5 m s-1, so that this could be a better threshold? It could also be helpful to know how many data points are in the upper spectrum of wind speeds still considered.

We agree with hindsight that this threshold is insufficient to reduce the likelihood of surface perturbation, and to address this we now use the 10-minute data from PROMICE. It is important to note here that 209 out of the total 237 sampling days have daily maximum wind speed exceeding 5 m s^{-1} and no events had wind-speed consistently below 5 m s^{-1} (two had 5.1 m s^{-1}). In addition, snowdrift events were documented in the EastGRIP field diary and correspond to wind-speeds above 7 m s^{-1}. Several events have maximum wind-speed between 6- 7 m s^{-1}, and no snowdrift documented. Based on this analysis and observations from the literature, we define two wind categories, as briefly suggested by the reviewer in a later comment, we have added a secondary wind-speed category for comparison of SSA decay when wind-speed is <6 m s^{-1} (low-wind events), and when maximum wind-speed is between 6- 7 m s^{-1} (moderate-wind events). The following text is added to the document:

"A set of criteria are required to reduce the potential of analysing events with wind-perturbed surfaces, resulting in the removal of surface snow. In Antarctica, unconsolidated surface snow has been observed to drift at wind speeds as low as 5 m s−1 measured at 2 m height (Birnbaum et al., 2010). However, a study from Greenland documented snowdrift starting at 6 m s−1 (Christiansen, 2001), likely due to warmer temperatures allowing for the surface snow to become more bonded (Li and Pomeroy, 1997). At EastGRIP, calm conditions correspond to wind speeds from 0 –5.2 m s−1 according to field diary observations. The mean daily maximum wind speed for the three sampling seasons was 6.8 m s−1, while blowing snow was documented only when wind speeds exceeded 7 m s−1. Based on this assessment, we define two wind-speed categories for comparison of the effects of wind-speed on SSA decrease. The first includes events with wind-speed consistently below 5.2 m s−1, hereafter referred to as low-wind events, to ensure no surface perturbation. Secondly, we consider events where the maximum wind-speed is between 6 –7 m s−1, hereafter referred to as the moderate-wind events. The inclusion moderate-wind events allow an assessment of the influence of wind-speed on SSA decrease."

Two SSA decay events are below the 6ms-1 threshold, both of which are from 2018. The remaining SSA decay events, E10 and E11, have maximum values of 5.1 m s^{-1}, and 5.07 m s^{-1}, respectively and last for 3-days each.

Out of the 21 initially defined events, only 2 are below the wind-speed threshold with maximum values of 5.1 m s^{-1} in both events. We expect negligible snowdrift for these two events allowing us to confidently argue that the surface is unperturbed and isotopic change is the result of snow metamorphism. The likelihood of drifting snow during moderate-wind events is considered using the equation defined from Li and Pomeroy (1998), where the threshold wind-speed for snowdrift is defined as a function of temperature.

Following the same structure as in the original manuscript, we construct the SSA decay model with parameter values set for the two wind-regimes. We add the revised figure to this response. Intuitively, the SSA decay rate is higher for moderate-wind events (-0.53 m^2 kg^{-1} day^{-1}) compared to low-wind events (-0.41 m^2 kg^{-1} day^{-1}). As the reviewer will see later in this response, we add the results from the comparison of our data and SSA decay model to existing models from Flanner and Zender (2006) and Taillandier et al. (2007).

The wind-speed distributions for the daily maximum and 10-minute mean values are also added to the supplement. For isotopic analysis we now focus on the low-wind events alone and describe the latent heat flux and temperature gradients during the two events.

L162-164: I think that you are making an important point here. Could you clarify this sentence so that it becomes obvious why you chose -25°C and not -22°C as the boundary of your SSA decay model, given that this is where snow crystal shape changes? And maybe this is better placed in the methods section.

We agree that the temperature boundaries are clearly an interesting feature of the work. Nonetheless, due to the updated wind-speed criteria, we have ultimately removed this temperature boundary condition given that the low-temperature event coincides with high-winds.

Figure 1: Firstly, the layout of this figure does a good job at visualising the sampling procedure. Unfortunately, I cannot read the site labels and the legend in panel (a). Personally, I can recommend the open-source software QGIS for designing maps. Table 1: How is the data coverage of the AWS for the seasons 2017-2019? How many data points are missing? I think that '.2' should be amended to '0.2'. The term EC needs explanation here, as it is the first time, this is mentioned.

We thank the reviewer for the suggestion to use QGIS. We have simply replaced the map as the legend in the previous figure was not relevant to the study, but QGIS will definitely be beneficial for future work. '.2' has been changed to '0.2' and added information about the eddy-covariance tower and the measurement instruments from PROMICE to the table.

Results

When it comes to the presentation of results, certain parts of the description appear repetitive (e.g. L270-273), while major conclusions are only mentioned once and are not stated clearly enough (e.g. L283-285). Your work is really interesting, so that I would like to see (1) a concise description of all records of relevance, (2) a step-by-step line of interpretation, in which your outcomes become more visible. At the moment, the measured results and their interpretation are often mixed and the sub-division into chapters not very clear. Moreover, the chosen language is sometimes vague, leaving out important details which allow the reader to know exactly which parameter you are talking of (e.g. L240-249). I would recommend making the descriptions as precise and specific as possible, e.g. in L87 'the specific sampling dates' would be better.

Based on the reviewers' comments, we have restructured the results to improve clarity and strengthen our arguments. The new format is broadly as follows and we have included the updated figures.

1) Description of all used datasets (time-series and basic statistics between years) has been added in the first results section. Here we look mostly at the inter-annual variability and highlight the significantly lower accumulation for 2017.

2) EOF analysis follows the meteorological description to show the relationship between the dominant modes of variance of SSA, d18O and d-excess. The three parameters, SSA, d18O and d-excess are described before presenting the EOF analysis. By moving this section, the motivation for exploring the relationship between isotopic composition and SSA later in the paper becomes clearer. Here we also add the revised accumulation data for each sampling season.

3a) Description of SSA decay events extracted by the threshold, with clear explanation that events with snowfall/fog/snow drift (from field-diary) and high wind speeds are removed from further analysis. The identification of similar decay shapes in SSA time series are then noted.

3b) The empirical model to describe the SSA decrease behaviour during periods of rapid SSA decay is described for the previously described wind-speed categories. A linear regression between dSSA and SSA for the two wind-speed categories is noted to describe the decay rate and decay constant in the decay model. Based on the reviewer's comment, we first show the mean decays for each event, and in the second panel the modelled decay. In addition, we compare the model from this study to previous models from the literature. The model from Flanner and Zender (2006) is based on theoretical grain growth, and thus we can compare the observed behaviour - and our empirical model - to their physical-based model.

4a) As previously mentioned the isotopes are measured from each SSA sample, giving us a direct comparison for analysis of SSA decay events. In the same format as the original manuscript, the isotopic changes over a single day and 2-days are documented for both the low- and moderate-wind events.

4b) We then look in more detail at the two low-wind events given that we can be more certain of minimal surface perturbation. Latent heat flux and temperature gradients during these events are presented to explain the direction of fluxes.

(If repeated, precipitation isotopic composition would be measured to determine the proportion of precipitation isotope signal in a snow sample, and thus observe the change in isotope signal from the exact precipitation signal).

L223-224: Can you provide an estimate of the probability that the top 2.5 cm sample contains material from several precipitation events? This is one part, where a more detailed climate description upfront including accumulation event frequency would be helpful.

The reviewer is indeed here asking an interesting question. Accumulation data is now added to Fig. 2 to address this point. The accumulation data shows that all the SSA samples on the first day of each decay event contained snow from more than one deposition event, given that no daily increase exceeded 2.5 cm. The uncertainty for the accumulation measurements is up to 1 cm, and therefore we cannot confidently use these measurements to approximate the number of precipitation events in one sample of snow. In addition, based on the data presented in this paper, we cannot be certain that a precipitation layer is not subsequently removed by the wind. This is added as a limitation to this study.

To account for this, we approximate the accumulation for the low-wind events, and use the field observations to identify the conditions preceding these events. The following text to the paper:

"Both E10 and E11 had consistent clear sky conditions. We note here that E11 was preceded by significant ground fog, not snowfall, indicating that the peak value of 46 m2 kg-1 was likely the result of surface hoar, and thus, the SSA decay follows an SSA peak not caused by precipitation."

"As mentioned in Section 3.2, ground fog preceded the SSA peak in E11, corresponding to negligible accumulation. In contrast, approximately 1 cm of snow was accumulated during the day prior to E10, corresponding to observation of snowfall."

L292-293: This appears to be a sentence with crucial interpretation of your records, which I think you should expand on. I am aware that the line between results and discussion section can be drawn before or after the interpretation of results, but I would like to see a clearer structure and separation from the discussion in the context of previous research.

We agree with this suggestion and propose to firstly include these previous observations more explicitly in the introduction. By focussing on the two low-wind events and their associated fluxes, the comparison to previous studies becomes more fluid. Quantification of sublimation flux during this period can potentially be added to quantify the fractionation effect. Uncertainty regarding the 2.5 cm bulk isotope measurement would hinder this approach.

"Documentation of strong sublimation during the day and weak deposition during the night corresponds to decreases in d-excess (up to 6‰) and increases in d18O of up to 1.8‰. This observation agrees with previous observation of equilibrium fractionation during sublimation (Hughes et al., 2021; Wahl et al., 2021; Casado et al., 2021). "

L304: We may be well familiar with this, but could you give a reference to back this statement, which is the result of earlier studies?

Apologies, the references Cabanes et al. (2002, 2003), Legegneux et al. (2003, 2004), Taillandier et al. (2007) and Flanner and Zender (2006) have now been added here which documents the decreased rate of snow metamorphism with lower temperatures.

Figure 3: In my opinion, this is the most important figure when it comes to describing SSA observations and the model performance, and it nicely highlights the rapid decay at the start of SSA decay events. For some parts of your model performance discussion, it would be helpful to see observations and model outcome in one panel, so I suggest amending the current panel layout or splitting this figure into two figures about (a) observation and (b) model performance. Furthermore, I recommend using one term, i.e. 'rapid SSA decay events' or similar, throughout the manuscript to be more specific than 'events' here. And since you point out the higher intercept for temperatures <-25°C (L198) and same regression slope (L207), I suggest adding a linear regression line to panel (a) and noting somewhere that the x-axis doesn't extend to 0.

We agree with the reviewer here and have changed the figure to show a column with observed decays for b) moderate-wind events and c) low-wind events. A second column shows the modelled outputs for these events (d) and e)).

The model evaluation section is extended to include a comparison to existing models. This enables us to determine what is 'meant to be' according to physical models and compare this to observations and our model with parameters set for low-wind and moderate-wind events. The additional comparison to the moderate-wind events allows for a general assessment of the additional influence of wind on the decay rate.

The lower row of Fig. A2. now shows two events - E2 from 2017 and E18 from 2019 - that have maximum daily wind speed of 6.26 m s^{-1} and 6.28 m s^{-1} respectively, and no observed snowdrift. Based on the drift threshold defined in Li and Pomeroy (1998), E2 has potential influence from snowdrift, but not E18 (U(10) = 7.09 m/s and 8.17 m s^{-1} for E2 and E18 respectively), which agrees with an underestimation of decrease from FZ06 compared to observation during E2. Interestingly, we get the lowest RMSE values for FZ06 and the moderate wind events. Possible explanations include the initial snow conditions and event duration, which are included in the discussion.

Figure 4: Is there a way to enhance the contrast between the thick line as mean and thinner individual records? Personally, I find it a challenge to see the thick line.

Yes of course, the plot has been changed to show the individual samples as crosses ('+').

Discussion

The discussion could benefit from a wider literature context.

The discussion has been largely rewritten and more relevant recent literature has been included in the discussion. Furthermore, changes have also been made to account for our changes in the structure of the results section and our methods related to event criteria. In this revised version of the manuscript, we first discuss the different regimes resulting from the EOF analysis, referring directly to papers such as Casado et al. (2021) where they identify the relative influence of precipitation and snow metamorphism on the isotopic signal in Antarctica.

Our approach to the decay model in the study is subsequently discussed, with a focus on the comparison to previous models. We highlight the limitations relating to the fact that the two low-wind events are from 2018 while the strong coherence between d-excess and SSA from EOF analysis is observed in 2019. We highlight that the purpose of SSA decay models to predict change in SSA of a snow sample through time is not readily applied to exposed surface snow, and that there is potentially an alternative direction for future studies to focus on the multiple mechanism of surface snow reworking, that would be useful for surface energy budget calculations using remote sensing.

The structure of the isotopic analysis has been modified for more stringent comparison of our results to expectations of isotopic change from previous studies. Some sections have been merged to be more concise.

L317-318: Here, it would be good to clarify that this is in agreement with the study Taillandier et al. (2007). Are there other studies that you could compare your approach/results to?

Of course, we develop this section based on results from the model intercomparison. This enables us to discuss our empirical model with respect to the physical based model from Flanner and Zender (2006) based on theoretical grain growth. The RMSE values in Table 2 indicate that FZ06 best predicts the decay of both low- and moderate-wind events.

L333: This sentence is actually the first time you state a causal connection between SSA and d-excess development, and I recommend including this section 4.3 earlier as part of the interpretation section.

We agree with the reviewer and follow the reformatted results structure to first discuss the results from EOF analysis. We focus on the inter-annual difference in regimes, where a very strong relationship is observed in 2019, while d18O and d-excess are decoupled, compared to the opposite relationships in 2018. Our results are compared to recent work from Casado et al., 2021, who document a similar inter-annual variability in Antarctica.

L351: It would be good to see references of earlier research on these factors, i.e. sublimation, deposition and vapour diffusion, cited here.

Of course, these references have been added to show the previous work that, specifically referring to Casado et al. (2021). In addition, we propose to add more structure to the isotopes discussion by primarily identifying the expectation of isotopic change during precipitation resulting from different processes (as mentioned in the response to the previous comment).

L372: While you identify ‘initial snow metamorphism’ after deposition as driver of d- excess, I think that you should be more specific and discuss the importance of deposition-free phases, here described as overcast and clear-sky conditions (Table A1), for d-excess.

This point from the reviewer is appreciated and we have added a more extensive description of conditions for the events used to assess isotopic change.

A detailed description of temperature gradients and latent heat flux data during the two low-wind SSA decay events allow us to identify the processes controlling the change in isotopic composition. The text added in response to the comment starting L393 addresses.

L381: I understand that winter snow layers have undergone more isothermal metamorphism, which is less efficient than temperature-gradient metamorphism acting especially during spring and autumn. Therefore, I recommend rephrasing 'winter layers which are less influenced by snow metamorphism'.

We agree with the reviewer and propose the following text instead:

"Snow metamorphism is thermally activated given the dominant influence of sublimation and deposition (Cabanes et al., 2002, 2003; Legegneux et al., 2004). During winter, the temperatures are very low (<-30C) and minimal insolation reduces the diurnal near-surface snow temperature gradients, resulting in isothermal metamorphism being dominant which reduces the rate of snow metamorphism, or SSA decay, compared to temperature gradient snow metamorphism (Dadic et al., 2008)*."*

L393: Section 4.6 is a very interesting and important one. The first sentence of the second paragraph appears to be a major jump in the train of thought, which I struggle to follow. Especially, the last paragraph of the conclusion contains important findings. I wish to see the last statement (L426-428) put for discussion with the same clarity earlier in the manuscript. Then, the conclusion will become a summary.

We have explained the point in L426-428 with analysis of latent heat flux and temperature gradients corresponding to isotopic change during low-wind events. As the reviewer will see, the revised structure facilitates a more concise discussion with regard to processed driving isotopic change. The following text has been added to the discussion from which we compare our observations*:*

"Three key mechanisms are expected to drive the rapid SSA decays; 1) large grains growing at the expense of small grains (Legagneux et al., 2004; Flanner and Zender, 2006), 2) diffusion of interstitial water vapour (Ebner et al., 2017; Touzeau et al., 2018; Colbeck, 1983), 3) sublimation due to the wind ventilating the saturated pore air, known as 'wind-pumping' (Neumann and Waddington, 2004; Town et al., 2008). The dominant mechanisms can theoretically be identified by a combination of the change in isotopic composition - indicating the fractionation effect - and the LE and temperature gradient data.

In theory, mechanism 1) causes minimal change in the bulk isotopic composition of a snow layer under isothermal conditions (Ebner et al., 2017). Therefore, observations of SSA decay corresponding to negligible isotopic composition change could be explained by this mechanism. We observe no events with consistent isotopic composition throughout. In the instance of 2) interstitial diffusion, light isotopes are preferentially diffused, while the heavy isotopes will be preferentially deposited onto the cold snow grains (Ebner et al., 2017; Touzeau et al., 2018; Colbeck, 1983). Thus, diffusion of water vapour in the pore space causes a decrease in d-excess and slight increases in δ18O due to kinetic fractionation (Casado et al., 2021). 3) Sublimation has been widely documented to cause an increase in δ18O of the remaining snow mass due to equilibrium fractionation, and a significant decrease in d-excess due to kinetic fractionation (Ritter et al., 2016; Madsen et al., 2019; Hughes et al., 2021; Wahl et al., 2021; Casado et al., 2021).

An overall increase in δ18O and decrease in d-excess during E10 can be attributed to a combination of 2) and 3) based on observation of net-sublimation and high amplitude diurnal temperature gradient variability indicating vapour transport within the pore space. The period between 9th June at 15:18 UTC and 10th June 10:40 UTC recorded net deposition corresponding to an overall decrease in δ18O during the first day and minimal decrease in d-excess, potentially due deposition of atmospheric water vapour (Stenni et al., 2016; Feher et al., 2021; Casado et al., 2021).

A 30% decrease in d-excess corresponds to negligible change in δ18O during E11. Net-sublimation double that of E10 is measured, but with reduced amplitude in both TGs. Moreover, the largest decrease in d-excess occurs after the first day when the surface-subsurface TG is consistently negative. This indicates that vapour diffusion is controlling the isotopic composition, and the effect of equilibrium fractionation during sublimation from the surface only weakly influences the bulk isotopic composition (Casado et al., 2021)."

L414: In my opinion, simply applying this model at other sites goes a bit too far, because site-specific accumulation seasonality/frequency plays a major role for the near-surface metamorphism. I therefore suggest elaborating on the potential and limitations of the SSA decay model for other sites in greater detail in the discussion section.

We fully acknowledge this point from the reviewer, and instead compare to physical based models from the literature. The observed influence of wind-speed on the SSA decay rate is also discussed, with reference to the limitations of such field-based studies. For example, we are limited by persistent moderate winds potentially perturbed the snow surface, as evidenced by 209 out of the 287 sampling days (2017-2019) having maximum wind-speed above 5 ms-1 based on 10-minute mean values. Although there is a low probability of snowdrift up to 6 ms-1 based on the equation below defined by Li and Pomeroy (1998), we acknowledge the potential and highlight this as a limitation.

New text: *"The SSA decay model described in this study is intended as an investigation into the in-situ behaviour of surface snow SSA through time."*

L419: While you state earlier that d-excess varies with d18O at the beginning of the season and with SSA later during summer, you state that mainly SSA and d-excess are coupled. Please be consistent with your earlier interpretation here.

We apologise for the inconsistency here. The text has been edited to reflect the different regimes between the sampling years, where for 2019 the SSA and d-excess are coupled, while the *δ18*O and d-excess are coupled during 2018. We propose to remove any generalisation and focus instead on the potential causes for the opposing regimes. We discuss the EOF results in the context of the isotopic change during the SSA decay events to improve the coherence of the discussion.

When it comes to supplementary material, I could imagine a more detailed presentation of the AWS data to be helpful for readers as a meteorological background for this study. Figure A1 is already a good start, which a bit more of a description would help.

The supplementary information has been extended, with a number of plots to support statements in the paper, specifically the covariance between principal components and wind-speed distributions for 10-minute data and the daily maximum values. In-text references to these figures have been updated and we hope this helps with clarity for explanations.

Technical details

L20: 'first order parameters' - here and in other parts of the manuscript, a hyphen is required ('first-order').

The text has been changed to "first-order parameters".

L105: As you are describing a value range here, an en-dash is needed for 2 -15–130 m kg . Same applies for value ranges throughout the manuscript.

All ranges presented in the manuscript have been corrected for this mistake.

L116: To avoid any misreading, I suggest that the equation is placed in a separate line and to replace the en-dash in 'd-excess' on the left side of the equation with a hyphen. This could also be a good place to give the d18O equation.

The d-excess equation has been moved to a separate line, we have ultimately decided not to include the d18O equation given the primary focus on SSA and d-excess.

L121: Since you are talking about events in time, 'where' should be replaced with 'when'.

This has been changed to:" This study focuses on the events when the SSA measurements decrease rapidly".

L132: Equation 1 requires a multiplication sign.

A multiplication sign has been added to equation 1 and the additional equation 2.

$$SSA(t) = SSA_0 \cdot e^{-\alpha t} \qquad SSA(t) = B - A \cdot ln(t + \Delta t),$$

L180: I think it would be helpful to reference that Table A1 is part of the Appendix. This applies here and for all other references to the Appendix/Supplementary Material. L190: 'snow fall' should be corrected to 'snowfall'.

The accumulation plot has been corrected and incorporated into the description of meteorological conditions at the start of the results. The supplementary material now includes the Table describing event conditions based on field diary observations, the relationships between the principal components from the EOF analysis, and the spatial variance of each relevant parameter (SSA, d18O and d-excess).

Please go through the entire manuscript once more and check:

The proper use and non-use of articles to achieve concise language; Inserting spaces between values and units; Introducing abbreviations when first used, both in the text and in figure captions.

We apologise for errors in the text. The revised manuscript will be thoroughly checked for all the above.

Response to Review 2:

We thank the reviewer for their helpful comments and their insight on this subject. The authors acknowledge the constructive criticism and comments from the reviewer and propose the following revisions. We appreciate the comments by the reviewer which have resulted in a significantly strengthened manuscript.

The original comments from the reviewer are in black and in blue are the author's responses, with blue italics to show the in-text changes. The authors want to point out that due to many useful suggestions, the major revisions have been implemented resulting in significant changes to the manuscript, as can be seen in the document attached below.

Overview

This paper investigates the relationship between changes in snow specific surface area (SSA) and its isotopic composition, focused on d-excess, at EastGRIP. The Authors focus on precipitation events, after which rapid SSA decays are observed, coupled to a decrease in d-excess. The Authors propose an exponential rate law for SSA decay, which is temperature independent between 0 and -25°C. The Authors then discuss the interplay between snow metamorphism and d-excess, and the possible impact of their findings on the interpretation of the ice core isotopic record.

General comments

The idea underlying this research is very nice: snow metamorphism results in sublimation-condensation cycles which should lead to isotopic fractionation. SSA decay is taken as a proxy for the intensity of metamorphism, and the expected correlation between SSA decay and isotopic fractionation is found, and is readily visible in d-excess. Such a study is clearly relevant to the interpretation of the ice core isotopic record and the data presented therefore deserves attention.

However, my opinion is that the experimental protocol is partly flawed, and this unfortunately casts doubt on the validity of the data obtained and on the conclusions derived. The first point is that SSA is measured on a 1 cm thick layer while isotopes are measured on a 2.5 cm thick layer. Furthermore, no detailed observations of surface snow are mentioned to ensure that the thicker 2.5 cm sample was the same snow layer as the top 1 cm snow. In many cases, the authors may then be measuring 2 little-related snow samples, which would in fact completely invalidate their study.

The reviewer addressed a major concern related to the sampling protocol for SSA and isotopes. The authors primarily want to clarify that the isotopic composition was *directly* measured from each SSA sample. Thus, each SSA sample has a corresponding isotopic composition. The offset we refer to comes from the measurement resolution of SSA due to the e-folding depth of 1310 nm radiation in high density snow. We apologise that this was not made clear enough in the original manuscript, and we hope that this clarification gives the reviewer increased confidence in the sampling protocol. We add the following text to the manuscript:

"Individual SSA samples were put in separate bags and subsequently sampled for water isotopic composition. Thus, each day the 10 SSA samples have a corresponding isotopic composition."

Many processes can affect the very surface snow layer. These include fog deposition, the formation of surface hoar or sublimation crystals, and wind drifting. All this is hardly mentioned, so that I am not even sure that adequate observations were systematically made. These are absolutely necessary for any careful snow physics investigation. If a 0.5 cm-thick fog deposit or surface hoar formation takes place, then clearly the SSA value will mostly reflect this deposit while the isotopic measurement will mostly characterise the underlying snow layer. Relating both measurements will then be totally meaningless. It is clear to me that the authors should have sampled only the top layer for isotopic measurements. If not enough material was present in their ICE CUBE sample holder, then they should simply collect more surface sample nearby.

The reviewer here addresses important comments related to other relevant processes for surface snow. Daily observations were recorded for snowfall, snowdrift, and ground fog, although there was no consistent documentation of surface hoar/sublimation crystal surface features. There is no doubt that fog deposition and surface hoar etc are processes that are important for SSA studies as documented by Domine et al., 2009; Gallet et al., 2014; Fergyresy et al., 2018. However, the observed SSA value for surface hoar is ~54 m^2 kg^{-1} (Domine et al., 2009), is similar to the values on the initial day of our events. We would therefore most often expect an increase in SSA in the instance of surface hoar and snow drift (Kuhn et al., 1977; Grenfell et al., 1994; Domine et al., 2009; Libois et al., 2014).

We add the following text to highlight the importance of addressing potential of such surface features. In the methods, to clarify the potential that SSA increase is the result of precipitation, snowdrift or surface hoar:

"We here use the term deposition events to describe rapid increases in SSA, expected to be from precipitation, drifted snow or hoar formation. Previous studies have indicated that surface hoar and sublimation crystal-like grain growth features at the surface have an SSA value around 54 m^2 kg^{-1}, based on the SSA of hoar frost (Domine et al., 2009)."

In the discussion:

"However, we consider potential increases in SSA in the absence of precipitation under the following conditions: 1) surface hoar formation on an aged snow surface (SSA < 50 m^2 kg^{-1}), 2) the effective sieving of small, fragmented grains into the pore space via wind, and 3) from sublimation and subsequent fragmentation of snow grains while suspended by the wind (Domine et al., 2009). Selecting only rapid decreases in SSA reduces the probability of capturing these processes in our analysis."

Regarding the depth of the sample, we add that each sample had 2.5 cm of snow. However, we can only say for certain that the top 1 cm of each sample was measured given the e-folding depth (now edited in manuscript from light penetration depth) for 200 kg m^{-3} is 1 cm, which is lower than the mean density for EastGRIP surface snow. We state this as a limitation.

Wind drifting is another important process, which is not detailed. The threshold of 6 m/s for the mean daily wind speed is simply not adequate. Hourly values must be considered, and in fact ideally maximum, not average values, are most useful to evaluate wind speed effect on drifting. But the best data on this aspect is observations. Wind drifting can easily be detected by observations. I appreciate that such observations cannot be done 24 hours a day, but the consequences of wind drifting are easily observable by looking at changes in the snow scene.

We agree with hindsight that this threshold is insufficient to reduce the likelihood of surface perturbation, and to address this we now use the 10-minute data from PROMICE. It is important to note here that 209 out of the total 237 sampling days have daily maximum wind speed exceeding 5 m s^{-1} and no events had wind-speed consistently below 5 m s^{-1} (two had 5.1 m s^{-1}). In addition, snowdrift events were documented in the EastGRIP field diary and correspond to wind-speeds above 7 m s^{-1}. Several events have maximum wind-speed between 6- 7 m s^{-1}, and no snowdrift documented. Based on this analysis and observations from the literature, we define two wind categories, as briefly suggested by the reviewer in a later comment, we have added a secondary wind-speed category for comparison of SSA decay when wind-speed is <6 m s^{-1} (low-wind events), and when maximum wind-speed is between 6- 7 m s^{-1} (moderate-wind events). The following text is added to the document:

"A set of criteria are required to reduce the potential of analysing events with wind-perturbed surfaces, resulting in the removal of surface snow. In Antarctica, unconsolidated surface snow has been observed to drift at wind speeds as low as 5 m s−1 measured at 2 m height (Birnbaum et al., 2010). However, a study from Greenland documented snowdrift starting at 6 m s−1 (Christiansen, 2001), likely due to warmer temperatures allowing for the surface snow to become more bonded (Li and Pomeroy, 1997). At EastGRIP, calm conditions correspond to wind speeds from 0 –5.2 m s−1 according to field diary observations. The mean daily maximum wind speed for the three sampling seasons was 6.8 m s−1, while blowing snow was documented only when wind speeds exceeded 7 m s−1.Based on this assessment, we define two wind-speed categories for comparison of the effects of wind-speed on SSA decrease. The first includes events with wind-speed consistently below 5.2 m s−1, hereafter referred to as low-wind events, to ensure no surface perturbation. Secondly, we consider events where the maximum wind-speed is between 6 –7 m s−1, hereafter referred to as the moderate-wind events. The inclusion moderate-wind events allow an assessment of the influence of wind-speed on SSA decrease."

Out of the 21 initially defined events, only 2 are below the wind-speed threshold with maximum values of 5.1 m s^{-1} in both events. We expect negligible snowdrift for these two events allowing us to confidently argue that the surface is unperturbed and isotopic change is the result of snow metamorphism. The likelihood of drifting snow during moderate-wind events is considered using the equation defined from Li and Pomeroy (1998), where the threshold wind-speed for snowdrift is defined as a function of temperature.

Following the same structure as in the original manuscript, we construct the SSA decay model with parameter values set for the two wind-regimes. We add the revised figure to this response. Intuitively, the SSA decay rate is higher for moderate-wind events (-0.53 m^2 kg^{-1} day^{-1}) compared to low-wind events (-0.41 m^2 kg^{-1} day^{-1}). As the reviewer will see later in this response, we add the results from the comparison of our data and SSA decay model to existing models from Flanner and Zender (2006) and Taillandier et al. (2007).

Drifting can remove newly precipitated snow or accumulate it some places. This must be recorded when sampling. It is fairly easy to recognize snow layers from careful observations. All these mandatory observations do not appear to have been done.

I very strongly recommend that the authors detail whatever observations were done and clearly say what has not been done. In their analysis, they should only keep data for which they are certain that SSA and isotopic measurements were on the same layer. All data with surface hoar, fog or sublimation crystals should be eliminated. Drifting events resulting in non-homogeneous layers that were sampled must likewise be eliminated. If there are not sufficient observations to sort the data, then I fear the study may be invalid.

We refer back to our previous response regarding the documentation of snowfall, snowdrift, and ground fog. We remove the events with snowfall and wind drifted snow and Table A with event overview is kept in the Appendix. In addition, we add the following text to the Methods section "Defining SSA decay events".

"We here use the term deposition events to describe rapid increases in SSA, expected to be from precipitation, drifted snow or hoar formation. Previous studies have indicated that surface hoar and sublimation crystal-like grain growth features at the surface have an SSA value around 54 m^2 $kg^{-1}day^{-1}$, based on the SSA of hoar frost (Domine et al., 2009). If snowfall/snowdrift/ground fog was documented during the SSA decay, this event is removed from analysis due to perturbation of the surface layer."

We wish to highlight that the one of the low-wind events was preceded by ground fog, not snowfall. We see value in including these events given that we have ensured negligible wind-perturbation during the event. It is interesting to compare the isotopic change during these two events. We now explicitly include this in the results section "3.2 SSA decay events":

"Both E10 and E11 had consistent clear sky conditions. We note here that E11 was preceded by significant ground fog, not snowfall, indicating that the peak value of 46 m^2 kg^{-1} was likely the result of surface hoar, and thus, rapid SSA decay follows an SSA peak not caused by precipitation."

To further accommodate this comment, we present the latent heat flux and temperature gradient data from the two low-wind events, and extend the discussion of isotopic change with regard to the near surface fluxes. "4.3 Rapid SSA decay and isotopic composition". Here we state that a lack of consistent observation of surface hoar in the SSA samples as a limitation to the study, but we take every precaution to ensure we are analysing unperturbed surface snow.

The organization of the paper must also be modified. Data appear in the discussion. All results should be reported in the results section and extra figures showing wind speed and snow surface conditions must be drafted.

The structure of the paper has been modified to address this comment. Most restructuring is applied to the results, and the discussion then follows suit. Meteorological conditions are presented in the first section of the results, highlighting the inter-annual variability in temperature, accumulation, and latent heat flux between the sampling years. A description of SSA and isotopic composition is then presented alongside the EOF analysis, before focussing on the SSA decay events. Having outlined the modified event criteria in the methods, the suitable events are defined, and the decay model is presented with parameter values best fit to the two wind-regimes. Comparison to physical based models from the literature is included in the model evaluation. The final results section on isotopic change primarily considers events from both the low- and moderate-wind regimes, before focussing in detail on the two low-wind events. The latent heat flux and temperature gradients are assessed to infer processes driving isotopic change. The revised results facilitate a more concise discussion.

Regarding the SSA decay rate law, I am not sure this is the best formula. Since sublimation is thermally activated, the absence of a temperature effect is strange. Perhaps when data is sorted, such an effect will appear. The authors quote (Cabanes et al., 2003) to support their choice of analytical expression, but those Authors had a temperature-dependent rate law. Furthermore, subsequent studies on SSA decay rate laws proposed other analytical expressions, and their exploration should be discussed when the rate law is investigated, not line 309 in the discussion.

We appreciate that the reviewer has pointed this out. The temperature-dependence is now stated from Cabanes et al. (2003) in the introduction, along with the subsequent models proposed by Legagneux et al. (2004), Flanner and Zender (2006) and Taillandier et al. (2007). We have added the following text to the introduction:

"Previous studies have proposed SSA decay models using a combination of field measurements and controlled laboratory experiments (Cabanes et al., 2002, 2003; Legagneux et al., 2003, 2004; Flanner and Zender, 2006; Taillandier et al., 2007). Exponential models to describe SSA decay are documented to be the best fitting to in-situ data from Arctic Canada (Cabanes et al., 2003). However, the lack of physical basis led Legagneux et al. (2003) to construct a new equation based on laboratory experiments to describe a temperature dependent SSA decay."

The rarity of consistent low-wind conditions limits all in-situ studies regarding the duration of SSA decay events. However, we feel the documentation of SSA decay at the surface is valid and useful for planning of future campaigns, where more detailed observations would be beneficial, and for remote sensing studies.

In summary, this potentially interesting study may be partially of totally invalidated by an inadequate experimental protocol, at least based on the information supplied in the paper. If the authors have made observations not reported in this version, they should report all relevant information in a revised version. I then recommend sorting the data and removing all data where there is a reasonable suspicion that SSA and isotopic measurements were not on the same snow layer. I also strongly recommend a more logical organization of the paper. The discussion is often unfounded speculation and must be considerably shortened. I propose below numerous specific comments that I hope will be useful to the Authors in preparing an extensively revised version, for which I recommend a second round of review. These comments were written before the general evaluation, so there is some repetition. And finally, I kindly request that *all* Authors involved in this work make a careful reading of the revised version. This does not seem to have been done for the version I read, which is not very respectful for the reviewers.

We are grateful for the time and effort taken by the reviewer to comment on this manuscript. The edited manuscript follows a more logical format and the edits made based on the reviewer's comments have improved the quality of the study. We apologise for mistakes in the original manuscript, we will ensure the revised document is carefully checked for errors.

Specific revisions required:

Line 35. Spell out SSA=specific surface area, which is the surface are of the ice-air interface per unit mass of snow, expressed in m2 kg-1. It is not assumed to be linked to the optical grain size dopt, as mentioned by the Authors, it is rigorously and simply linked by a geometric relationship SSA=6/pice dopt, as shown in equation (1) of (Gallet et al., 2009), which is probably a more relevant reference than Linow 2012. In fact this relationship was already implicitly mentioned by (Grenfell and Warren, 1999), although they did not use the term specific surface area.

We apologise for missing this, we have changed this to:

*"The snow-air interface can be described by the widely used parameter snow specific surface area (SSA), where the SSA of a snow sample is dependent on optical grain radius and density of ice (SSA = 6 / rho_{ice}*d_{opt}) (Gallet et al., 2009), and can be utilised as a measure for snow metamorphism (Cabanes et al., 2002, 2003; Legagneux et al., 2002)."*

Lines 41-43. The reasons for SSA decrease (of dry snow) are not explained well and even erroneously. Wind fragmentation in fact increases SSA since smaller crystals are formed (Domine et al., 2009). Sublimation does not necessarily lead to SSA decrease as it reduces crystal size; and likewise vapor diffusion does not necessarily lead to SSA decrease. What actually leads to SSA decrease is the disappearance of small structures, often by sublimation, and the growth of larger crystals, often but not only by vapor diffusion in the pore space.

We appreciate the reviewer's insight here and have made changes to the text to correct this mistake.

Introduction: *"Freshly deposited snow has a high SSA which decreases with time under both isothermal (<10 °C m−1) and temperature gradient (>10 °C m−1) conditions (Cabanes et al., 2002; Legagneux et al., 2004; Domine et al., 2007; Genthon et al., 2017). Decrease in SSA is predominantly the result of Ostwald Ripening, where large grains grow at the cost of smaller grains (Lifshitz and Slyozov,1961; Legegneux et al., 2004), vapour diffusion in the pore space driven by sublimation and deposition (Flin and Brzoska, 2008; Sokratov and Golubev, 2009; Pinzer et al., 2012), and wind effects (Picard et al., 2019). Under natural conditions SSA decrease is driven by a combination of these processes depending on surface conditions (Cabanes et al., 2003; Pinzer and Schneebeli, 2009a), each potentially modifying the isotopic composition of the snow (Ebner et al., 2017)."*

An additional sentence or two are proposed for the discussion to explain the influence of wind, specifically relating to the results from EOF analysis to mention the potential for SSA increase due to sieving of fragmented grains (Domine et al., 2009), and wind-pumping potentially reducing SSA via sublimation (Town et al., 2008). This is particularly of interest when we observe the covariance between the SSA and isotopic parameters, given that some increases in SSA could be due to this effect, and the corresponding isotopic change would be the result of fractionation and not from precipitation or wind-blown snow. To account for the ambiguity, we focus on decreases in SSA where grain growth is likely happening and refer to latent heat fluxes and temperature gradients when assessing isotopic change.

Line 47. It is erroneous to state that "While current versions of the so-called decay models exist, these are mostly based on lab-experiments and non-polar snow observations". The works of Cabanes and Taillandier are mostly based on Arctic and subarctic observations. Granted, none of these studies used data obtained on ice sheets, and this could be mentioned, if there are reasons to believe that ice sheet processes involved in SSA decrease are in general different from those on seasonal Arctic snowpacks. By the way, (Carmagnola et al., 2014) tested various SSA decay models against data from Summit, Greenland, and this may me relevant to the authors' topic.

We thank the reviewer for pointing this out and have corrected this error. The paper Carmagnola et al. (2014) is a useful reference for the comparison to models. Like Linow et al. (2012), they look at the snow properties over a vertical profile as opposed to looking at the temporal evolution of the exposed surface snow. We therefore maintain that our continuous SSA data from EastGRIP is a valid approach to quantify the in-situ SSA decay under natural conditions. Even in the case of elevated wind-speed, we believe it is useful to document how the surface SSA is influenced with regard to remote sensing, as the reviewer also pointed out. The analysis for remote sensing was outside the scope for this paper unfortunately.

The following edit is proposed to acknowledge the previous SSA studies for polar snow, and highlight that we are referring here to SSA studies in the accumulation area of ice sheets:

"While continuous surface SSA measurements exist from Antarctica (Gallet et al., 2011; Gallet et al., 2014; Picard et al., 2014), those from Greenland focus on the depth evolution of SSA (Linow et al., 2012; Carmagnola et al., 2013). A continuous dataset of daily SSA and corresponding isotopic composition measurements from the accumulation zone of the Greenland Ice Sheet can contribute to understanding the relevance of snow metamorphism for surface energy budget and for ice core studies."

Line 78. What is meant by surface temperature? Is this the skin temperature measured by IR emission? Or is it the air temperature near the surface? Mentioning a reference is not sufficient. A paper must be self -standing and must not require looking up references for understanding, especially for such a central variable. If this is skin temperature, all relevant details must be given here, including the instrument used, the wavelength range and the emissivity value used. Furthermore, validation of the skin temperature measurements would be desirable. IR sensors require very careful calibration to be accurate.

We apologise for the oversight here and have added instrument specifics to Table 1. The surface temperature is calculated from upwards and downwards longwave radiation with long wave emissivity set to 0.97 and is added to the text.

"Surface temperature from PROMICE is calculated from upwards and downwards long-wave radiation (measured using Kipp & Zonen CNR4 radiometer) with long-wave emissivity set to 0.97."

Line 85 ff. Sampling procedure. It is essential to note when there is a change in the snow layer sampled, i.e. when there was wind drift or precipitation. I guess precipitation events were readily identified, but what about wind drift? Did the authors note when the layer being sampled changed because of wind erosion of wind accumulation? This is critical for data interpretation.

Wind drift was documented in the field diary as well as snowfall and ground fog. However, detailed observations of surface features were not measured consistently over the 3 sampling years. High spatial variability in SSA and accumulation gives us an indication of a heterogeneous surface. Moreover, we consider each sample site individually to avoid attenuation of signals by using the mean. The field observation protocol is added in the methods, and a description of the surface conditions has been added in the results.

Line 100. "Light penetration depth in snow of 200 kg m−3 is approximately 1 cm". Light penetration does not just depend on density, but also on SSA. Thus for 200 kg m-3, a penetration depth of 1 cm corresponds to a precise SSA value. Furthermore, penetration depth is not very meaningful. Do the authors mean e-folding depth? Note that if the e-folding depth is 1 cm, still 27% of the reflected light intensity will be due to depths >1 cm. Also did the authors make detailed observations of detailed surface processes such as surface hoar, sublimation crystals or rime events (these are frequent at Summit, perhaps also at EastGrip)? This is important because these thin surface deposits will greatly impact measured SSA, while they will be diluted in isotopic measurements. To evaluate penetration depth and the impact of surface deposits on SSA measurements, the Authors can use the TARTES model. https://snow.univ-grenoble- alpes.fr/snowtartes/ . This will allow them to make valid quantitative statements, and to explore the impact of surface deposits on measured SSA.

We appreciate the reviewer's insight here and clarify that we are referring to e-folding depth which has been corrected in the manuscript. As previously mentioned, significant fog, snow drift and snowfall were documented in the field diary. However, no consistent detailed observations of surface features such as surface hoar/rime/sublimation crystals were made. We propose to use the eddy-covariance LE measurements to identify the potential of these deposits during the low-wind events used to observe concurrent isotopic change. The reviewer mentions the TARTES model which is a valuable tool. Nonetheless we are constrained by the nature of our Greenland surface observations and unfortunately this limits us from getting accurate additional information. For future work, TARTES is surely very useful. The following text has been updated in the methods:

"The e-folding depth of 1310 nm radiation in snow of 200 kg m^{-3} is approximately 1 cm (Gallet et al., 2009). At EastGRIP, the mean snow density from 2017, 2018 and 2019 is 293 kg m^{-3}

resulting in each measurement being heavily weighted to the top <1 cm of the 2.5 cm sample (307 ± 40 kg m^{-3}, 278 ± 47 kg m^{-3} 294 ± 50 kg m^{-3} for 2017, 2018 and 2019 respectively)."

Line 117-118. It is strange the Authors did not sample the top 1 cm for isotopic measurements, to ensure better correspondence with the SSA measurements.

In our responses above we have clarified the sampling procedure in greater detail than provided in the original manuscript. To ensure that the isotopes correspond to the SSA samples directly, this procedure was preferentially used, instead of taking two separate snow samples for SSA and isotopes. We hope these answers fulfil the reviewers request on these matters.

Table 1. Usually Table captions are concise and explanation are in footnotes. Most of the caption is in fact unnecessary and can be deleted.

All the Table captions have been edited to be more concise.

Lines 132-133. Eq. (1) was indeed proposed by Cabanes et al. as the most empirically accurate, but this was just to fit their limited data set. Legagneux (2005) proposed a theoretically correct equation (his Req. 2). That equation was also used by (Flanner and Zender, 2006). Taillandier et al. (2007) used an approximation of that equation to fit experimental data and their equation has a log form. I believe the expression of Taillandier is more suitable. From the discussion, the Authors tested it, but this should be detailed here, not in the discussion.

We acknowledge the usefulness in presenting the results of our inter-model comparison and have added the results in Section 3.3 Model Evaluation. Prior to this, the following text has been added to the methods section '2.2.1 Modelling SSA decay" to accommodate this suggestion:

"The first empirical SSA decay model was proposed by Cabanes et al. (2003) who described a temperature-dependent exponential decay based on snow samples collected from the Alps (Cabanes et al., 2002) and Arctic Canada (Cabanes et al., 2003). A following logarithmic equation (Eq. log) fit controlled to laboratory experiments was proposed by Legegneux et al. (2004), where parameters A and B are arbitrarily related to the decay rate and initial SSA of each sample and are linearly correlated at -15°C. To improve the physical basis of the model, the theory of Ostwald Ripening, describing grain growth driven by a physical need to reduce surface energy, was implemented into the model (Legagneux et al., 2005). The equation (Eq. 4) has two parameters τ and n; T is the decay rate and n relates to the grain growth. The physical model was developed by Flanner and Zender (2006) to incorporate more specific physical quantification to the parameters to include information about temperature, temperature gradient and density. Based on these three conditions, they created a look-up table for τ and n.

Taillandier et al. (2007) proposed two equations based on the logarithmic model first proposed by Legagneux et al. (2004) to define the decay rate under isothermal and temperature gradient conditions where they were able to directly incorporate a surface temperature *parameter.*

An empirical decay model is constructed upon previous studies (Cabanes et al., 2002, 2003; Flanner and Zender, 2006; Legagneux et al., 2002, 2003; Taillandier et al., 2007). This model uses continuous daily SSA measurements from EastGRIP to describe the behaviour of surface snow SSA in polar summer conditions. All samples of defined SSA decay events are used to quantify surface snow metamorphism."

Lines 162-164. Ground temperatures are not very relevant to the explanation of crystal shapes, as these form in clouds at a different temperature. And by the way Domine et al. (2008) is not the most suitable reference for this. I recommend (Kuroda and Lacmann, 1982) and references therein.

This is a valid point which we overlooked; however, this explanation has ultimately been removed from the revised manuscript given that the SSA decay during the single 'cold' event is likely to have been influenced by snowdrift. The reference to Kuroda and Lacmann (1982) is appreciated for general understanding, and we apologise for the inaccurate referencing here.

Line 165. The upper threshold for wind speed used here is a daily mean value of 6 m s-1. When the daily mean value is 6 m s-1, It is very likely that gust speeds were much higher and that wind drifting took place, with major modifications in SSA. Perhaps transport even brought other layers. I think combining events with and without snow drift is not adequate to derive SSA decay rate laws. At the minimum, events with and without drifting should be treated separately to investigate wind effects. Regarding isotopes, the sampling of blowing snow would have been interesting. Was that performed?

To address this comment, we refer back to our response to an early comment in the 'General comments' section. As we previously noted, the SSA decay rate for moderate-wind events (max. wind-speed 6- 7 m s^{-1}) is substantially higher than for low-wind events (< 6 m s^{-1}). Here, we make use of the physical based model from Flanner and Zender (2006) and Taillandier et al. (2007) by comparing their predictions to those of our data and empirical model. These comparisons are presented in the results section "Model evaluation", and then discussed in the section "SSA decay at EastGRIP". Unfortunately, there was no sampling of blowing snow, but we mention this, as well as sampling of surface hoar, as a suggestion for future studies.

We add an additional figure (Figure A2) to show the results of the model comparison for the two low-wind events (E10 and E11), and for examples of moderate-wind events (E2 from 2017 and E18 from 2019). The two moderate-wind events have maximum 3 m wind-speeds of 6.26 m s^{-1} and 6.28 m s^{-1}. Based on the drift threshold defined in Li and Pomeroy (1998), E2 has potential influence from snowdrift, but not E18 (U(10) = 7.09 m s^{-1} and 8.17 m s^{-1} for E2 and E18 respectively), which agrees with an underestimation of decrease from FZ06 compared to observation during E2. Interestingly, we get the lowest RMSE values for FZ06 and the moderate wind events. Possible explanations include the initial snow conditions and event duration, which are included in the discussion.

Line 178. What is the RMSE? This is mentioned line 194 but would be better mentioned here in context.

Yes of course, this has now been added earlier in the text for all models used. Based on the revised analysis, the RMSE based on low-wind events is 3.64 m^2 kg^{-1} for the exponential model from this study, 3.45 m^2 kg^{-1} for FZ06 and 6.34 m^2 kg^{-1} for T07 based on the individual sample sites. For the moderate-wind events the RMSE is actually smaller, the values are 2.48 m^2 kg^{-1}, 1.28 m^2 kg^{-1} and 5.63 m^2 kg^{-1} for this study, FZ06 and T07 respectively.

Line 190. The authors indicate intermittent snowfall during day 2 of E14. Why did they not remove this presumably thin new layer to avoid this artefact? The thin layer greatly affected the SSA measurement but probably had little impact on the 2.5 cm-thick isotope sample.

Events with intermittent snowfall/snowdrift/ground fog are now removed from further analysis. Removing surface artefacts would likely result in a degree of compaction in the sampling holder, and therefore to avoid any disturbance to the samples, they were handled as little as possible.

Line 197. Why is not an equation proposed and tested for the lower temperatures?

During our sampling period, there was only one event with mean temperatures below -30°C. As previously mentioned, the wind-speed during this event is higher than the threshold. During the initial analysis, we grouped the events by temperature ranges, however, we did not observe a clear temperature dependence of the decay rate. After the removal of events likely to have surface perturbations, we observe a single event in the moderate-wind category which is poorly predicted by the equation for the wind-speed category. As the additional text below explains, this event had the lowest mean air temperatures and thus we do observe the expected temperature dependence.

"Event 9 in 2018 is poorly represented by the moderate-wind SSA decay model from this study. The mean air temperature for this event was -20.8◦C, 5◦C less than the next coldest (E11 at -15.3◦C). Fitting the model for E9 alone gives a decay rate of 0.44 m^2 kg^{-1} day^{-1}, similar to that of the low-wind events. We therefore observe a temperature dependence of SSA decay like Cabanes et al. (2003). Based on the limited number of events used here, we document low-winds having a similar effect to air temperatures below -20◦C on the SSA decay rate."

Line 208. Are the units correct here?

Apologies, these have been changed.

Lines 204-205. No influence of basic environmental variables. How about cloudiness? A very important variable for SSA decay is the temperature gradient in the snowpack. Near the surface, this is going to be greatly affected by cloudiness. In the absence of clouds, there will be a much stronger temperature gradient near the surface than under cloudy conditions. This probably deserves a bit of exploration. Various proxies for cloudiness can be tested, in particular the longwave budget.

We had explored this in the original manuscript and found that there is no significant relationship between the SSA decay rate and cloudiness based on linear regression analysis. However, to clarify, we are not suggesting that these variables do not affect the SSA and the decay rate, but that based on our data alone, we do not observe a significant relationship. We do observe an interesting relationship between the principal components of SSA, d-excess and δ^{18}O, and cloudiness/longwave radiation over the entire sampling period. The purpose of this analysis was to identify any systematic influence of the decay rate for the defined events, and therefore, we decide to focus on the dominant influences on the events we are analysing.

We evaluate cloudiness when assessing the isotopic change during low-wind events. However, both events correspond to near constant clear skies.

Lines 242-243. Shaded regions in Fig 4 are said to indicate largely homogeneous snow cover. But The caption to Figure 4 says "Grey shaded regions indicate periods of high spatial variability in isotopic composition." I am confused.

Apologies for the mistake. To fix this inconsistency and to improve the coherence of the manuscript, we move the EOF analysis prior to the SSA decay model results. The principal components of each variable (SSA, δ^{18}O and d-excess) are assessed for statistical significance, and we find that there are opposing regimes between the years. In 2019, δ^{18}O and d-excess covary in the spatial and temporal dimensions, contrasted with the strong significant relationship between the principal components of SSA and d-excess in 2019. It is apparent that the two years differed significantly in overall temperature conditions**,** which is clear is the mean δ^{18}O values, which is potentially related to the opposing NAO phase in 2017/2018 and 2019. Even in the SSA decay events the behaviour is different. The specific SSA decay shape, which is clearly identifiable in 2017 and 2019 is less obvious in 2018. Furthermore, this is relevant for the discussion of processes driving isotopic change in the low-wind events.

Lines 241-249. This discusses the correlation between SSA and d-excess. The coherence is better when the snow layer is homogeneous. Could that just be due to wind effects? When the wind speed is low and there is no wind drifting, the snow remains unperturbed and *a priori* homogeneous. On the contrary, under greater wind speeds, drifting takes place, heterogeneity is generated and SSA and d-excess become decorrelated. Furthermore, since SSA measurements probe about the top 1 cm while isotopic measurements probe the top 2.5 cm, it is clear that when wind drifting takes place, both measurements may measure highly different layers, explaining the decorrelation. How about limiting data analysis to those events without wind speed?

This is a useful insight from the reviewer, and we acknowledge that this could be the case. The correlation in 2019 is continuous throughout the season, which suggests that increases in PC1 of SSA, closely linked to precipitation, and decreases, closely linked to post depositional processes, are similarly influencing d-excess. The following text is added to the discussion:

"PC1 of SSA is interpreted as depositional events causing increase in SSA in the positive mode (Domine et al., 2009), and snow metamorphism or wind erosion in the negative (Cabanes et al., 2002, 2003; Legagneux et al., 2003, 2004; Taillandier et al., 2007a; Flanner and Zender,

2006). However, we consider potential increases in SSA without precipitation in the instance of 1) surface hoar formation on an aged snow surface (SSA < 50 m^2 kg^{-1}), 2) the effective sieving of small, fragmented grains into the pore space via wind, and 3) from sublimation and subsequent fragmentation of snow grains while suspended by the wind (Domine et al., 2009).

For the revised manuscript, we look in detail at the low-wind events only to ensure the same surface layer persists. By reducing the number of events, we can assess temperature gradients and latent heat flux for individual events, allowing for a more concise discussion.

An issue with limiting EOF analysis to the low-wind events alone is that the deposition/precipitation input is then removed, which is a key component of the relationship between SSA and d-excess while at the surface. A later comment from the reviewer observes that large increases in SSA (possibly precipitation, or another form of deposition) corresponds almost always to an increase in d-excess. We argue that this observation supports the argument that there is an overall decrease in d-excess during snow metamorphism.

Lines 256-257. Here the authors mention fog and negative LHF, i.e. likely surface hoar formation. Thus the authors may have observed snow conditions. All these observations must be mentioned when results are first presented. Data analysis must consider which processes were involved for each event. By the way, the standard abbreviation for latent heat fluxes is LE, not LHF.

We hope the previous responses have clarified the observations that were made. Observations are in Table A1 in the appendix, as well as a new plot with these observations indicated on the timeseries. LHF has been changed to LE throughout the text. Isotopic analysis of low-wind events now includes the LE and temperature gradient measurements to infer the vapour fluxes in the surface snow.

Line 268. The authors invoked re-exposed old snow to explain some d-excess values. Careful observations during sampling can answer this question. If there was 1 cm of recent snow over old snow, the SSA measurement will have measured recent snow while isotopic measurements will have measured predominantly old snow. This will affect the quality of the SSA-d-excess correlation analysis. Again, inadequate samples must be removed from the analysis.

Unfortunately, there is no precise documentation of layering of the snow used for samples. Instead, we refer to the accumulation data to identify changes in snow surface height during the analysis of isotopic change for the low-wind events.

Line 287-288. Changes in snow physical properties observed are probably not due to precipitation and metamorphism *sensu stricto* (i.e. involving only water vapor transport within the snow layer). Processes involved also include wind drift, fog deposition, surface hoar deposition, and also possibly sublimation crystal formation. This last process is due to vapor transport within the snow, but since the growth of completely new crystals is involved, I suspect their isotopic composition would be very different from that of the snow layer they originate from. Sublimation crystals are in fact very frequent on cold snow under intense sunlight, even though reports are few (Weller, 1969; Gallet et al., 2014).

These are really useful points from the reviewer. Looking at surface crystal growth through the perspective of isotopes to determine sublimation crystals from deposition of hoar crystals would be interesting, and a great contribution to the quantification of sublimation driven isotopic fractionation. The sampling strategy used here favoured a broad study looking at the macroscale relationships between snow metamorphism and isotopic composition, and the large decrease threshold was used to extract changes in SSA over the transect after high initial SSA values had been recorded.

Given that surface hoar/sublimation crystals were not documented, we use LE measurements to determine whether there was significant surface hoar formation during analysed events. Determining sublimation crystals is more ambiguous here but we look at temperature gradients throughout the events to explore the possibility. We refer here to the recent paper by Casado et al. (2021) where the snow isotopic composition and modelled precipitation isotopes were used to infer the relative influence of precipitation and snow metamorphism on the isotopic signal. To accommodate this comment and significantly strengthen our study, the revised discussion presents the expected fractionation effects of processes driving snow metamorphism and infers the mechanisms of isotopic change based on previous studies (Hughes et al., 2021; Wahl et al., 2021; Casado et al., 2021). The following text is added:

"Three key mechanisms are expected to drive the rapid SSA decays; 1) large grains growing at the expense of small grains (Legagneux et al., 2004; Flanner and Zender, 2006), 2) diffusion of interstitial water vapour (Ebner et al., 2017; Touzeau et al., 2018; Colbeck, 1983), 3) sublimation due to the wind ventilating the saturated pore air, known as 'wind-pumping' (Neumann and Waddington, 2004; Town et al., 2008). The dominant mechanisms can theoretically be identified by a combination of the change in isotopic composition - indicating the fractionation effect - and the LE and temperature gradient data.

In theory, mechanism 1) causes minimal change in the bulk isotopic composition of a snow layer under isothermal conditions (Ebner et al., 2017). Therefore, observations of SSA decay corresponding to negligible isotopic composition change could be explained by this mechanism. We observe no events with consistent isotopic composition throughout. In the instance of 2) interstitial diffusion, light isotopes are preferentially diffused, while the heavy isotopes will be preferentially deposited onto the cold snow grains (Ebner et al., 2017; Touzeau et al., 2018; Colbeck, 1983). Thus, diffusion of water vapour in the pore space causes a decrease in d-excess and slight increases in δ18O due to kinetic fractionation (Casado et al., 2021). 3) Sublimation has been widely documented to cause an increase in δ18O of the remaining snow mass due to equilibrium fractionation, and a significant decrease in d-excess due to kinetic fractionation (Ritter et al., 2016; Madsen et al., 2019; Hughes et al., 2021; Wahl et al., 2021; Casado et al., 2021).

An overall increase in δ18O and decrease in d-excess during E10 can be attributed to a combination of 2) and 3) based on observation of net-sublimation and high amplitude diurnal temperature gradient variability indicating vapour transport within the pore space. The period between 9th June at 15:18 UTC and 10th June 10:40 UTC recorded net deposition corresponding to an overall decrease in δ18O during the first day and minimal decrease in d-excess, potentially due deposition of atmospheric water vapour (Stenni et al., 2016; Feher et al., 2021; Casado et al., 2021).

A 30% decrease in d-excess corresponds to negligible change in δ18O during E11. Net-sublimation, double that of E10 is measured, but with reduced amplitude in both TGs. Moreover, the largest decrease in d-excess occurs after the first day when the surface-subsurface TG is consistently negative. This indicates that vapour diffusion is controlling the isotopic composition, and the effect of equilibrium fractionation during sublimation from the surface only weakly influences the bulk isotopic composition (Casado et al., 2021).”

Line 291-292. For older snow also, sublimation and vapor diffusion are not the only processes involved. In particular, wind drifting is probably important.

This has been included in the text.

Line 297. The correct reference is Cabanes 2003, not 2002

We apologise for this mistake and have changed this in the text.

Line 309-310. The comparison with the equation of Taillandier should be indicated in results. In fact, the choice of Cabanes’ equation should be justified earlier on. Its interest as well. By the way, (Cabanes et al., 2003) used a temperature-dependent exponential coefficient.

In addition to a more extensive introduction to the models in the methods “modelling surface snow metamorphism” we have added a brief inter-model comparison to the results, using the temperature-gradient model from Taillandier et al. (2007), and the model from Flanner and Zender (2006), with tau and n determined by their look-up table based on the event conditions.

Lines 311-318. This paragraph is not physically very sound and is not based by any quantitative analysis. Since the temperature gradient near the snow surface is not evaluated, there is no basis to say that isothermal metamorphism is dominant after precipitation. Then, since the Authors do not find any significant effect of temperature, they assume their observations are explained by the temperature gradient, implicitly implying that the temperature gradient show little variations between events. This paragraph should just be removed. All the statements are unsubstantiated. Furthermore, what is important in TG metamorphism is not the magnitude of the temperature gradient, but the magnitude of the water vapor flux, which is temperature- dependent. Lastly, it can be affected by wind speed through wind pumping and also by convection (Trabant and Benson, 1972; Benson and Trabant, 1973; Johnson et al., 1987;Sturm and Johnson, 1991). All these aspects would need to be discussed and quantified to engage in the discussion proposed in this paragraph.

We apologise for not stating that there are snow temperature measurements from PROMICE from 2017 and 2018, and from a separate campaign from 2019. The inclusion of all events in the original manuscript did not facilitate in-depth analysis of individual events. However, thanks to the reviewers’ suggestions, the revised manuscript now includes the temperature gradient and latent heat flux for the low-wind events. Ultimately, this paragraph has been removed, but the influence of temperature gradients on the low-wind events has been discussed in the following sections, where aspects of both paragraphs have been merged.

Lines 319-322. Here again, the authors make unfounded statements. How do they know the temperature gradient is negligible during polar night? Under clear sky conditions, radiative cooling will on the contrary induce strong temperature gradients near the surface of the snow. The authors may just conclude that since their model is empirical it only applies under the conditions where data were obtained. In fact, it may not even be valid at this site in summer during other years.

The paragraph has been corrected and instead of suggesting that temperature gradients are minimal, we have discussed this in terms of absolute temperatures being lower, and thus the SSA decay would be slower (Flanner and Zender, 2006), as evidenced by E7 with temperatures < -30°C.

"Snow metamorphism is thermally activated given the dominant influence of sublimation and deposition (Cabanes et al., 2002, 2003; Legegneux et al., 2004). During winter, the temperatures are very low (<-30°C) and minimal insolation reduces the diurnal near-surface snow temperature gradients, resulting in isothermal metamorphism being dominant which reduces the rate of snow metamorphism, or SSA decay, compared to temperature gradient snow metamorphism (Dadic et al., 2008)."

Furthermore, we appreciate that the empirical model construction in this study is limited by synoptic weather variability being consistent wind and potential for surface perturbation. With consideration to this limitation, we believe it is still useful to document with the decay model, given the relationship between SSA and surface energy budget.

Lines 324-331. Could not the authors compare their model to data obtained using the algorithms developed in (Kokhanovsky et al., 2019)? It seems possible to determine precipitation events using Sentinel data, as indicated by high-SSA periods, and then investigate the decay to test whether the model developed here indeed applied to the accumulation zone of the GIS. This paragraph lacks convincing arguments and sound a bit like just wishful thinking, while tests are possible.

Yes, we agree that this would be a useful comparison. However, for this paper we decided to focus on the relationship with isotopes. This paragraph is removed, and the satellite potential is mentioned briefly in the previous section instead related to the usefulness of defining the SSA decay rate as a function of different wind-regimes.

Lines 336-337. Why would this correlation between SSA and d-excess be observed in only 72% of cases? I think it would be interesting to explore which events actually monitored a constant layer, rather than a layer perturbed by wind drift, the formation of surface hoar or sublimation crystals, or fog deposition.

This is a useful point from the reviewer, and we have added a section in the results that looks only at the isotopic change during the minimally perturbed low-wind events. We have included LE and temperature gradient data to identify the dominant direction of vapour flux during the events. Isotopic change is now documented in the context of sublimation and deposition between the surface and atmosphere, while the 10 cm snow temperature data gives an indication of the direction of vapour flux within the snow. The discussion is edited in parallel with a more concise comparison to expectations from previous studies such as Casado et al. (2021). The same analysis has now been applied to events with minimal perturbation from ground fog, snowdrift, and snowfall.

Lines 339-351. This discussion of snow metamorphism could be significantly improved. I am not sure surface curvature effects played a detectable role. In any case, the authors need to substantiate this with quantitative calculations, they cannot just make such statements without a demonstration. I would think water vapor fluxes caused by temperature gradients and wind pumping, and perhaps thermal convection, can explain most observations.

We acknowledge the reviewer's suggestions and have modified the discussion to explain the increased decay rate under moderate-wind conditions. The following text is added to the discussion:

"The expected temperature dependence on the SSA decay rate is apparent during E9, where the mean air temperature in less than -20◦C, which agrees with the accepted knowledge that snow metamorphism is slower in colder conditions due to sublimation and deposition being thermally activated processes (Cabanes et al., 2003). In addition, we focus on the influence of wind-speed of the SSA decay rate and observe a more rapid SSA decay with increased wind-speed, potentially due to increased ventilation of saturated pore air acting as a catalyst for snow metamorphism (Cabanes et al., 2003; Flanner and Zender, 2006; Neumann and Waddington, 2004). Wind erosion cannot be definitively ruled out due to dis-continuous documentation of surface conditions. However, high wind-speeds are documented to increase SSA via fragmentation and sublimation of suspended snow crystals, which are then re-deposited and effectively sieved into the pore spaces of the surface snow layer (Domine et al., 2009)."

Lines 360-366. This paragraph discusses the relationship between SSA increases and concomitant d-excess increases. However, this seems very misleading to me. This paper is focused on SSA decrease of a given snow layer over time. Here, the approach is different. **T**he authors consider changes in the SSA of surface snow, regardless of whether these changes involve the same layer. In fact, their SSA increases seems to always involve a change in layer, e.g. due to precipitation. Therefore, plotting data obtained by the evolution of a given identified layer together with data involving a change of layer seems meaningless to me. What I understand from this paragraph is that new layers with high SSA have a higher d-excess value than older (and different) layers with low SSA. This may be interesting, but is different from the main topic of this paper, and should therefore not presented as the same topic.

We acknowledge that there was a lack of clarity here and appreciate the reviewer's comments to allow us to clarify and strengthen our findings. By measuring the isotopic composition of the SSA sample, we remove the uncertainty from spatial variability. Analysing isotopic change over 2-days ensures that new/re-deposited snow will have more time to equilibrate with the sub-surface snow. If repeated, precipitation and surface hoar isotopes would be measured to determine the influence of the surface depositions on the 2.5 cm isotope measurements. We add this as a limitation of our study.

Regarding the observations of snow with high SSA having a higher d-excess value than old snow, we acknowledge the reviewer's comment that this is not the same topic but propose the this feature as supporting evidence. Given that we observe no seasonal trend in d-excess, the consistently increased d-excess values with high SSA cannot be attributed to increasing d-excess throughout the season. Moreover, the documentation of d-excess decrease during low-wind events ensures negligible removal of snow. Therefore, with the support of LE and temperature data, we argue that this feature is the result of decrease in d-excess during snow metamorphism due to the combined influence of grain growth via vapour diffusion, and sublimation into the atmosphere (Ebner et al., 2017; Hughes et al., 2021; Wahl et al., 2021; Casado et al., 2021).

Lines 368-373. It is surprising to see data presented in the discussion. This should be in the results section. So in fact there seems to have been observations of snow surface conditions and changes. Wind drifting, a key process for data interpretation, may have been observed after all. We need to see those data. Fig. A1 needs to also show mean hourly wind speed, and ideally maximum hourly wind speed if available, as well as observations of drifting. In fact, all surface snow observations, including fog deposition, the formation of surface hoar or sublimation crystals, and any other relevant information, must be shown in a Figure.

This figure has been incorporated into the results section, where we present the daily and 2-day change in one figure and only for events with minimal surface perturbation. The additional figures and description of conditions have been added at the start of the results.

Lines 393-399. The speculation between insolation, temperature gradient and d-excess may be potentially interesting, but lacks a clear basis. Since the authors did not measure T gradients and did not adequately discuss their role on d-excess, I think this paragraph is not very useful. Please substantiate or remove.

This paragraph has ultimately been removed. We agree with the reviewer that this is an interesting discussion point, but based on our results alone, we feel we cannot adequately substantiate the arguments.

The section on ice core implications could perhaps be strengthened a bit by treating specific examples. For examples, how is the d-excess signal affected by more frequent precipitation that metamorphose without wind perturbation, in comparison to precipitation events that rapidly form a wind slab with time-stable SSA? How does that relate to climate scenarios (e.g. glacial vs. interglacial). This is just a suggestion. I am sure the Authors can present other interesting cases. This is where I expected more in-depth discussions.

We agree that there is a lot of potential discussion points relating to implications for ice core studies. Specific examples are addressed in the section "Isotopic change during SSA decay events", where we compare our observations to the fractionation effects expected from the different processes driving snow metamorphism. In addition, we discuss the inter-play between precipitation intermittency and temperature conditions as an explanation for the different regimes between 2018 and 2019. We appreciate that there are numerous interesting discussion points which could be added, and we thank the reviewer for the suggestions made here.

Exploring the role of snow metamorphism on the isotopic composition of the surface snow at EastGRIP

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Abstract.

Stable water isotopes from polar ice cores are invaluable high-resolution climate proxy records. Recent studies have aimed to improve ~~knowledge~~ understanding of how the climate signal is stored in the stable water isotope record by addressing the influence of post-depositional processes on the surface snow isotopic composition. In this study, the relationship between ~~changes in surface snow microstructure after precipitation/deposition events~~ surface snow metamorphism and water isotopes during precipitation-free periods is explored using measurements of snow specific surface area (SSA). Continuous daily SSA measurements from the East Greenland Ice Core Project site (EastGRIP) situated in the accumulation zone of the Greenland Ice Sheet during the summer seasons of 2017, 2018 and 2019, are used to develop an empirical decay model to describe events of rapid decrease in SSA, ~~driven predominantly by vapour diffusion in the pore space and atmospheric vapour exchange. The SSA decay model is~~ linked to snow metamorphism. We find that SSA decay during precipitation-free periods at EastGRIP is best described by the exponential equation ~~$SSA(t) = (SSA_0 - 26.8)\,e^{-0.54\,t} + 26.8$. The model performance is optimal for daily mean values of surface temperature in the range 0 °C to -25 °C and wind speed < 6 m s^{-1}. The findings from the SSA analysis are used to explore the influence of surface snow metamorphism on altering the isotopic composition of surface snow. It is found that rapid SSA decay events correspond to decreases in d-excess over a 2-day period in 72 % of the samples. Detailed studies~~ $SSA(t) = (SSA_0 - 22) \cdot e^{-\alpha t} + 22$, and has a dependency on temperature and wind-speed. The relationship between surface snow SSA and snow isotopic composition is primarily explored using Empirical Orthogonal Function ~~(EOF) analysisrevealed a coherence between the dominant mode of variance of SSA and d-excess during periods of low spatial variability of surface snow over the sampling transect~~analysis. A coherence between SSA and *d*-excess is apparent during 2017 and 2019, suggesting that processes driving change in SSA also influence ~~d-excess. Our findings highlight the need for future studies to decouple the processes driving surface snow metamorphism in order to quantify the fractionation effect of individual processes on the snow isotopic composition.~~ snow isotopic composition. In contrast, 2018 was characterised by a covariance between SSA and δ^{18}O highlighting the inter-annual variability in surface regimes. Moreover, we observed

changes in isotopic composition consistent with fractionation effects associated with sublimation and vapour diffusion during periods of rapid decrease in SSA. Our findings support recent studies which provide evidence of isotopic fractionation during sublimation.

1 Introduction

The traditional interpretation of stable water isotopes in ice cores is based on the linear relationship between local temperature and first order first-order parameters δ^{18}O and δD of surface snow on ice sheets (Dansgaard, 1964). The second order parameter d-excess (d-excess = δD - 8 $\cdot$ δ^{18}O) is a result of kinetic fractionation caused by different molecular diffusivities of oxygen and hydrogen and has traditionally been interpreted in ice core records as reflecting moisture source conditions (Merlivat and Jouzel, 1979). Many factors must be accounted for when reconstructing temperature in ice cores, including Accurate reconstruction requires consideration of precipitation intermittency (Casado et al., 2020; Laepple et al., 2018), past variations in ice-sheet elevation (Vinther et al., 2009), sea ice extent (Faber et al., 2017; Sime et al., 2013), and firn diffusion (Johnsen et al., 2000; Landais et al., 2006; Holme et al., 2018). In addition, recent , which influence the water isotopic composition in ice cores. The second-order parameter deuterium excess (d-excess) is defined by the deviation from the near-linear relationship between δ^{18}O and δD which is driven by non-equilibrium (kinetic) fractionation (d-excess = δD - 8 $\cdot$ δ^{18}O). d-excess in ice cores is understood to reflect moisture source conditions (Dansgaard, 1964; Merlivat and Jouzel, 1979; Johnsen et al., 1989) , changes in moisture source region (Masson-Delmotte et al., 2005), and can be modified during snow crystal formation in supersaturated clouds (Ciais and Jouzel, 1994; Sodemann et al., 2008).

Recent studies have documented isotopic composition change in the surface snow during precipitation-free periods (Steen-Larsen et al., 2014; Ritter et al., 2016; Casado et al., 2018; Hughes et al., 2021), linked to synoptic variations in atmospheric water vapour composition and subsequent snow-vapour exchange (Steen-Larsen et al., 2014). Current research aims to quantify the influence of post-depositional processes on isotopic change exchange with the surface snow (Steen-Larsen et al., 2014; Ritter et al., 201 . Post-depositional processes at the surface involve additional kinetic effects adding complexity to the interpretation of d-excess (Hughes et al., 2021; Casado et al., 2021). Here we focus on processes influencing isotopic composition of the surface snow (Steen-Larsen et al., 2014; Ritter et al., 2016; Madsen et al., 2019; Wahl et al., 2021)after deposition while exposed to surface processes and concentrate on the second order parameter d-excess.

Surface snow undergoes structural changes , as grains form bonds, grow. This process is called After deposition, snow grains undergo structural changes known as snow metamorphism, which is active at the surface and at greater depths, depending on temperature (gradient) conditions (Colbeck, 1983; Pinzer and Schneebeli, 2009b). A major change the snow is undergoing, is the reduction of the ice-air interface to reduce energy (Legagneux and Domine, 2005)(Colbeck, 1983; Pinzer and Schneebeli, 2009a) . Surface snow metamorphism is initially driven by a reduction in the snow-air interface to reach thermodynamic stability (Colbeck, 1980; Legagneux and Domine, 2005). The snow-air interface can be described by the widely used parameter SSA. It is assumed to be linked to the optical grain size equivalent (Linow et al., 2012) and can be utilized snow specific surface area (SSA), which is dependent on optical grain radius and density of ice ($SSA = 3/\rho_{ice} \cdot r_{opt}$) (Gallet et al., 2009), and can be used as a measure for snow metamorphism (Cabanes et al., 2002, 2003; Legagneux et al., 2002). In this study we use SSA to describe the (rapid) change of surface snow as one measure for snow metamorphism.

This manuscript focuses on surface snow property changes after precipitation. We here explicitly refer to snow which is lying at the surface for an unknown amount of time and thus does not directly represent freshly precipitated snow.Fresh snow crystals have a high value of SSA. After deposition of the crystals on the surface Freshly deposited snow has a high SSA which decreases with time under both isothermal ($<10\,^{\circ}\mathrm{C\,m^{-1}}$) and temperature gradient ($>10\,^{\circ}\mathrm{C\,m^{-1}}$) conditions within the snow (Cabanes et al., 2002; Legagneux et al., 2004; Domine et al., 2007; Genthon et al., 2017). Decrease in SSA is predominantly the result of Ostwald Ripening, where large grains grow at the cost of smaller grains (Lifshitz and Slyozov,1961; Legegneux et al., the SSA rapidly decreases from its initial value due to crystal growth (Cabanes et al., 2002; Legagneux et al., 2004; Domine et al., 2007) . The reasons for the SSA decrease are wind-driven fragmentation (Comola et al., 2017; Neumann et al., 2009), interstitial vapour diffusion in the pore space between snow crystals (Pinzer et al., 2012; Flin and Brzoska, 2008) and sublimation (Sokratov and Golub 2004), interstitial vapour diffusion (Flin and Brzoska, 2008; Sokratov and Golubev, 2009; Pinzer et al., 2012), and wind effects (Picard et al., 2019). Under natural conditions, SSA decrease is driven by a combination of these processes depending on surface conditions (Cabanes et al., 2003; Pinzer and Schneebeli, 2009a), each potentially modifying the isotopic composition of the snow (Ebner et al., 2017).

Models can provide a quantitative description of the rapid SSA decrease after precipitationdeposition. Previous studies have proposed SSA decay models using a combination of field measurements and controlled laboratory experiments (Cabanes et al., 2002, 2003; Legagneux et al., 2003, 2004; Flanner and Zender, 2006; Taillandier et al., 2007). While current versions of the so-called decay models exist, these are mostly based on lab-experiments and non-polar snow observations. Exponential models are documented to produce the best fit to in-situ SSA decay data (Cabanes et al., 2003). A subsequent physical-based model was defined by Legagneux et al. (2003) to describe SSA decay based on grain growth theory, which was then further developed by Flanner and Zender (2006), who defined parameters based on surface temperature, temperature gradient and snow density. Existing SSA decay models have rarely been applied to polar ice sheet surface snow (Linow et al., 2012; Carmagnola et al., 2013) . Conditions for surface snow on polar ice sheets such as Greenland are however are not necessarily comparable to other alpine regions. The dry-accumulation zone of the Greenland ice sheet has only small amounts of intermittent precipitation. Furthermore, the and Arctic regions due to negligible melt and the high-latitude radiation budgetis different than in other alpine regions.

Only few continuous datasets of daily . Moreover, while continuous surface SSA measurements exist from the remote regions of the polar ice sheets (Libois et al., 2014; Picard et al., 2014). While SSA observations from Greenland exist (Carmagnola et al., 2013; Lin , diurnal datasets covering multiple months and years provide a better foundation for Antarctica (Gallet et al., 2011, 2014; Picard et al., 2014 , those from Greenland focus on the depth evolution of SSA (Carmagnola et al., 2013; Linow et al., 2012). Continuous datasets of daily SSA and corresponding isotopic composition measurements from the accumulation zone of the Greenland Ice Sheet can contribute to understanding the relevance of snow metamorphism for ice core studies. In particular, studies of SSA and snow metamorphism from Greenland are relevant for isotope surface energy budget and for ice core studies. This is because snow metamorphism is expected to influence the snow isotopic composition as The latter is of particular interest owing to observations of isotopic fractionation during snow metamorphism documented in laboratory studies (Ebner et al., 2017) and field experiments ~~(Hughes et al., 2021)~~(Hughes et al., 2021; Wahl et al., 2021; Casado et al., 2021). Nonetheless, few studies have focused on the direct relationship between physical snow properties, such as SSA, and post-depositional changes in isotopic composition.

~~An SSA decay model optimized for Greenland conditions would provide a better quantitative foundation for a process-based understanding of surface snow metamorphism on Greenland. Furthermore, a quantitative description of Greenland SSA decay would provide a basis to explore how snow metamorphism at the surface plays a role for the alteration of isotopic composition of Greenland snow after deposition.~~

In this manuscript, the aim is to explore the behaviour of surface snow metamorphism on polar ice sheets using daily SSA measurements ~~, and compare~~ from Northeast Greenland during summer, and to compare the change in physical properties to the isotopic composition measurements. The primary focus is to document events where changes in SSA occur rapidly over a ~~duration of a few days.~~ number of precipitation-free days, which we use as a proxy for snow metamorphism. ~~We first identify events of rapid SSA decreases (decays) and explore how the isotopic composition of the snow changes during these events. Using daily field observations of snow properties from Northeast Greenland during summer, events of~~ Events of rapid SSA decrease (SSA decay events) are used to 1) quantify and model surface snow metamorphism in polar snow and, 2) assess isotopic change during surface snow metamorphism ~~.~~ in-situ. The data presented here has ~~the potential to contribute to the~~ great value for our understanding of the influence of post-depositional processes on physical and isotopic changes in the polar ice sheet surface snow. This allows for ~~better~~ deeper understanding of snow properties at remote regions of polar ice sheets ~~, and contributes~~ and contributes to the interpretation of water isotopes in polar ice cores.

2 Study site and methods

2.1 EastGRIP site overview and meteorological data

All data used in this paper ~~were~~ was collected as part of the Surface Program corresponding to the international deep ice core drilling project at the East Greenland Ice Core Project site (EastGRIP 75.65°N, 35.99°W; 2,700 m.a.s.l) during summer field seasons (~~May-August~~May-August) of 2017, 2018 and 2019. The local accumulation rate is approximately 14 cm water equivalent per year (Schaller et al., 2017).

Meteorological data used for this study are from the Program for Monitoring of the Greenland Ice Sheet (PROMICE) Automatic Weather Station set up by the Geological Survey of Denmark and Greenland (GEUS) at EastGRIP in 2016 (Fausto et al., 2021). The data are 10-minute mean values for a number of variables. In addition to the surface variables, snow temperature was measured using a thermistor string at 0.1 m intervals during 2017 and 2018 but was modified to 1 m intervals in 2019. An additional thermistor string was thus installed in May of 2019, from which we use the 0.1 m measurements. Relevant weather variables for this study are surface temperature (calculated from longwave radiation down and longwave radiation up with longwave emissivity set at 0.97), air temperature and wind speed (Van As, 2011). Mean weather conditions vary between sampling years, as outlined in Table 1 ~~. Instrument specifics can be found in Fausto et al. (2021). Mean summer surface~~

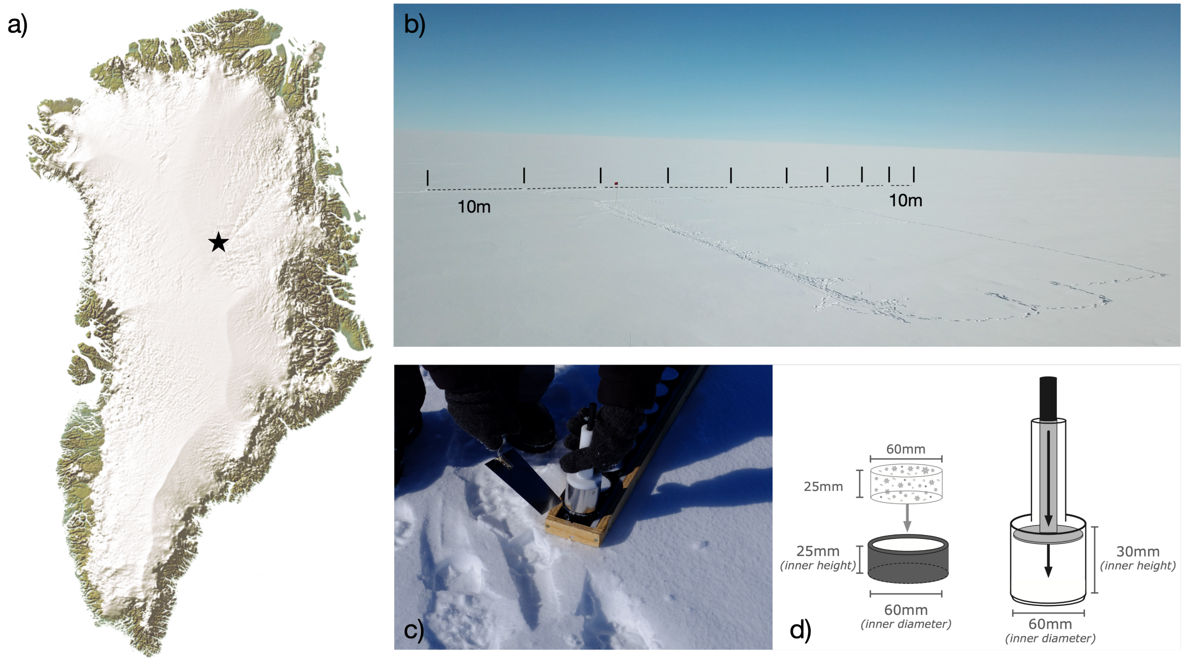

Figure 1. ~~*SSA Sampling Procedure*~~a) A map of Greenland with a black star indicating the EastGRIP site (Source: ~~Eric Gaba – Wikimedia Commons user: Sting~~VisitGreenland). b) A photograph of the clean snow area at the field site (Credit: Bruce Vaughn), ~~with~~ black lines ~~indicating~~ indicate the SSA sampling transect with 10 m spacing shown as dashed lines. c) A photograph of SSA sampling cups (Credit: Sonja Wahl), and d) an illustration of the sampling device from Klein (2014).

~~temperatures for 2019 were -10.6±5 °C, 5 °C higher than 2017 and 2018. Westerly winds prevail, with mean wind speed of 4.5 m s^{-1} (Madsen et al., 2019).~~ with prevailing westerly winds throughout the sampling seasons.

An ~~Eddy-Covariance tower~~ eddy-covariance (EC) measurement tower was set up at EastGRIP ~~in 2016. The relevant variable measured from this system is~~ for every summer observation period (Madsen et al., 2019; Wahl et al., 2021). Here we use the 30-minute latent heat flux (~~LHF) which is directly determined by~~ LE) measurements which are calculated from the measurement of humidity fluxes between the surface and atmosphere. Positive ~~LHF~~ LE indicates upwards energy flux in the form of sublimation in Table 1. ~~All field seasons had net sublimation, with the highest magnitude observed in 2019 (See Data Availability Section A).~~

Significant weather conditions such as ground fog, drifting snow and snowfall, were documented each day in the EastGRIP field diary.

Weather statistics - 2017, 2018 and 2019 The table present the mean

Table 1. Weather statistics - 2017, 2018 and 2019. Mean and standard deviation for the weather variables , surface during the three sampling seasons. Surface temperature, relative humidity with respect reference to ice , wind speed and latent heat flux. Surface temperature and wind speed are from the use PROMICE weather station based on hourly 10-minute measurementsduring the field seasons of 2017, 2018 and 2019. Relative humidity with respect to ice is calculated from vapour pressure of the air and saturation vapour pressure over ice. Latent heat flux is taken a 30-minute mean upwards flux from the EC eddy-covariance towerdataset.

		2017	2018	2019
	Instrument	*06/05 - 05/08*	*04/05 - 07/08*	*24/05 - 01/*
Mean Mean Mean height**Surface Temperature** (°C)	(Kipp and Zonen CNR1/CNR4 radiometer)	-14.5 ± 6.2	-15.76 ± 7.6	-10.6 ± 5
Relative Humidity (with respect to ice) (%%)	(Calculated)	96 95.8 ± 15	96 95.9 ± 16	94 93.3 ±
Wind Speed ($m\,s^{-1}$)	(R.M. Young 05103-5 $\pm 0.3\,m\,s^{-1}$)	4.9 ± .2 0.2	4.2 ± 1.9	4.5 ± 1.6
Latent Heat Flux ($W\,m^{-2}$ $W\,m^{-2}$)	1.3 (IRGASON Campbell Scientific)	1.28 ± 4 4.2	1.1 1.3 ± 3.9 4.3	2.6 ± 5.9 5

2.2 Snow sampling procedure and snow accumulation

Each summer season of 2017, 2018 and 2019 snow samples were taken once a day, primarily in the morning, from May to August at 10 sampling sites, each . Each site was marked by a stick, along a 90 m transect with 10 m spacing upwind of the EastGRIP camp to ensure clean snow (Fig. 1b). The specific dates for each season are given in Table 1. The precise location of each sample was marked by a small stick to ensure the adjacent snow is sampled the next day and to avoid sampling snow from different depths. A 6 cm diameter sampling device collected the top 2.5 cm of surface snow (Fig. 1c). Snow density is determined using the weight of each snow sample with a known volume. At the start of each season, sticks Sticks were placed at each site and snow heightwas determined by sampling site at the start of each season to measure snow height, that is, the distance between the snow surface and top of the stick . Accumulation with a ruler with an uncertainty margin of ±0.5 cm. Accumulation, used here to describe the change in snow height (cm), was calculated using the cumulative sum of the daily difference between measurements of snow height from each site. The resultant datasets consist of 10 daily measurements of three parameters, SSA, density and accumulation, over a 92, 100 and 66 day period for snow accumulation. The field season for 2018 started on the 5th of May, 9-days earlier than 2017 , 2018 and (14th May), and 22 days earlier than 2019 respectively. (27th May). The meteorological data is re-sampled to the SSA sampling time-periods to ensure consistent comparison.

Although samples were measured each day, the exact sampling time varies. Snow sampled during the afternoon would have had extended time exposed to solar radiation maximum, compared to snow sampled during the morning. Furthermore, the sampling time has implications for capturing precipitation events.

2.3 SSA measurements

2.4 ~~Ice Cube calibration~~

Each snow sample is placed into the Ice Cube sampling container below an Infra-Red (IR) laser diode (1310 nm), where the SSA is calculated based on IR hemispherical reflectance, as explained in Gallet et al. (2009)~~, while~~. More information on the Ice Cube device can be found in Zuanon (2013). ~~Light penetration depth~~ The e-folding depth of 1310 nm radiation in snow of 200 $\mathrm{kg\,m^{-3}}$ is approximately 1 cm ~~(Gallet et al., 2011), resulting in a measurement of the top <1~~(Gallet et al., 2009). Thus, as the mean snow density from all field seasons is 293 ~~cm of each sample (Mean snow density at EastGRIP 2017, 2018 and 2019 =~~ $\mathrm{kg\,m^{-3}}$ (307 ± 40 $\mathrm{kg\,m^{-3}}$, 278 ± 47 $\mathrm{kg\,m^{-3}}$, 294 ± 50 $\mathrm{kg\,m^{-3}}$ ~~)~~for 2017, 2018 and 2019), each measurement will be heavily weighted towards the top <1 cm of the 2.5 cm sample. The light reflected from the snow samples is converted into inter-hemispheric IR reflectance using a calibration curve based on methane absorption methods (Gallet et al., 2009). A radiative-transfer model is used to retrieve SSA from inter-hemispherical IR reflectance. To avoid influence from solar radiation, SSA was measured inside a ~~ventilated white tent~~ white tent or in a snow cave kept at temperatures between -5 °C and ~~-10~~-20 °C. ~~SSA measurements have~~ We assume an uncertainty of 10~~% for values between 5-130~~% for SSA measurements between 5–130 $\mathrm{m^2\,kg^{-1}}$ (Gallet et al., 2009).

2.4 Surface snow isotopes

~~Samples collected following the sampling procedure outlined in Section 2.2 were also used for isotopic composition measurements, resulting in~~ Individual SSA samples were put in separate bags and subsequently measured for water isotopic composition. Thus, every day the 10 ~~daily isotope measurements taking~~ SSA samples have a corresponding isotopic composition. The resultant isotope value is the average composition over the top ~~25~~2.5 ~~mm~~ cm of snow. Each sample was ~~sealed in polyethylene bags to avoid any air to equilibrate with the snow and affect the isotopic composition. All samples were~~ kept frozen during transportation and storage.

~~After melting, each bag was shaken to ensure the isotopic composition of the sample is representative. 1.25 μl of each sample was then pipetted into a vial ready for isotopic analysis. The snow~~ The samples were then analysed at ~~Alfed~~ Alfred Wegener Institute in Bremerhaven using a cavity ring-down spectroscopy instrument ~~model~~ (Picarro L-2120-i and L-2140-i) following the protocol of Van Geldern and Barth (2012). This technique ~~is used to obtain measurements of~~ produces δ^{18}O and δD measurements with an uncertainty of 0.15 ‰ and 0.8 ‰ respectively. ~~d-excess is calculated by the equation $d-excess = \delta D - 8 \cdot \delta^{18}O$ with a resultant~~ The calculated values for d-excess have an uncertainty of 1 ‰. ~~Observing relationships between our SSA and isotope data requires consideration for the depth offset between the SSA measurements and the isotopic composition measurement which measures the entire 2.5 cm snow layer.~~

2.5 Data analysis

2.6 ~~Data analyses~~

2.5.1 Defining SSA decay events

~~This study focuses on the events where the SSA measurements decay rapidly over a duration of a few days. SSA decays are here defined as the~~ Freshly deposited snow has a high SSA that slowly decreases through time due to snow metamorphism. Based on this understanding, two terms are defined: 1) SSA increase indicating deposition events in the form of precipitation, drifted snow or surface hoar formation, and 2) SSA decay due to snow metamorphism and other post-depositional processes such as wind-erosion, where the SSA decreases. Identification of such SSA decays in the time-series are required to quantify snow metamorphism and corresponding isotopic change during precipitation-free periods. Surface conditions are subsequently assessed to remove events where the ~~2-day change of daily mean values are higher than a given threshold. This threshold is the same value for all years and is calculated based on the 10th percentile of the decays and set at -13~~surface snow layer is likely to have experienced perturbation via deposition or erosion.

A threshold is derived to systematically identify periods of rapid SSA decay - hereafter referred to as SSA decay events - over a two-day period which was found to be the most representative time step to capture SSA decay events for all sampling years. SSA decay events captured by this threshold are defined by the peak SSA value (day-0), through to the next increase in SSA (rather than decrease).

A set of criteria are required to reduce the potential of analysing SSA decay events with wind-perturbed surfaces. In Antarctica, unconsolidated surface snow has been observed to drift at wind speeds as low as 5 m~~^{2}kg~~ s^{-1} ~~2-day~~measured at 2 m height (Birnbaum et al., 2010). However, a study from north-east Greenland documented snowdrift starting at 6 $m\,s^{-1}$ (Christiansen, 2001), due to warmer temperatures facilitating bonding of the surface snow (Li and Pomeroy, 1997). Field-diary observations from EastGRIP document snowdrift when wind speeds exceeded 7 $m\,s^{-1}$. ~~If the daily mean changes over a 2-day period is higher than the threshold, then this period is selected as a rapid SSA decay event. The duration of the event is set to start at the rapid decay~~

Based on this assessment, we define two wind-speed categories for comparison of the effects of wind-speed on SSA decay. The first includes events with daily maximum wind-speed below 6 $m\,s^{-1}$, hereafter referred to as low-wind events, with negligible surface perturbation. Secondly, we consider events where the daily maximum wind-speed is between 6–7 $m\,s^{-1}$, hereafter referred to as the moderate-wind events. The inclusion of moderate-wind events facilitates an assessment of the influence of wind-speed on SSA decay, while the threshold wind-speed for snowdrift based on temperature conditions from Li and Pomeroy (1997) is used to ensure minimal chance of drift.

2.5.2 Modelling surface snow metamorphism

The first empirical SSA decay model, Eq.(1), was proposed by Cabanes et al. (2003) who described a temperature-dependent exponential decay based on snow samples collected from the Alps (Cabanes et al., 2002) and Arctic Canada (Cabanes et al., 2003)

. Legagneux et al. (2003) found Eq.(2) to best describe experimental SSA decay under controlled laboratory conditions.

$$SSA(t) = SSA_0 \cdot e^{-\alpha t} \quad (1)$$

$$SSA(t) = B - A \cdot ln(t + \Delta t) \quad (2)$$

Parameters A and B in Eq.(2) were found to be arbitrarily related to the decay rate and initial SSA of each sample. To improve the physical basis of the model, the theory of Ostwald Ripening, describing grain growth driven by thermodynamic instability, was implemented into the model (Legagneux et al., 2004). Eq. (3) has two parameters τ and end on n; τ is the day when the mean SSA measurements increase (rather than decrease)again. decay rate and n relates to theoretical grain growth. The physical model was further developed by Flanner and Zender (2006) to incorporate a physical quantification of the parameters including information about temperature, temperature gradient, and density. Based on these three conditions, they created a look-up table for τ and n.

$$SSA(t) = SSA_0 \cdot \left(\frac{\tau}{t+\tau}\right)^{1/n} \quad (3)$$

2.5.3 Modelling surface snow metamorphism

Taillandier et al. (2007) proposed two equations based on Eq. (2) to define the decay rate under isothermal and temperature gradient conditions where they were able to directly incorporate a surface temperature parameter (T_m).

An empirical decay model is constructed building

$$SSA(t) = [0.659 \cdot SSA_0 - 27.2 \cdot (T_m - 2.03)] - [0.0961 \cdot SSA_0 - 3.44 \cdot (T_m - 1.90)] \cdot (t + e^{\left(\frac{0.659 \cdot SSA_0 - 27.2 \cdot (T_m - 2.03)}{[0.0961 \cdot SSA_0 - 3.44 \cdot (T_m - 1.90)]}\right)}) \quad (4)$$

Building upon previous studies(Cabanes et al., 2002, 2003; Flanner and Zender, 2006; Legagneux et al., 2002, 2003; Taillandier et al., 2 . This model uses , we define an empirical SSA decay model using continuous daily SSA measurements from EastGRIP to describe the behaviour of surface snow SSA in polar summer conditions (Cabanes et al., 2002, 2003; Flanner and Zender, 2006; Legagneux et . A recent study at EastGRIP has shown the significant heterogeneity in surface snow due to post-depositional reworking from the wind (Zuhr et al., 2021), and therefore each sample is treated individually to avoid signal attenuation. The post-precipitation decreases in SSA are hereafter referred to as decays.

$$SSA(t) = SSA_0\, e^{-\alpha t}$$

3 Results

~~Eq. (1) is proposed by Cabanes et al. (2003) as the most accurate description of SSA decay, where SSA_0 is the initial SSA value, α the decay rate. To best describe grain coarsening and the processes of sublimation and deposition driving mass redistribution of a new snow layer, days with mean wind speeds above 6~~

3.1 EastGRIP meteorological conditions

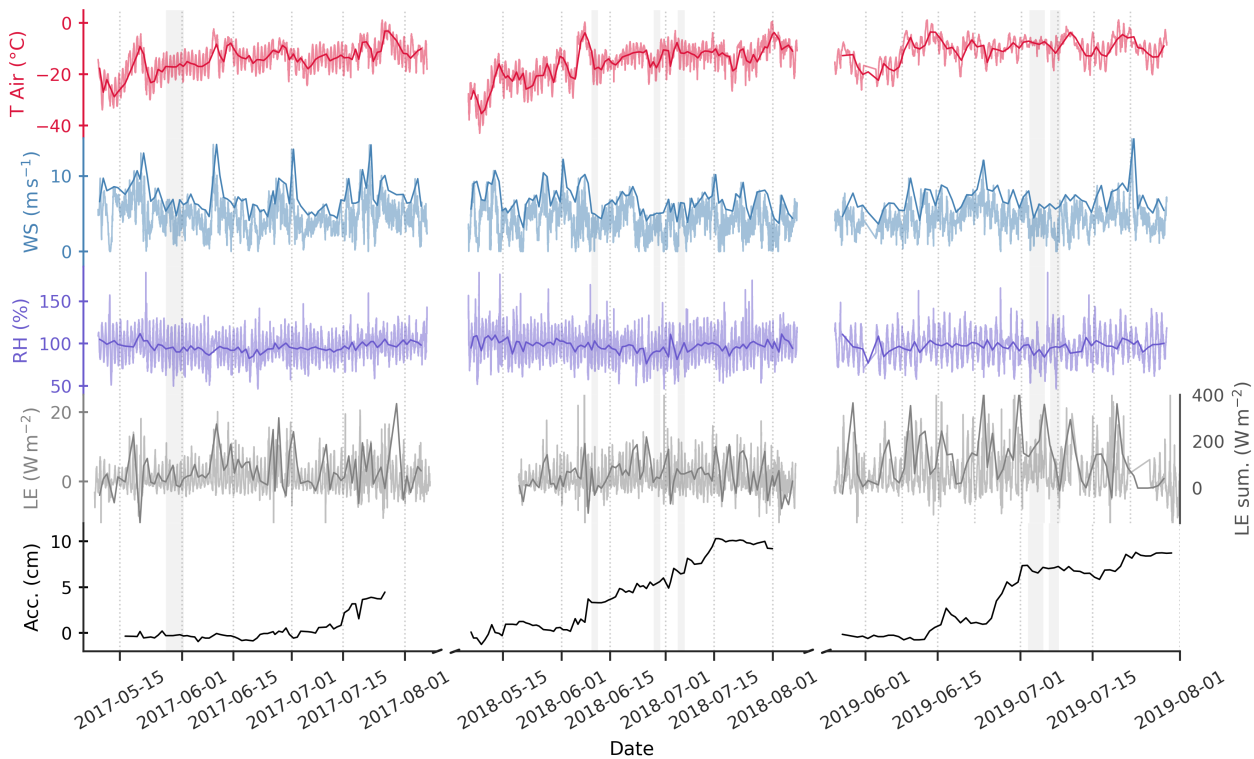

Figure 2. Time series of the ambient conditions during the sampling periods. Data covers the specific sampling periods each year. 10-minute mean data from the AWS is presented for air temperature, wind-speed and relative humidity. Mean values (bold lines) are shown for air temperature and relative humidity, while daily maximum is shown for wind-speed. Latent heat flux data are 30-minute averages from the eddy-covariance tower, with the daily sum shown in bold. Snow accumulation is presented in the lower panel as the daily mean over the 10 sampling sites (see Section 2.2). Grey bars indicate the derived SSA decay events.

Meteorological variables over the three sampling seasons vary substantially as shown in Fig. 2. Air temperatures were below -30 °C between May 5th and May 8th in 2018. Such low temperatures were not recorded for 2017 and 2019. Moreover, when comparing the period from May 27th to August 5th of each year (duration of 2019 season), 2018 air temperatures (-13.3 °C) were still 0.5 °C lower than 2017 and 3.2 °C lower than 2019.

The 2017 season was characterised by high wind intrusions of $>13\,\mathrm{m\,s^{-1}}$ are removed to reduce the influence of wind redistribution. Individual sample analysis is preferentially used to avoid daily mean values possibly attenuating any signals due to spatial variability in surface snow age. Aged snow patches are expected to respond differently to surface processes than new snow patches due to different original crystal structures at the start of eventsat approximately 20-day intervals. Considering all three sampling years, the average daily maximum wind speed is $7\,\mathrm{m\,s^{-1}}$, with 209 out of the total 237 sampling days having maximum wind speed above $5\,\mathrm{m\,s^{-1}}$. The distributions of daily maximum wind-speed compared to 10-minute mean values are found in the Supplemental Fig. A1. Between the start and end of the 2017 field season, we observed net-accumulation of 4.81 cm of snow over the 89-day season, compared to 9.30 cm in 2018 and 8.58 cm in 2019. In addition, the total sum of LE during 2019 was 30% greater than in 2018 indicating strong sublimation. Eddy-covariance LE measurements are supported by LE from AWS observations which indicate the same magnitude of difference between the years.

4 Results

3.1 SSA decay events

3.0.1 Spatial and temporal snow surface variability

Seasonal variability is observed in SSA, δ^{18}O and *d*-excess throughout the field seasons of 2017, 2018 and 2019 (Fig.3), with highest daily spatial variability in isotopic composition. SSA is characterised by peaks, often corresponding to high spatial variability, followed by gradual decreases over a number of days, the SSA decay feature which is most prominent during 2017 and corresponds to negligible or decreasing accumulation. High SSA values at the start of the 2018 season (daily mean $88\,\mathrm{m^2\,kg^{-1}}$) correspond to low and spatially homogeneous δ^{18}O.

SSA data collected at EastGRIP indicate continuous changes in the physical structure of the snow crystals during all sampling seasons Inter-annual difference is observed in δ^{18}O, with seasonal mean values of -31.6 ± 2.1‰, with both temporal and spatial variability. The temporal SSA variability shows changes in physical snow structure with peak values closely associated with precipitation and decreases due to post-depositional re-working of the snow. Summer seasonal SSA evolution is presented in Fig. ?? -32.7 ± 1.3‰ and -27.3 ± 2.1‰ for 2017, 2018 and 2019 with each faded line representing individual samples (10 per day), and the bold line showing the daily mean. Spatial variability between sites is most prevalent when there are high SSA values, indicating fresh snowrespectively (Fig. 3). Throughout the season δ^{18}O follows a gradual increasing trend from May to August following increasing temperatures. Note that the 2019 field season started approximately 15 days later than 2017 and 2018, resulting in a bias towards mid-summer conditions. Cases of abrupt decreases (-10‰) are observed in the late summer, for example, on July 12th in 2018 and July 25th in 2019, which correspond to late-summer snowfall events. No clear seasonal trend is observed in *d*-excess, but rather there are periods of gradual decrease in *d*-excess during periods with no accumulation in all years. The most apparent is from May 15th to June 14th in 2017 corresponding to 0 cm net-accumulation (Fig. 3). The maximum daily spread in δ^{18}O and *d*-excess is approximately 15‰, indicating strong surface heterogeneity.

~~A total of 21 rapid SSAdecay events are identified, with 6, 9 and 6 events for~~ Empirical Orthogonal Function (EOF) analysis is applied to the data to identify the dominant modes of variance in both the temporal and spatial dimensions for each parameter - SSA, δ^{18}O and *d*-excess. Using a confidence interval of 95% ($p<0.05$), the relationship between SSA and isotopic composition is tested. The spatial and temporal principal components returned for each variable by the EOF are presented in Fig. 3. During 2017, 2018 and 2019 ~~respectively. Grey bars in Fig. ?? highlight events defined by the decrease threshold. Maximum SSA values for 2018 and~~ all variables have one dominant mode of variance, or principal component (PC1). PC1 of SSA ($PC1_{SSA}$) explains 61 %, 77 % and 72 % of variance for the respective years, PC1 of δ^{18}O ($PC1_{\delta^{18}O}$) explains 69 %, 83 % and 75 % of the total variance respectively, while PC1 of *d*-excess ($PC1_{dxs}$) explains 47 %, 51 % and 60 %.

Results from the EOF analysis reveals distinct differences between the sampling years, most prevalent is the opposing regime from 2018 to 2019. During 2018, $PC1_{\delta^{18}O}$ and $PC1_{dxs}$ have an inverse correlation in the spatial dimension (r = -0.6),

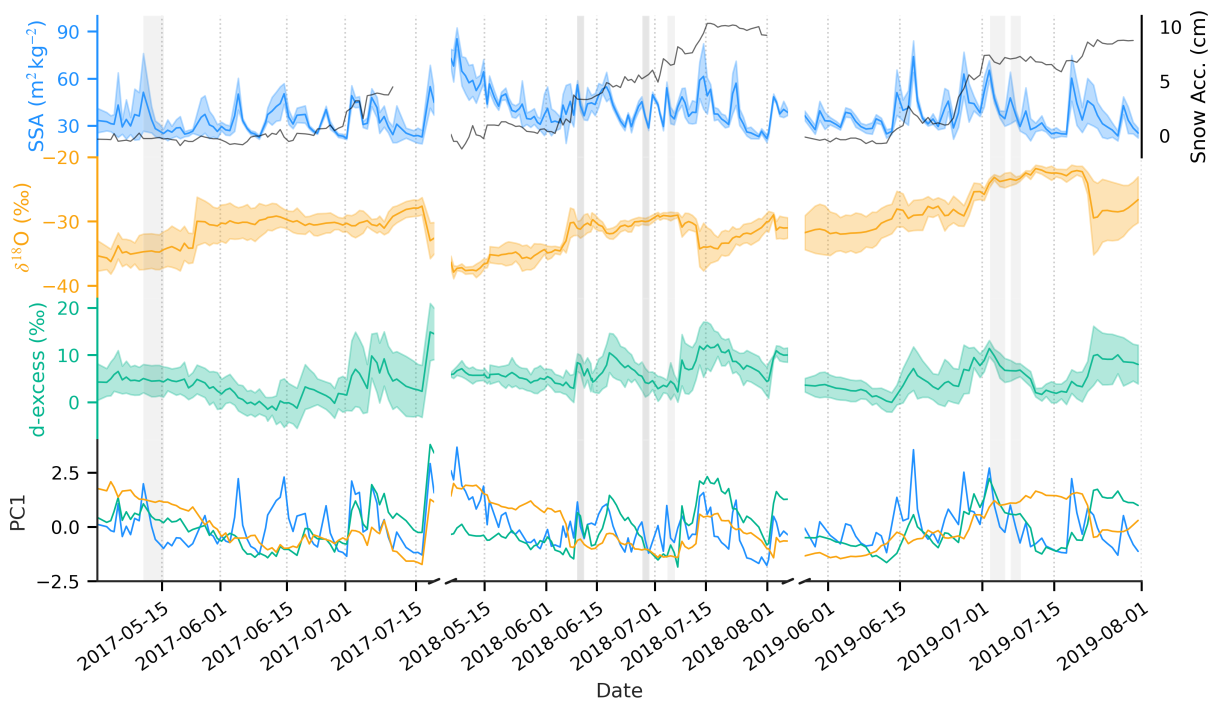

Figure 3. ~~*SSA Timeseries 2017, 2018 and 2019*~~Time-series of SSA ~~time-series between May and August for a~~(blue)~~2017~~, ~~b~~d18O (orange)~~2018~~ , *d*-excess (green) and ~~c~~the first principal components (PC1) ~~2019. Faded lines represent~~ of each variable in the ~~10 individual samples from~~ lower panel. Bands in the ~~90 m~~ upper three panels show spatial standard deviation between the 10 sampling ~~transect, while~~ sites. The secondary y-axis in the ~~bold line~~ top panel shows the ~~daily mean values~~average snow accumulation. ~~Gaps in the timeseries represent missing data. Grey~~ The grey bars ~~highlight~~ indicate the ~~periods of decrease in~~ SSA ~~defined by the threshold algorithm for each year. Six decrease~~ decay events~~are observed in 2017 and 2019, while nine are observed in 2018. Decrease events are interpreted as rapid grain growth due to snow metamorphism, and stars indicating days with precipitation~~.

and a significant positive correlation between PC1$_{\delta^{18}\mathrm{O}}$ and PC1$_{d\mathrm{ssa}}$ in the temporal dimension (p<0.05, r=0.5) (Fig. A2 and Fig. A3). In contrast, data from 2019 are 92characterised by significant positive correlations between PC1$_{\mathrm{SSA}}$ and of PC1$_{d\mathrm{xs}}$ in both the spatial (p m^2<kg^{-1} and 820.05, r m^2=kg^{-1} respectively, while during 0.75) and temporal dimensions (r=0.3, p>0.05), while no relationship is observed between PC1$_{\delta^{18}\mathrm{O}}$ and PC1$_{d\mathrm{xs}}$. During 2017there are only two instances of daily mean SSA being above 60, there is a weak positive correlation the temporal component of PC1$_{\mathrm{SSA}}$ and PC1$_{d\mathrm{xs}}$ (p m^2<kg^{-1}. 0.05, r=0.3), and the temporal PC1$_{\delta^{18}\mathrm{O}}$ and PC1$_{d\mathrm{xs}}$ (p<0.05, r=0.4). There is an apparent shift after July 15th where PC1$_{d\mathrm{xs}}$ transitions from co-varying with PC1$_{\delta^{18}\mathrm{O}}$ to co-varying with PC1$_{\mathrm{SSA}}$. Figure A2 and Fig. A3 in the supplement illustrate the spatial and temporal components of the EOF results.

A visual inspection of the decay events in Fig. ?? indicates

3.1 SSA decay events

3.1.1 Observations

In agreement with Eq. (1), we observe a relationship between initial SSA and subsequent magnitude of decrease . To test whether the mechanisms of decay are consistent throughout events when evaluating the SSA decay events (Fig 3). From the years 2017, 2018 and 2019 a total of 21 events are identified that fulfill the SSA decay criteria (as defined in Section 2.5.1). These events are named E1, observed SSA decays are analysed to construct an empirical model. E2 etc (Table A).

3.2 EastGRIP SSA decay model

Continuous SSA measurements allow for the construction of an empirical model to describe SSA decay at EastGRIP through time while exposed to surface processes. All samples of defined SSA decrease events Prior to analysis, we assess the meteorological conditions and field observations to remove SSA decay events with potentially perturbed surface snow. This includes all events coinciding with observations of ground fog, snowdrift, and snowfall, and events where the wind-speed exceeds the thresholds defined in Section 3.1 are used to quantify surface snow metamorphism. For all eventswith mean temperature above -252.5.1. Out of 21 events captured by the SSA decay event threshold, 15 are influenced by either snowdrift, snowfall, or ground fog according to field diary observations, or high wind-speeds (maximum wind-speed >°C, the mean SSA of the final day is around 307 m s^{-1}). Of the remaining 6 events, two are in the low-wind category (E10 and E11 = 5.1 m s^{-1}), and 4 in the moderate-wind category. Both E10 and E11 had consistent clear sky conditions. Note that E11 was preceded by significant ground fog, not snowfall, indicating that the peak value of 46 m^2 kg^{-1} (referred to as the background decay state). A relationship is observed between the was likely the result of surface hoar, and thus, rapid SSA decay follows an SSA peak not caused by precipitation.

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The rate of SSA decay is closely linked to the SSA value at the start of each event (initial SSA vs. magnitude of decrease strongly influenced by the initial SSA during the decay period $r^2 = 0.4$) (Fig. 4), suggesting showing that the rate of change is proportional to the absolute value, as described by an exponential decay law (r=-0.71 and r=-0.91 for low- and moderate-wind events respectively). The mean air temperature for all SSA decay events was between -17.3 °C and -7 °C. The first day of each event is characterised by the largest change in SSA, followed by a decrease in magnitude over the subsequent days, with negligible change in SSA below 22 $m^2\,kg^{-1}$.

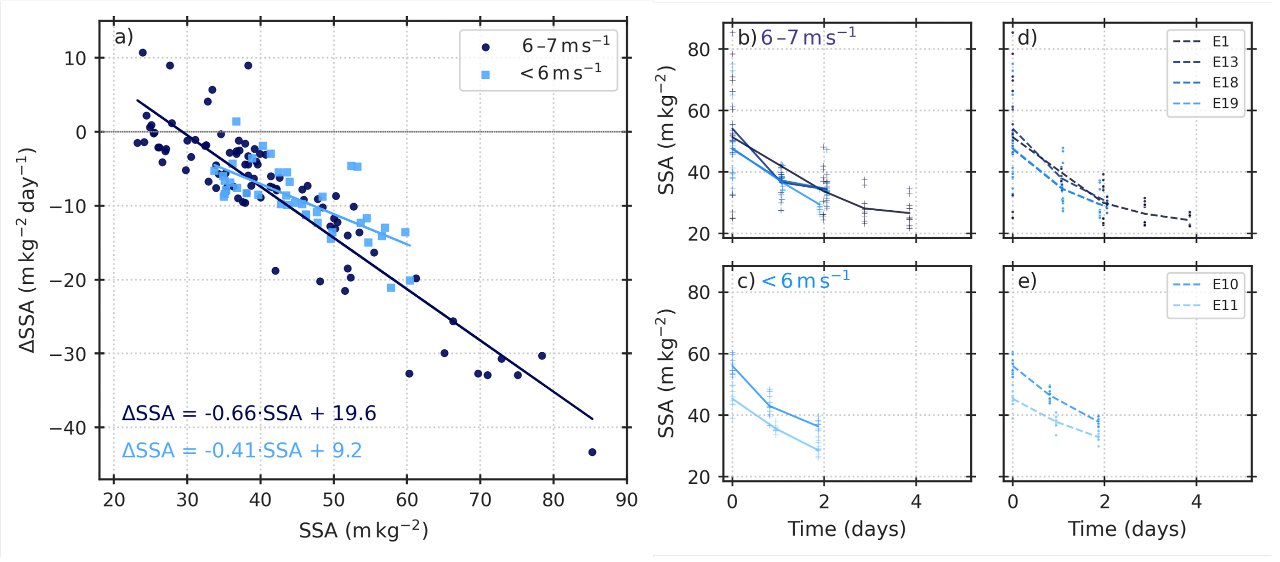

Figure 4. Linear regressions for change in SSA against the SSA for the low-wind (light-blue) and moderate-wind (dark-blue) SSA decay events (a) considering all individual samples. The observed SSA decays are shown for the moderate-wind events (b), and the low wind events (c), followed by the modelled SSA decays for the respective events in d) and c). The legend in d) and e) corresponds to SSA decay event number in Table A

3.1.1 Model

SSA decay rate is quantified by plotting the rate of change in SSA per day against the absolute SSA value for all 10 sampling sites for ~~all~~ low- and moderate-wind events (Fig. 4a). We observe a linear relationship between the ~~rate of~~ change in SSA ~~per day~~ from one day to the next (ΔSSA) and SSA. ~~Outliers are measurements from days with mean air temperature below -25 °C as highlighted in Fig. 4a. This observation is in agreement with theoretical understanding of snow crystal formation transitioning from dendrites to columns at approximately -22 °C (Domine et al., 2008). We therefore define the SSA decay model for a temperature range between -25 °C and 0 °C and daily mean wind speeds below 6 $m\,s^{-1}$ based on hourly averaged values.~~

~~Constructing the~~ The SSA decay model for EastGRIP is ~~based on~~ constructed using the differential equation for the linear relationship between ΔSSA and absolute SSA~~which is defined as Eq. (??).~~. Solving the differential with respect to time (t), produces the SSA decay model defined as Eq. (5), which follows the equation structure ~~from~~ of Eq. (1).

$$\frac{dSSA}{dt} SSA(t) = -0.54 (SSA_0 - 22) \cdot e^{-\alpha \cdot t} + 14.69\,22 \quad (5)$$

$$SSA(t) = (SSA_0 - 26.8)\, e^{-0.54t} + 26.8$$

Where SSA(t) is the SSA measurement at a given time in days since the first measurement (initial SSA), SSA_0 is the initial SSA value, and -0.54 $m^2\,kg^{-1}\,day^{-1}$ α is the decay rate(α), as defined by the slope of Eq. (??). To account for a non-zero decay constant , the value 26.8, and a decay constant of 22 $m^2\,kg^{-1}$ is defined by for both equations by the minimum SSA value where the derivative of SSA is equal to 0 $m^2\,kg^{-1}$. The decay rate, determined by the value of x when the linear regression crosses the y-axis (Fig. 4a). The SSA decay model describes rapid decrease in SSA based on empirical data from EastGRIP, Greenland.

3.1.2 Model evaluation

*Decay Model Construction and Predictions*All samples for all events are included in plot a) showing the relationship between the rate of change in SSA per day (ΔSSA day^{-1}) against the daily absolute values. Points are coloured by the daily mean surface temperature. The linear regression is based on values for surface temperatures between -25 °C and 0 °C, and daily mean wind speeds below 6 $m\,s^{-1}$. b) shows a comparison between the model predicted SSA values using Eq. (5), against the SSA observations. The marker colour represents the day of the events (DOE). Marker style represents the sampling year to assess inter-annual variability for 2017 (o), 2018 (x) and 2019 (□). c), d) and e) show all included events in full-line and f), g) and h) show the model predictions as the dashed line. E1-E21 refers to events as listed in Table A. Missing data day-1 E1.

Model performance is tested by comparing daily predicted decrease to the 10 daily observations. Model-data residuals for daily data are normally distributed, suggesting no systematic errors in model predictions. Figure 4 shows the construction of the model (slope of the linear regressions in Fig. 4, a-b) and prediction of SSA decay (Fig.4,f-h). Note that events are here named E1, E2... consistent with Fig. ?? and also listed in Table A.

There is a minor tendency for the model to underestimate the SSA decrease and thus overestimate the predicted values of SSA as seen in Fig. 4b. Model limitations are most evident during the first day, as seen in Fig. 4, where the modelled decay consistently underestimates the magnitude of decrease . The model has limited ability to predict observations below in the lower range of SSA observations as seen in Fig. 4f, g and h, where the modelled and observed values are compared for each event.

Following our definition in Section 3.1 the events have an extent of 2-5 days. To assess model performance in predicting magnitude of SSA decrease for events of different time periods, we compare the predicted versus measured SSA. For rapid events lasting 2-days the model tends to underestimate the rate of decrease. This is most apparent on Day 1 (24h after peak) for 2017 and 2018, while for 2019, Day 1 SSA is accurately predicted , with residuals increasing on Day 2. In comparison, events lasting 5-days show an underestimation for 2017 with negligible daily change in residuals, while the model overestimates the decay rate of E14 in 2018. However, field documentation suggests intermittent snow fall during Day 2 of E14, causing increase in SSA. Consideration for environmental context is explored in Section 2.5.1. E16 is characterised by the highest initial SSA values, and the largest residuals, suggesting the model is limited at very high initial SSA values.

The model requires only initial SSA as a parameter and predicts SSA decrease at EastGRIP within the defined conditions with an averaged root mean squared error (RMSE) of 5.6is higher for moderate-wind SSA decay events (-0.66 $m^2\,kg^{-1}$when considering all sample sites individually. The model predicts SSA decay over 2-5 day periods (r^2 = 0.89), with the highest

RMSE of 6.17 day^{-1}) than for low-wind SSA decay events (-0.41 m^2 kg^{-1} for 2019 compared to 4.97 day^{-1}). Within the temperature range of low- and moderate-wind SSA decay events from this study, there is no observable temperature dependence of the SSA decay rate. However, such a temperature dependence is clear in events which were excluded due to potential surface perturbations, where there is a decrease in decay rate and increase in the background SSA value with low temperatures (Fig. A4). Our results indicate a slower rate of decay under decreased wind-speed conditions.

3.1.2 Model performance

Table 2. RMSE values for model evaluation. This Study uses the respective α for the low- and moderate-wind events for daily (mean) and individual samples. FZ06 parameters τ and n are defined from the look-up table in Flanner and Zender (2006). T07 uses the mean surface temperature for each event as an input parameter.

	Low-wind		**Moderate-wind**	
	Mean	Individual	Mean	Individual
	$m^2\,kg^{-1}$	$m^2\,kg^{-1}$	$m^2\,kg^{-1}$	$m^2\,kg^{-1}$
This Study	2.48	3.50	2.60	4.28
FZ06	6.46	6.90	7.90	9.52
T07	5.63	6.10	5.27	6.49

Model performance is tested by comparing daily predicted decrease to the 10 daily observations, and by comparing model predictions from this study to those from Flanner and Zender (2006) hereafter referred to as FZ06, and the model defined by Taillandier et al. (2007), hereafter T07, as defined in Section 2.5.2. Residuals between our model and the observations are normally distributed, suggesting no systematic errors in model predictions. The root mean squared error (RMSE) between our model predictions and observed mean SSA is 2.48 m^2 kg^{-1} and 4.72^{-1} and 2.60 m^2 kg^{-1} for 2017 and 2018 respectively. The model adequately predicts rapid SSA decay at EastGRIP within the temperature range, while for colder temperatures, the decay rate is the same but the intercept is significantly higher (Fig. 4a). Overall, for all included events during the three sampling years, behaviour of SSA decay is clearly captured by the model (Fig. 4c, d and e). Exploring temperature conditions alone we find that the model performs well when daily mean surface temperatures are between -25 °C and 0 °C. low-wind and moderate-wind SSA decay events respectively.

3.1.3 Environmental conditions during SSA decay events

Intuitively, environmental conditions would be considered to play a role for surface snow metamorphism and the rate of SSA decay . To explore this, hourly weather measurements from the PROMICE AWS and field report weather observations are analysed to provide environmental context to SSA decay events. Weather station data shows no systematic influence of basic weather variables, relative humidity, surface temperature and wind speed on the model-data residuals, with linear regressions resulting in $r^2 < 0.1$ for all variables. An overview of event conditions using field observations are Parameter values for τ

and n in FZ06 are defined for each event based on mean density, surface temperature and temperature gradient using the extensive look-up table referenced in Flanner and Zender (2006). FZ06 consistently overestimates the SSA decay rate, with residuals increasing throughout the events (See Fig. A5). T07 is able to accurately predict the moderate-wind events, with largest errors associated with E1, the event featuring the lowest temperatures and highest wind-speeds. which has relatively lowest temperatures and highest wind-speeds. However, for low-wind events T07 consistently underestimates the SSA decay rate. RMSE values presented in Table A. Temperatures below -25°C are characterised by the same slope defined by the model (-0.54 $m^2 kg^{-1} day^{-1}$), but with a significantly higher intercept of 29 $m s^{-1} day^{-1}$ compared to 14.7 $m s^{-1} day^{-1}$ for temperatures above -25°C. Significant wind drift is expected when hourly mean wind speed exceeds 6 $m s^{-1}$, which happens during 144 days out of the total 258 sampling days from 2017, 2018 and 2019. Results indicate weather has no systematic influence on SSA decay during the first 2-5 days exposed at the surface, and that conditions vary for each event. The model is able to predict all defined decay events between -25°C and 0°C, indicating mechanisms of decay are the same. Daily mean values are more accurately predicted by the SSA decay model than individual sample sites due to snow surface variability. In-homogeneous surface snow is especially important to consider for isotopic composition, because there is potential for samples to contain snow from different precipitation and/or deposition events. 2 indicate that the model from this study predicts decay with the least error, for both wind-speed categories.

3.2 Isotopic change during SSA decay events

3.2.1 Low- and moderate-wind event analysis

3.2.2 Surface snow spatial variability

The characterization of the SSA decays provide a basis to explore how snow metamorphism of surface snow plays a role for the alteration of isotopic compositionof Greenland snow after deposition. A recent study at EastGRIP has shown the significant in-homogeneity in surface snow due to post-depositional reworking of the snow (Zuhr et al., 2021). The focus for this manuscript is to identify signal coherence between physical properties and isotopic composition of surface snow subject to precipitation/deposition and post-depositional processes. Autocorrelation analysis shows that isotopic composition values are spatially decorrelated after 10 m ($r^2 < 0.3$ after 10 m). Therefore, to avoid attenuation of isotopic signal, each sample is treated as independent. Isotopic composition is measured from each SSA sample containing snow from the top 2.5 cm of the snow surface, potentially containing snowdeposition layers from multiple precipitation events. Surface heterogeneity is considered by using Empirical Orthogonal Function (EOF) analysis to determine the dominant mode of variance for each sampling year. Figure **??** shows timeseries of $\delta^{18}O$ (a), d-excess (b) and SSA (c) with faded lines showing each sample site. The first principal components (PC1) of $\delta^{18}O$, d-excess and SSA are presented in Fig. **??**d. All parameters continuously change throughout the field seasons of 2017, 2018 and EOF analysis in Section 3.0.1 indicates a relationship between SSA and isotopic composition, most pronounced in 2019. Isotopic composition measurements (Fig. **??**a, b) have larger spatial variability than With the understanding that decreasing SSA for low- and moderate-wind events is the result of snow metamorphism of an

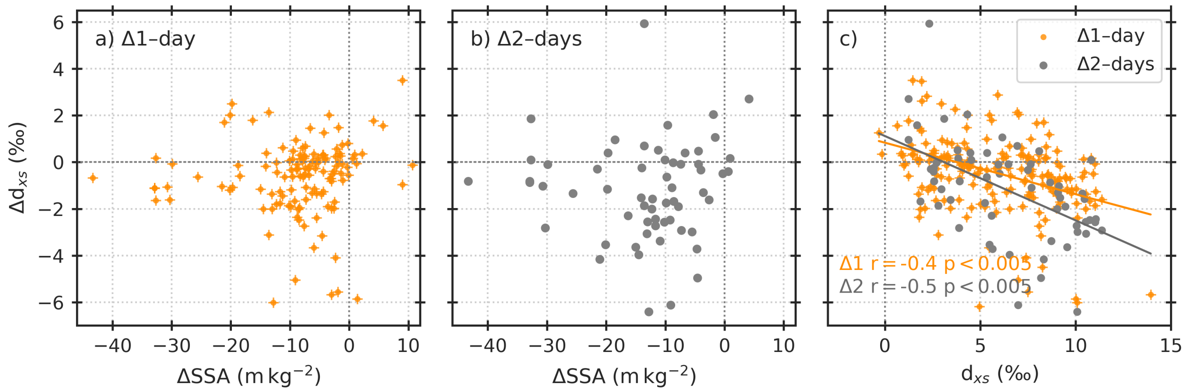

Figure 5. *Timeseries of snow isotopes and SSA*Timeseries of δ^{18}O (a)Isotopic changes during all the analysed events are shown, d-excess with each point indicating a specific sampling site. The daily change in *d*-excess (bd$_{xs}$) and SSA (eis presented in a)for 2017, 2018 change in *d*-excess and 2019 sampling seasons. d) shows SSA over the principle components first 2-days of each parameter with colors corresponding to the color used to show absolute values. The black vertical lines indicate a break event is shown in the x-axis. Each faded line represents individual sample site valuesb), and the thick line is respective changes in *d*-excess are plotted against the daily mean. Grey shaded regions indicate periods of high spatial variability absolute *d*-excess values in isotopic compositionc). Linear regressions are included for daily change (orange) and 2-day change (grey).

unperturbed snow surface, we can now document concurrent isotopic changes in the snow. For both low- and moderate-wind events, rate of change in *d*-excess is plotted against the rate of change in SSA (Fig. ??c). Inter-annual variability is observed in δ^{18}O, with seasonal mean values of -31.6‰5), -32.7‰ and -27.3‰ for 2017, 2018 and 2019 respectively (Fig. ??a). Note that the 2019 field season started approximately 15 days later than 2017 and 2018, resulting in a bias towards mid-summer conditions. Throughout the season δ^{18}O follows a gradual increasing trend from May to August. Some cases of abrupt decreases (-10‰) are observed in the late summer, for example at July 12th in 2018 and July 25th in 2019. No clear seasonal trend is observed in d-excess (Fig. ??b) but with periods of gradual decreases. Total daily spread in δ^{18}O and d-excess is 15‰.

During 2017, 2018 and 2019 SSA has one dominant mode of variance (PC1) explaining 61 %, 77 % and 72 % of the total variance in after the first and second day of each event. We here include analysis of the respective datasets. PC1 of δ^{18}O explains 69 %, 83 % and 75 % of the total variance for the respective years. While PC1 of d-excess explains 47 %, 51 % and 60 % for 2017change in *d*-excess after the second day (referred to as a 2-day change), 2018 and 2019 respectively. PC1 of δ^{18}O and d-excess show strong coherence from May to early June during 2017 and 2018, while for the second half of the season, and throughout 2019, PC1 of d-excess corresponds to PC1 of SSA (Fig. ??d).

Surface variability due to post-depositional reworking of the snow is shown by a wide spread in SSA values during a given day. Time periods with low spatial variability indicate largely homogeneous snow cover over the transect, shown in Fig. ?? as shaded regions. High variability is defined by periods where the 5-day running-mean of spatial variance in δ^{18}O is greater than one standard deviation. During periods of low spatial variability in isotopic composition, there is greater coherence between PC1 of SSA and PC1 of d-excess, due to a reduction of noise in the dataset. PC1 of SSA and d-excess show a coherence during 2018 and 2019 seasons, while the signal is less clear during 2017 (Fig. ??b). However, the reduced signal coherence is concurrent with high spatial variability in isotopic composition.

A clear relationship between PC1 of SSA and PC1 of d-excess is observed when there is a relatively homogeneous snow layer over the sampling transect, defined by low spatial variance in δ^{18}Opresented in Table 3 for each low- and moderate-wind events.

3.2.2 Isotopic change during decay events

*Relationship between SSA and d-excess after the second day of each event*The relationship between the rate of change in SSA (ΔSSA $2days^{-1}$) and d-excess (Δd-excess $2days^{-1}$) over a 2-day period for a) individual samples for events presented in Table 3 for 2017 (o), 2018, (x) and 2019 (□), b) the same values colour coded by initial d-excess from each event. c) shows the relationship between change in d-excess after 2-days plotted against the initial d-excess value, with the linear regression line in black.

Using all 10 sample sites as independent values, the behaviour of isotopes during defined SSA decay events is analysed. To determine the isotopic change in the surface snow during rapid SSAdecays, the rate of change in d-excess is plotted against the rate of change in SSA (Fig. 5). The change in SSA over a 2-day period is used. The daily mean change over the first 48h of each event is presented in Table 3.

*Table of isotopic change for decay events*Behaviour

Table 3. Table of snow parameters during isotopic change for decay eventsare defined. The initialMean values on day-0 and day-2 of each event, 2-day and percentage change over a this 2-day period are presented for δ^{18}O, d-excess *d*-excess and SSA. All Low-wind events used for the decay model are presented here, thus only the low-temperature event E7 (<-30 °Cbold text) is removedand moderate-wind events are presented.

E2	-30.29	-30.15	0.5%	0.9	-0.3	-133%	50.1	28.2	-43.7%
E3	-29.55	-30.07	-1.8%	-0.2	-0.6	-200%	50.4	31.1	-38.3%
E4	-30.27	-30.15	0.4%	1.4	-0.2	-11[illegible]			
E14	-33.89	-34.26	-1.1%	11.5	12.3	7.0%	53.2	37.4	-29.7%
E15	-32.35	[illegible]							
E20	-22.27	-2[illegible]							

In all events , the isotopic composition is observed to change, with Both δ^{18}O increasing after O and *d*-excess change from the initial value (day-0) in all events, with the percentage change in *d*-excess being the same order of magnitude as for SSA, and an order of magnitude higher than that of δ^{18}O. Three out of six events are characterised by increasing δ^{18}O and decreasing *d*-excess after 2-daysbut mostly limited to 1±1‰ mean increase, with the exception of E17 . E1, E13 and E21 in 2019 (See Table 3) E19 deviate from this pattern. E13 and E19 both correspond to total increase in δ^{18}O and *d*-excess, whereas E11 is characterised by a slight decrease in δ^{18}O and decrease in *d*-excess (Table 3). E17 is characterised by significant ground fog and snowfall during the event, while E21 has negative LHF (net-deposition)measured from the eddy-covariance system over the event. The percentage change The Δd-excess over 1-day indicates a slight negative skew around a mean of d-excess is an order of magnitude higher than $\delta^{18}O$ - expected due to the definition of d-excess - and similar to SSA, with 14 out of 19 events showing a decrease in d-excess during the first 2-days of each event. Further analysis looks specifically at the relationship between d-excess and SSA given the coherence observed between their PCs, and the significant change observed in Table 3.

SSA decreases by between 30-0.3 % and 53‰. 4 of 6 events (61% of all sample sites) experience a decrease in *d*-excess by day-2. The mean is shifted to -1.2 % during the first 2-days, the largest change corresponding to the highest initial SSA value of 74‰ over a 2-day period with decreases in *d*-excess documented in 45 out of the 60 samples (75%) during precipitation-free periods with minimal surface perturbation. Initial *d*-excess is observed to have a significant influence on the magnitude of *d*-excess decrease over the defined period (Fig. 5c), with high initial *d*-excess corresponding to the largest decreases in *d*-excess.

3.2.2 Low-wind event analysis

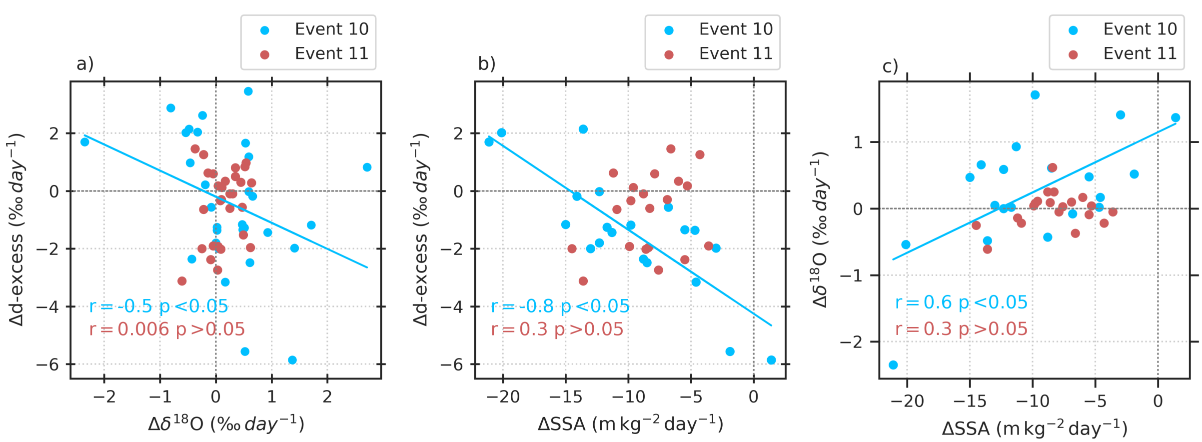

Figure 6. Isotopic change analysis for low-wind events, E10 and E11. Panel a) shows daily change in *d*-excess against change in δ^{18}O for E10 and E11, b) shows change in *d*-excess against change in SSA, and c) shows change in δ^{18}O and change in SSA. The r- and p-value for each regression are indicating in the corresponding colours. Only significant linear regressions are indicated with a line.

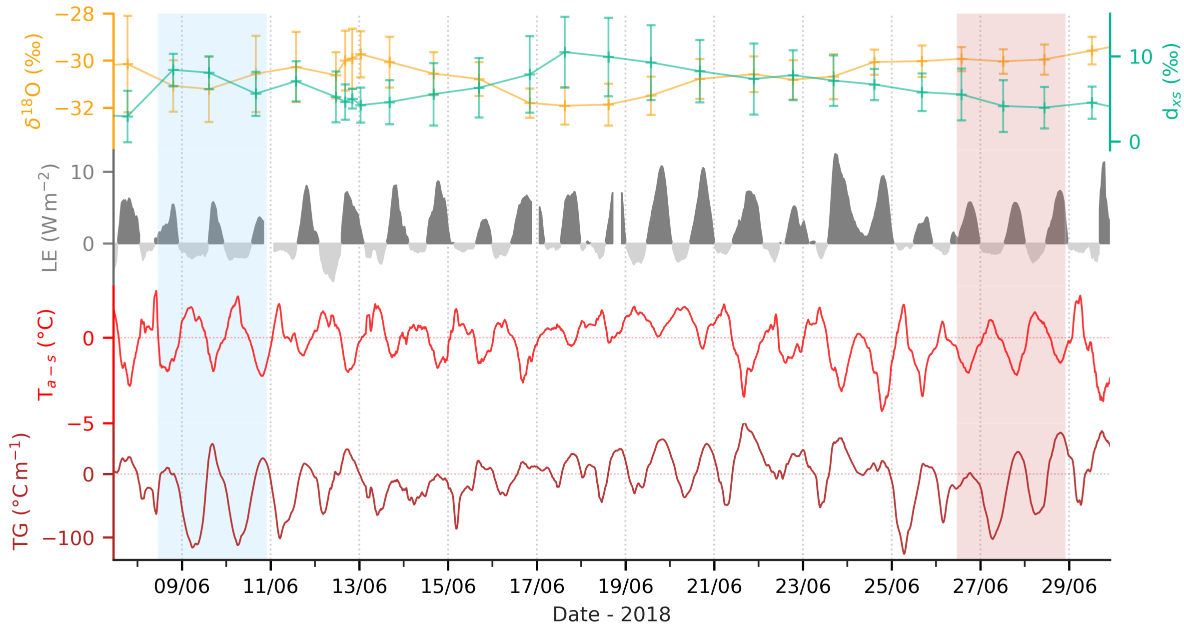

Figure 7. LE and temperature gradients for low-wind events. Latent heat flux (LE) (grey), air-surface temperature gradient (TG) (red) and surface-10 cm subsurface TG (red) during June 2018. E10 (blue) and E11 (red) are highlighted. Dark grey shading in LE indicates sublimation and light grey shows deposition.

The following section focuses on latent heat fluxes and near-surface temperature gradients corresponding to isotopic change during low-wind events only. This is to ensure that surface layer we are analysing is constant throughout the event to avoid inaccurate interpretation of isotopic change. As mentioned in Section 3.1, ground fog preceded the SSA peak in E11, concurrent with negligible accumulation recorded. In contrast, almost 1 $m^2\,kg^{-1}$ as defined by the decay model. Using a significance level of 0.01, cm of snow was accumulated during the day prior to E10, corresponding to observation of snowfall.

Figure 6 shows the relationship between change in d-excess after the second day of each event the daily change in isotopic composition for E10 and E11 (Δd-excess) and change in SSA over the same time period *d*-excess and $\Delta\delta^{18}$O) and SSA (ΔSSA)is assessed. Events presented in Table 3 are shown in Fig. ??a. 72. During E10, significant inverse correlations are observed between $\Delta\delta^{18}$O and Δ*d*-excess, and between ΔSSA and Δ*d*-excess (r% of decreases in SSA correspond to decrease in d-excess when treating each sample as an independent value. All large decreases in SSA correspond to high SSA values, as the model describes. Increases in d-excess are observed at 12 samples sites, 6 of which are during 2017 and all correspond to initial d-excess values =-0.5, r=-0.8), while $\Delta\delta^{18}$O and ΔSSA are positively correlated (r=0.6). In contrast, no significant relationship is observed between the Δ-parameters during E11, where there is negligible change in surface snow δ^{18}O (<5‰ (Fig. ??b). Thus suggests either low d-excess of deposited snow, or old snow that has been re-exposed. In addition, initial d-excess is observed to significantly influence that magnitude of d-excess change over the subsequent 48h of rapid SSA decay

(Fig. ??a and b). The largest changes in d-excess corresponds to high initial d-excess values. Moreover, increases in d-excess during rapid SSA decay follow very low initial d-excess values. In summary, in 720.7% (78 out of 108 samples)of cases decreases in SSA correspond to a decrease in d-excess of the snow sample during the first 2-days. Moreover, the magnitude of change in d-excess during rapid SSA decay shows a weak but significant dependence on the initial d-excess signal. ‰).

Significance of change in SSA and d-excess during events is tested by comparing the difference between the means of daily changes for event and non-event periods using a t-test with 0.01 significance level. Background variability in d-excess is 0.1±2.5The direction of vapour fluxes are inferred using temperature gradients determined from air, surface and subsurface (10‰ for non-event periods, compared to -0.4±2cm depth) temperature data, and LE, measured as an upwards flux. Net-sublimation is observed during both E10 and E11, with a total sum of 33.9‰ for events alone. Similarly for SSA, non-events daily change is 0.04W m^{2-2} and 55.8 kg^{-1} compared to -7.7W m^{2-2} for the respective events. LE is inversely related to the temperature gradient (TG) between the air and the surface, with strong sublimation (>kg^{-1} for events. SSA decay events exhibit significant difference in distribution to non-event daily changes ($p < 0.01$, $t = 4.0070$, df = 1715, Std. Err. = 0.125) . Moreover, changes in d-excess during events are double the magnitude of background variability with a consistently negative sign for all years, supporting evidence that d-excess of recently deposited snow has a 7210% chance of decreasing during surface snow metamorphism (SSA decay) during the first two days, according to our data. W m^{-2}), corresponding to a negative TG of 2.5°C between the air and surface on June 10th. A concurrent upwards vapour flux is observed between the subsurface and surface, most apparent on June 11th (Day-2 of E10).

Analysis shows that rapid SSA decay events correspond to decreases in d-excess over a 2-day period in 72Negative LE up to -4% of the samples. Results from EOF analysis during periods of low spatial variance in isotopic composition over the sampling transect reveals a coherence between the dominant mode of variance of SSA and d-excess, suggesting that processes driving change in SSA also influence d-excess. W m^{-1} are documented each night corresponding to the transition from a negative to positive TG between the air and surface. Net-deposition was recorded between sampling on 9th June at 15:18 UTC and 10th June 10:40 UTC (first day of E10) corresponding to a decrease in δ^{18}O and *d*-excess. The subsequent day, characterised by net sublimation, had a large increase in δ^{18}O and a larger decrease in *d*-excess. Contrary to E10, E11 is characterised by a large decrease in *d*-excess and a small decrease in δ^{18}O, both concurrent with net-sublimation and strong negative surface-subsurface TG. The air-surface TG during E11 has a lower mean and reduced diurnal amplitude than E10 facilitating sublimation for a longer period.

4 Discussion

Continuous daily SSA measurements at EastGRIP have enabled during the summer season of 2017, 2018 and 2019 have allowed for quantification of variations in snow physical properties due to precipitation deposition and snow metamorphismduring summer. Understanding the relationship between rapid decreases in SSA and corresponding change in isotopic composition require clearly defined events and environmental context. Using a multi-day SSA decrease threshold, 21 events are defined from the summer field seasons of 2017, 2018 and 2019. All events are characterised by a peak and subsequent decay in SSA , the rate of which is proportional to the initial SSA value. SSA decay in precipitation free periods is driven by sublimation and vapour diffusion which is expected to influence the snow isotopic composition (Ebner et al., 2017; Hughes et al., 2021). set of criteria, six SSA decay events during precipitation-free periods are defined and used to construct an empirical decay model with the decay rate tuned for low and moderate wind-speeds. We firstly discuss the behaviour of SSA decay at EastGRIP and compare to existing models. The isotopic change associated with low-wind SSA decay events is then considered, in the context of sublimation, interstitial diffusion and wind effects (Ebner et al., 2017; Hughes et al., 2021). Results from EOF analysis are used in combination with the isotopic change during SSA decay.

4.1 Decay model developments

4.1 SSA decay at EastGRIP

In this study, we present an empirical SSA decay model for surface snow of polar ice sheets based on continuous daily SSA measurements. The model describes SSA decay under natural summer conditions on the ice sheet. The findings from this study agree with previous studies, that SSA decayis most accurately Events of rapid SSA decay at EastGRIP are best described by an exponential function (Cabanes et al., 2002), and indicates that the crystal structure of a new snow layer is a key driver of decay rate within the defined conditions over 2-5 day periods.

Comparison with weather station data showed that the SSA decay rate during events had no systematic influence from weather variables (wind speed, temperature and relative humidity) decay function, in agreement with observations from Cabanes et al. (2003). No cold events (< -20 °C) are captured within the event criteria, potentially indicating 1) a need for warmer temperatures to induce such change in SSA over the time-period, or 2) that the local synopticity favours precipitation coincident with low temperature and high winds during the summer. Within this framework, the events captured by the threshold with mean temperatures below -20 °C are likely capturing wind-erosion, exposing sub-surface snow with lower SSA. The only exception is for temperatures outside the set range for the model. Surface temperatures below -25 °C were characterised by a significantly higher background SSA(defined as the mean SSA value of the final day of decay events) (Fig. 4), indicating high background SSA due to reduced snow metamorphism in colder conditions. This observation is supported by theory and observation that sublimation and deposition are thermally activated processes (Cabanes et al., 2003). Taillandier et al. (2007) (T07) developed an SSA decay model with a surface temperature parameter in addition to initial SSA which is able to capture the behaviour of decay during the cold event, E7, at EastGRIP suggesting temperature is important to consider when predicting SSA outside the defined temperature range. However, the influence of temperature on SSA decay rate within the defined temperature range is negligible. Model-observation comparisons show equal performance for the SSA

The narrow temperature range of SSA decay events does not facilitate a conclusive definition of a temperature-dependent decay rate (Cabanes et al., 2003; Legagneux et al., 2003; Flanner and Zender, 2006; Taillandier et al., 2007). We instead assess the influence of wind-speed on the SSA decay rate and observe a more rapid SSA decay with increased wind-speed, which can be explained by increased ventilation of saturated pore air acting as a catalyst for snow metamorphism (Cabanes et al., 2003; Flanner and Ze
.

Unsurprisingly, given the parameters are fit to the data, the model defined in the study predicts SSA decay for the low- and moderate-wind events with the lowest RMSE. The decay model from ~~this study ($r^2 = 0.89$) compared to~~ Taillandier et al. (2007) (T07~~temperature gradient metamorphism model ($r^2 = 0.9$) .~~

~~The top 1~~) performed well. performed well for the moderate-wind events, but underestimated the rate of decay for the low-wind events. T07 was defined based on the SSA decay of fresh snow with densities below 180~~cm of the 2.5~~kg~~cm SSA sample is measured by the Ice Cube device, and thus, is most likely to capture the precipitation signal (Gallet et al., 2009; Klein, 2014) . Directly after precipitation, isothermal snow metamorphism is expected to be dominant due to to high surface curvature of fresh snow crystals (Colbeck, 1980). Alternative SSA decay models are proposed by Taillandier et al. (2007) to describe snow metamorphism under temperature gradient (temperature driven recrystallisation) and isothermal (curvature driven recrystallisation) metamorphism, with the surface temperature and initial SSA being variable parameters. However, we find that all events are most accurately predicted using the temperature gradient decay equation, which accounts for the very low surface temperature observed in E7. The similarity in prediction for -25~~m^{-3} (Taillandier et al., 2007), compared to a mean density of 266~~°C to 0~~kg~~°C suggests the EastGRIP SSA decays are not only driven by crystal curvature but by temperature gradient vapour diffusion as well.~~

~~The influence of snow metamorphism after precipitation during winter is expected to be reduced due to low temperatures and negligible temperature gradients during polar night. Based on this~~m^{-3} for all low- and moderate-wind events in this study. The tendency for T07 to underestimate the SSA decay seems counter-intuitive given the possibility of aged snow in our study, which would plausibly be expected to experience SSA decay at a slower rate that fresh snow (Domine et al., 2007). In contrast, the model ~~is only recommended to use for polar ice sheet summer conditions only. Within the defined conditions, the SSA decay model is a simple empirical model to describe SSA decay in the accumulation regionsof the Greenland Ice Sheet, with dependence on the initial SSA alone~~from Flanner and Zender (2006) (FZ06) consistently overestimates the observed SSA decay rate, most pronounced in E10 and E18. The original parameter values τ and n were tuned to data from alpine regions, potentially explaining the poor fit.

4.2 ~~Decay model applications~~

~~Conditions for the model are expected to be applicable over the Greenland Ice Sheet interior under mean summer conditions . The model predicts decay events at EastGRIP with a r^2 of 0.89, compared to observation, within defined conditions. SSA estimates from satellites have previously been compared to ground observations and show a strong correlation between daily mean SSA and satellite retrieved SSA at EastGRIP(Kokhanovsky et al., 2019). The SSA decay model has the potential to predict SSA decay over the entire accumulation zone of the Greenland Ice Sheet using satellite data, the model can be evaluated for different sites to document the spatial variability in SSA over the entire ice sheet, and describe the summer SSA decay. This has additional benefits for quantification of surface mass balance and surface energy budget due to the relationship between snow microstructure and surface albedo.~~ The simple empirical model presented here is limited to conditions at EastGRIP within a narrow temperature range and therefore is likely to be unsuitable for sites with different conditions. However, large errors when using the models from the literature indicate that the low-latitude tuning is not optimal for predicting surface snow SSA decay at EastGRIP.

4.2 Isotopic change during SSA decay events

4.2.1 Low-wind events

4.3 ~~Rapid SSA decay and d-excess~~

Three key mechanisms are expected to drive the rapid SSA decays, 1) large grains growing at the expense of small grains (Legagneux et al., 2004; Flanner and Zender, 2006), 2) diffusion of interstitial water vapour (Colbeck, 1983; Ebner et al., 2017; Touzeau et , 3) sublimation reducing the dendricity of snow grains which is intensified by wind ventilating the saturated pore air, known as 'wind-pumping' (Neumann and Waddington, 2004). The dominant mechanisms can theoretically be identified by a combination of the change in isotopic composition - indicating the fractionation effect - and the LE and temperature gradient data to determine the direction of flux.

~~In this study, processes driving snow metamorphism are documented to influence isotopic composition of the snow after precipitation, supporting experimental observations and theoretical understanding (Ebner et al., 2017; Wahl et al., 2021; Hughes et al., 202 . Results from this study suggest that surface snow metamorphism following precipitation events corresponds to change in isotopic composition, most clearly observed in d-excess (Table 3). Based on our results, rapid decreases in SSA correspond to decreases in d-excess of a new snow layer in 72 % of cases during the first 2-days of rapid SSA decay .~~

~~Using the eddy-covariance latent heat flux measurements, we observed net sublimation during all decay events (with the exception of E21)used for isotopic analysis, which is in agreement with recent studies that document fractionation during sublimation results in~~ In theory, mechanism 1) causes minimal change in the bulk isotopic composition of a snow layer under isothermal conditions (Ebner et al., 2017). During no SSA decay events did the snow isotopic composition remain consistent. In the case of 2), interstitial diffusion, light isotopes are preferentially diffused, while the heavy isotopes will be preferentially deposited onto the cold snow grains (Colbeck, 1983; Ebner et al., 2017; Touzeau et al., 2016). Thus, diffusion of water vapour in the pore space causes a decrease in *d*-excess and slight increases in δ^{18}O ~~and decreases in d-excess (Madsen et al., 2019; Hughes et al., 2021; Wahl et al., 2021). However, sublimation is not the only process occurring. Vapour pressure gradients due to surface curvature drive snow metamorphism via vapour diffusion through the pore space and thus, kinetic~~ due to kinetic fractionation (Flanner and Zender, 2006). Similarly, mechanism 3), sublimation, is widely documented to cause an increase in δ^{18}O of the remaining snow-mass due to isotopic fractionation, and a significant decrease in *d*-excess expected to be due to kinetic fractionation (Ritter et al., 2016; Madsen et al., 2019; Hughes et al., 2021; Wahl et al., 2021; Casado et al., 20 . Conclusively identifying these mechanisms requires water vapour isotopes to model the fractionation ~~is expected to influence the isotopic composition. A larger influence is expected for d-excess than $\delta^{18}O$ because kinetic fractionation influences δD more than $\delta^{18}O$ ($d-excess = \delta D - 8\cdot\delta^{18}O$) with a stronger influence on d-excess than $\delta^{18}O$, which can explain the covariance between d-excess and SSA observed most clearly during 2019 (Cappa et al., 2003; Dadic et al., 2015). Our approach to the change over a 2-day period instead of daily change allows for increased propagation of the isotope signal~~

during SSA decay to account for the 1 cm representation from Ice Cube SSA measurements, compared to the 2.5 cm bulk isotope measurements (Gallet et al., 2009; Klein, 2014). A significant relationship is observed between change in d-excess and change in SSA effects. In the absence of this data, we infer potential explanations for isotopic change during the low-wind events.

An overall increase in δ^{18}O and decrease in *d*-excess during E10 is likely attributed to a combination of 2) and 3) based on observation of net-sublimation and high amplitude diurnal temperature gradient variability, indicating vapour transport within the pore space. The period between 9th June at 15:18 UTC and 10th June 10:40 UTC had net deposition corresponding to an overall decrease in δ^{18}O during the first 2-days compared to daily analysis (with an additional relationship observed during 2019 between daily change in d-excess and daily change in SSA). Decreases in d-excess are observed during rapid SSA decay, driven by a combination of sublimation, deposition and vapour diffusion through the pore spaceday and minimal decrease in *d*-excess. An increase in snow δ^{18}O would be expected during deposition (Stenni et al., 2016; Feher et al., 2021; Casado et al., 2021), however, disequilibrium between water vapour isotopic composition and snow isotopic composition may explain the decrease in δ^{18}O (Wahl et al., 2021).

Surface snow metamorphism is not confined to rapid SSA decreases, and thus isotopic composition change is observed continuously . However, results from this study indicate that d-excess changes during Both δ^{18}O and *d*-excess vary continuously throughout June 2018 (Fig. 7), with no clear relationship to total LE or temperature gradients. Strong diurnal surface and subsurface temperature gradients during the low-wind events can explain rapid SSA decay have significantly different distribution than the background non-event fluctuations. Our findings are in agreement with a study from Antarctica which showed a significant relationship between d-excess and physical snow properties with depth, while negligible relationship was observed for δ^{18}O (Dadic et al., 2015). Our study has selected rapid SSA decays fitting to the decay model to address how changes in snow crystal morphology after precipitation relates to change in isotopic composition . Future studies would benefit from using isotope flux models to account for the (Pinzer et al., 2012). We conclude that SSA of the surface snow is strongly influenced by surface-subsurface TG while the changes in isotopic composition are likely to be influenced by other factors such as the magnitude of vapour-snow isotopic disequilibrium during sublimation (Steen-Larsen et al., 2014; Hughes et al., 2021; Wahl et al., 2021). Decoupling the influence of sublimation and deposition, to determine unexplained isotopic composition change. interstitial diffusion within the snow requires additional measurements of isotopic composition of atmospheric water vapour to model associated fractionation effects (Wahl et al., 2021). Our results suggest that while processes driving SSA decay (snow metamorphism) do modify the isotopic composition of the surface snow, interstitial diffusion has a disproportionate effect on SSA decay.

An additional feature supporting the observation of processes driving surface snow metamorphismcorresponds to a decrease in d-excess, is a clear relationship between substantial increases in SSA and increase in d-excess (Fig. ??). The upper 10th percentile of ΔSSA increases (14.7

4.2.1 Inter-annual variability

The recurring difference in snow characteristics and temperature conditions during 2019 compared to 2017 and 2018 could be explained by the shifting phase of the North Atlantic Oscillation (NAO) which is in positive phase during 2018 and

2017 (below-average temperatures), and negative phase during 2019. A similar pattern is observed in the snow isotopes when considering the period between 27th May to 1st August where the mean $\delta^{18}O$ values during 2019 was -27.3 $m^2 kg^{-1}$) corresponds to positive Δd-excess in 70‰, which is 4.3 % of cases (Fig. ??). Large increases in SSA are closely associated with precipitation, however, increases are observed in a number of other scenarios (Domine et al., 2009). Precipitation is expected to cause the largest SSA, suggesting that the d-excess of precipitation is most often higher than existing surface snow. Our results therefore suggest that the precipitation isotopic composition signal is not always preserved after snow metamorphism due to (kinetic) fractionation during sublimation and other surface processes.

Change in d-excess per day (Δd-excess day^{-1}) vs. change in SSA per day (ΔSSAday^{-1}) The relationship between the rate of change in SSA per day (ΔSSA day^{-1}) and d-excess (Δd-excess day^{-1}) for all summer seasons 2017-2019 (light grey), all events (dark grey) and selected events based on substantial accumulation (dark turquoise). The box indicates the values corresponding to daily decrease in d-excess during decrease in SSA, with 81 % of selected events in this quadrant.

4.3 Influence of event conditions on isotopic change

Surface conditions prior to and during SSA decay eventsvary, with a number of events having no measured accumulation or observed snowfall (Fig. ??). Removing events with non-homogeneous increases in surface height and events where additional precipitation or significant snowdrift are observed, reveals that during rapid SSA decays following significant precipitation, there is increased likelihood of observing concurrent decrease in d-excess during the first day ‰ higher than 2018 (Fig -31.6‰) and 3.6‰ higher than 2017 (-30.9‰). While the difference in mean $\delta^{18}O$ can plausibly be explained by a 3.2°C mean air temperature difference, the isotope-SSA covariance is not so straightforward. ??) . This observation combined with results presented in Fig. ??a strongly suggests that initial snow metamorphism after precipitation corresponds to a decrease in d-excess of in the surface snow .

4.3 Spatial variability of snow surface

Low accumulation rates at EastGRIP result in the potential for winter snow layers to influence the isotopic composition in the 2.5 cm surface snow. Accumulation heterogeneity causes uneven mixing of layers at each sample site, which is observed clearly in the large spatial variability in isotopic composition measurements in Fig. ??a and b. EOF analysis is used to account for spatial variability at each site, and a coherence is observed between the principal components of d-excess and SSA.

The positive mode of PC1 is weaker when spatial variability is high, and during these periods the coherence between d-excess and SSA are muted. During the start of 2017 and 2018 $_{SSA}$ can be interpreted as increases in SSA from depositional events, such as precipitation, surface hoar formation, and wind-fragmented snowdrift (Domine et al., 2009), while the negative mode is associated with snow metamorphism or wind-erosion (Cabanes et al., 2002, 2003; Legagneux et al., 2003, 2004; Taillandier et al., 2007; Fl . Based on this interpretation, a covariance between PC1 of d-excess is coherent with $_{SSA}$ and PC1 of $\delta^{18}O$, and decoupled from PC1 of SSA. At the start of the season, the 2.5 cm sample will contain winter snow layers which are less influenced by snow metamorphism (Libois et al., 2015; Town et al., 2008), and thus, a coherent signal between d-excess and $\delta^{18}O$ is observed. The transition to a coherence between $_{dxs}$ or PC1 of d-excess and PC1 of SSA can be explained by summer snow layers, influenced by snow metamorphism, causing d-excess to appear to become decoupled from $\delta^{18}O$, which is less influenced by kinetic fractionation than δD (Masson-Delmotte et al., 2005) during snow metamorphism. δ^{18}O indicates that the mechanisms controlling SSA variability also influence the isotopic composition.

We observe a decoupling of the temporal variance in *d*-excess from that of δ^{18}O (Fig. 3) in 2019 which is can be attributed to the *d*-excess signal being more sensitive to kinetic effects during sublimation and grain growth between pore air water vapour and the snow grains (Ebner et al., 2017; Casado et al., 2021).

4.3 Implications to ice core interpretation

Ongoing work to decouple the processes driving change in isotopic composition - sublimation from surface or interstitial vapour diffusion between layers in the pore space - is vital for precise climate reconstruction in ice cores (Touzeau et al., 2018; Hughes et al., 2021; . Future studies would benefit from obtaining direct measurements of the isotopic composition of precipitation and surface hoar, to determine the fraction of such deposits in the SSA samples. Furthermore, a quantitative representation of vapour fluxes in the surface snow rather than the temperature-gradient based approximation used in this study would provide a basis from which to quantify the relative influence of fractionation during sublimation and interstitial diffusion.

4.3 Implications and perspectives

Documented changes in snow isotopic composition during surface snow metamorphism have potential implications for interpretation of stable water isotope records from ice cores, given that the current interpretation assumes the precipitation signal is preserved (Dansgaard, 1964). Seasonal transition from a coupling of PC1 of d-excess and PC1 of δ^{18}O, to a coherence between PC1 of d-excess PC1 of SSA at the latter part of the season, suggest that summer snow metamorphism causes d-excess to appear to decouple from δ^{18}O. Kinetic fractionation during sublimation is expected to be the cause a decrease in d-excess in the snow, given the different diffusivities of HDO and and $H_2{}^{18}O$ (Masson-Delmotte et al., 2005).

Seasonal signals are influenced by millennial scale insolation variability (Masson-Delmotte et al., 2006; Laepple et al., 2011) . An inverse relationship is observed between obliquity and d-excess over the past 250ka years at Vostok Variations of *d*-excess in ice core records are attributed to changes in source region, source region conditions and kinetic fractionation occurring during snow crystal formation in supersaturated clouds (Stenni et al., 2010; Jouzel and Merlivat, 1984). However, we show that there are substantial changes in *d*-excess during precipitation-free periods supporting recent work showing that post-depositional factors add complexity to the traditional interpretation of ice core water isotope records. Greenland ice core *d*-excess records show abrupt decreases in *d*-excess corresponding to warming transitions, which is attributed to the insolation gradient between high and low latitudes causing increases moisture transport from low latitudes relative to high latitudes (Vimeux et al., 2001, 1999). change in moisture source regions (Steffensen et al., 2008). Results presented in our study document decreases in snow d-excess *d*-excess during surface snow metamorphism associated with temperature gradients and sublimation, potentially contributing to the total decrease observed in the *d*-excess records. Millennial scale local insolation variability has a strong influence on temperature gradients in the snow (Hutterli et al., 2009). Thus, it is possible that local insolation variability may also influence d-excess due to temperature gradients in the snow driving snow metamorphism at the surface.

Our results highlight the need to consider the influence of surface snow metamorphism on isotopic composition in stable water isotope records as the traditional interpretation of d-excess ice core signal does not account for any post-depositional signal. Future work to decouple the processes driving change in d-excess (sublimation from surface or interstitial vapour diffusion in the pore space) is vital for modelling the change in isotopic composition down to the close-off depth in the firn (Touzeau et al., 2018; Neumann and Waddington, 2004). In addition, it would be beneficial to obtain direct measurements of the isotopic composition and SSA of precipitation , to determine the fraction of precipitation in the SSA samples.The findings of this exploratory study reiterate the importance of quantifying the isotopic fractionation effects associated with processes driving snow metamorphism during precipitation-free periods. Moreover, the inter-annual variability observed at EastGRIP between 2018 and 2019 suggests that precipitation intermittency and temperature (gradients) play a role in isotopic change, which is not readily identified in the surface snow SSA data.

5 Conclusions

This study addresses the rapid SSA decay driven by surface snow metamorphism. In particular, the study aims to explore how rapid SSA decay relates to changes in isotopic composition of the surface snow in the dry accumulation zone of the Greenland Ice Sheet. Ten individual snow samples were collected on a daily basis daily over a 90 m transect at EastGRIP in the period between May and August of 2017, 2018 and 2019. SSA and isotopic composition were measured for each sample. Periods of snow metamorphism after precipitation events are deposition events were defined using SSA measurements to extract periods of rapid decreases in SSA.

An exponential SSA decay model ($SSA(t) = (SSA_0 - 26.8)e^{-0.54t} + 26.8$ $SSA(t) = (SSA_0 - 22)\cdot e^{-\alpha\cdot t} + 22$) was constructed to describe surface snow metamorphism under mean in summer conditions for polar snow, with surface temperatures between -25above -20°C and 0with minimal surface perturbation. Two event categories were defined based on wind speed, with an upper threshold of 7°C and wind speeds below 6 $m\,s^{-1}$. The empirical model can be applied to remote areas of polar ice sheets and requires only initial SSA as the parameter, making it simple to use. The relationship between defined events of snow metamorphism and corresponding snow isotopic composition was then exploredm s^{-1} to minimise chance of snowdrift. Wind speed is observed to increase surface SSA decay rate showing that snow metamorphism is enhanced with increased ventilation.

We observe changes Changes in isotopic composition corresponding to post-depositional processes driving rapid SSA decay SSA decay are observed in all low- and moderate-wind events. A decrease in *d*-excess from day-0 to day-2 is observed in 4 out of the 6 events with no precipitation. Principal components from EOF analysis for SSA and d-excess indicate that under near-homogeneous surface snow conditions, d-excess varies in phase with SSA throughout a large proportion of the sampling seasons. This suggests that post-depositional processes and precipitationinfluence both physical snow structure and isotopic composition concurrently. Over the first 2-days of rapid Further analysis of low-wind SSA decay events , d-excess is observed to decrease significantly from the initial value for most events, at the same time we observe net sublimation. Significant changes in surface snow d-excess are observed during days following a precipitation event, suggesting that precipitation d-excess signal is altered after deposition, together with changes in physical snow properties (SSA). indicates that the combined effects of vapour diffusion and diurnal LE variability causes isotopic fractionation of the surface snow in the absence of precipitation. The differing fractionation effects are expected to be the result of vapour-snow isotopic disequilibrium. A strong correlation observed between SSA and *d*-excess found in 2019 was not present for 2018. We suggest that this is due to strong sublimation corresponding to high temperatures during 2019.

In summary, our results suggest support documentation of fractionation during sublimation and deposition between the snow surface and atmosphere, indicating that the precipitation isotopic composition signal is not always preserved due to isotopic fractionation during the processes driving surface snow metamorphism. Observations of post-depositional decrease in d-excess *d*-excess during rapid SSA decay hints to local processes influencing the d-excess *d*-excess signal and therefore an interpretation as source region signal is implausiblealone is insufficient.

Appendix A

Table A1. ~~*SSA Decay Event Conditions*~~Description of conditions for SSA decays captured by decrease threshold. Duration and conditions for all 21 events defined by the threshold. ~~'Initial Conditions' refers to~~ Observations were made of snowfall, snowdrift and ground fog. Presented here are the conditions during the day (~~-~~24h) ~~before the~~ preceding each event (Initial conditions), ~~while 'Event Conditions' describes~~ the dominant conditions ~~for~~ throughout the event ~~duration,~~ (Sky conditions) and observations of surface perturbations (Comments). based on field observations.~~'Surface Temperature' is the mean surface temperature during the event. 'Comments' highlight any significant weather behaviour during the event.~~

	Date	Event No.	Surface ~~Temperature~~ temp. (°C)	Initial ~~Conditions~~ conditions	~~Event Conditions~~ Sky conditions	
2017	27/05 - ~~01~~31/~~06~~05	E1	-17.3	No clear driver	Clear-sky	
	19/06 - 24/06	E2	-13.6	Snowfall	Clear-sky	
	30/06 - 02/07	E3	-14.0	Snowfall	Overcast	
	10/07 - 15/07	E4	-13.2	Snowfall	Clear-sky	
	18/07 - 19/07	E5	-11.7	Snowfall	Overcast	
	21/07 - 23/07	E6	-11.2	Snowfall	Overcast	
2018	07/05 - 10/05	E7	-33.7	Drift and fog	Clear/ice-fog	
	14/05 - 15/05	E8	-19.8	Snowfall	Clear-sky	
	16/05 - 18/05	E9	-21.5	Snowfall and fog	Overcast	
	09/06 - 11/06	E10	-14.9	~~Ground fog~~ Snowfall	Overcast	
	27/06 - 29/06	E11	-15.3	Ground fog	Clear-sky	
	30/06 - 03/07	E12	-11.2	Wind drifted snow	Clear-sky	
	04/07 - 06/07	E13	-10.2	Snowfall	Clear-sky	
	16/07 - 21/07	E14	-14.3	No clear driver	Clear-sky	~~E~~
	23/07 - 27/07	E15	-14.1	Ground fog	Clear-sky	
2019	17/06 - 20/06	E16	-11.4	Snowfall	Clear-sky	
	27/06 - 30/06	E17	-9.5	No clear driver	Overcast	
	02/07 - 05/07	E18	-7.0	Snowfall	Overcast	
	06/07 - 08/07	E19	-10.0	No clear driver	Clear-sky	
	18/07 - 20/07	E20	-7.6	Ground fog	Overcast	
	28/07 - 31/07	E21	-6.5	No clear driver	Clear-sky	

~~*Accumulation at each sample site*Accumulation measurements from each sample site over the 90 m sampling transect is shown here for 2017, 2018 and 2019 respectively. Each line represents an individual site. Negative values indicate a decrease in surface height, and positive values suggest precipitation or deposition adding to the surface height. The grey bars show the individual events defined in Section 3.1~~

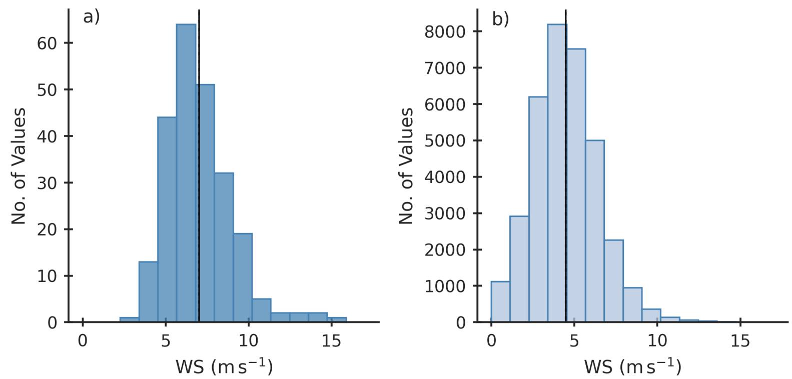

Figure A1. *Wind-speed Distribution*

Histograms showing a) the daily maximum values and b) the 10-minute mean values for all sampling days of 2017, 2018 and 2019. The black line indicates the mean.

Data availability. The SSA, density and accumulation data for all sampling years is available on the PANGAEA database with the DOI:***. Snow isotope data is also available on the PANGAEA database with the DOI:***. Data from the Programme for Monitoring of the Greenland Ice Sheet (PROMICE) 400 were provided by the Geological Survey of Denmark and Greenland (GEUS) at http://www.promice.dk. Eddy Covaraniance Tower measurement are available on the PANGAEA database with the DOI: https://doi.org/10.1594/PANGAEA.928827.

Author contributions. HCSL, AKF and RHS designed the study together. AKF, SW, MH, MB, AZ, SK and HCSL carried out the data collection and measurements. RHS, AKF and HCSL worked directly with the data. RHS, AKF and HCSL prepared the manuscript with contributions from all co-authors. AKF contributed largely to the manuscript text and structure. HCSL designed and administrated the SNOWISO project.

Competing interests. The authors declare that they have no conflict of interest.

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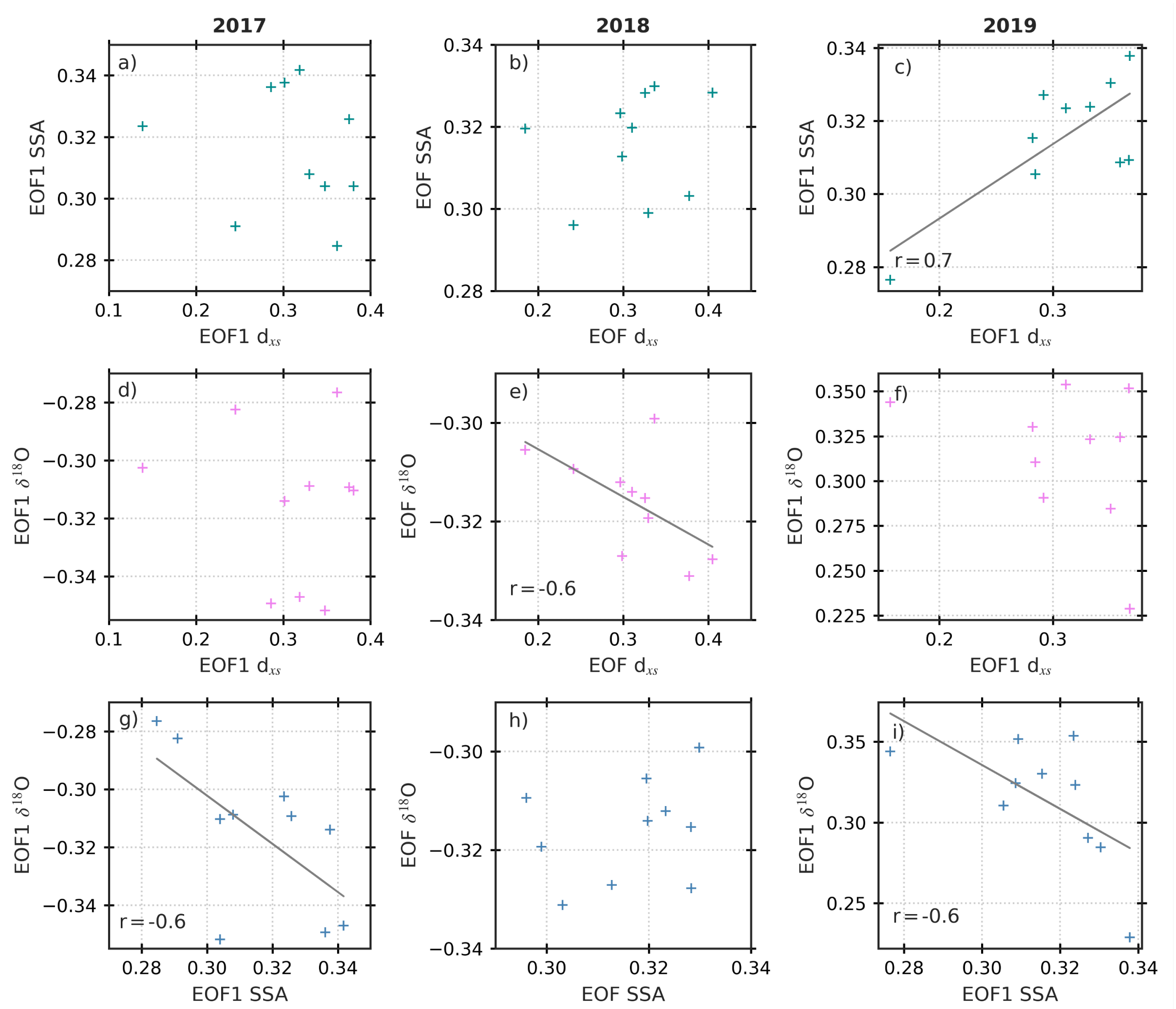

Figure A2. Results from the EOF analysis showing the relationship between SSA, *d*-excess and δ^{18}O in the spatial dimension. Linear regressions are included in plots with significant correlations ($p<0.05$) between variables.

Foundation), France (French Polar Institute Paul-Emile Victor, Insti-tute for Geosciences and Environmental research), and China (Chinese Acad-emy of Sciences and Beijing Normal University).

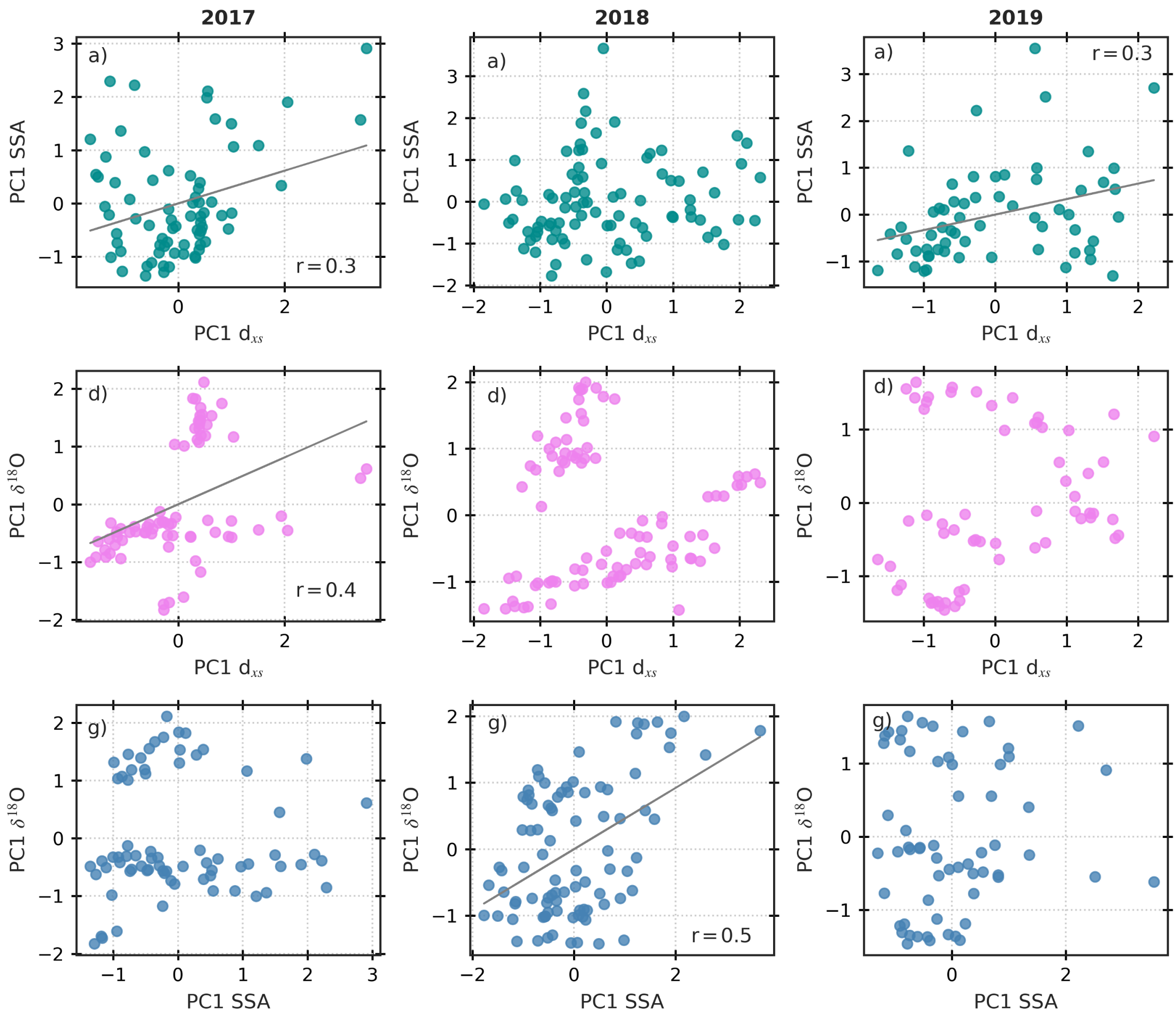

Figure A3. Results from the EOF analysis showing the relationship between SSA, *d*-excess and δ^{18}O in the temporal dimension. Linear regressions are included in plots with significant correlations ($p<0.05$) between variables.

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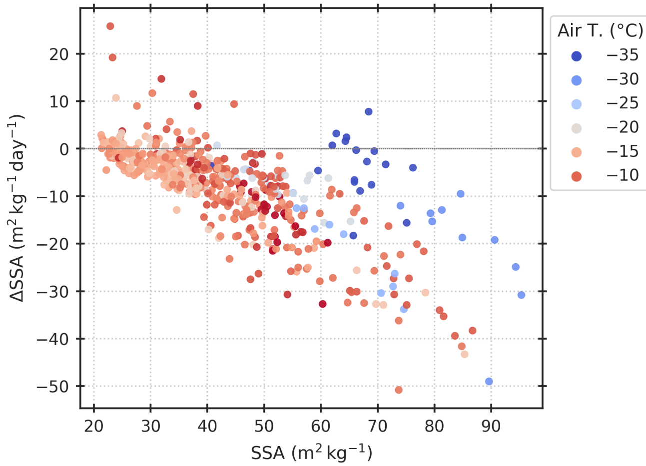

Figure A4. The derivative of SSA is shown as a function of SSA. All events captured by the decrease threshold are included here. The markers are coloured by mean air temperature between sampling.

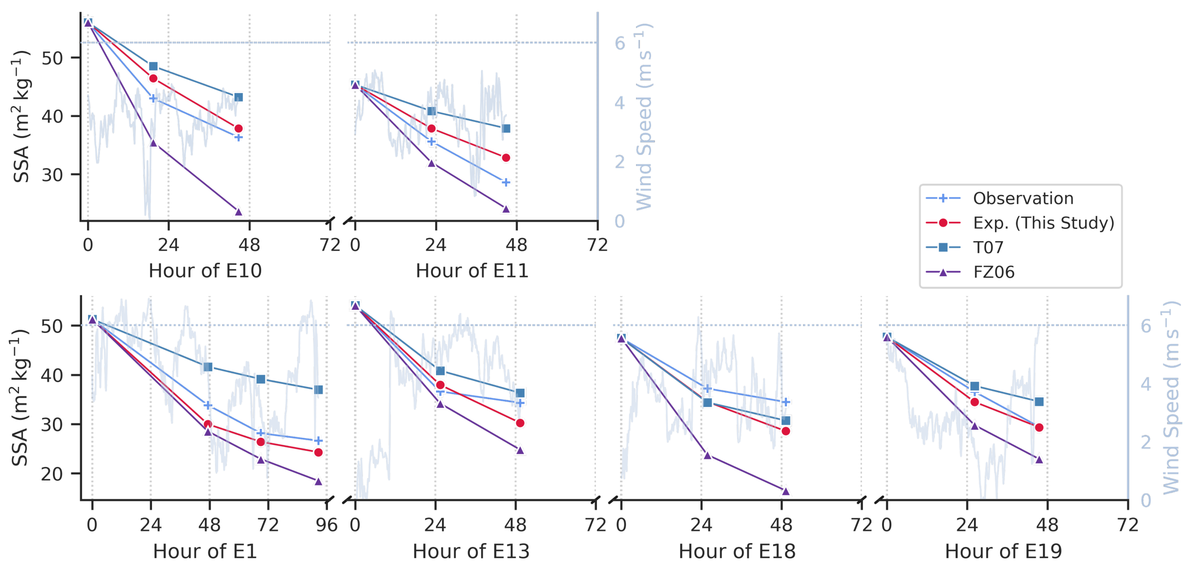

Figure A5. SSA decay model evaluation and a comparison to observations. Included models are the decay model from this study and the existing decay models from Flanner and Zender (2006), FZ06, and Taillandier et al. (2007), T07. The 10-minute averaged wind-speed is shown on the secondary y-axis, with the $6\,\mathrm{m^2\,kg^{-1}}$ thresholds indicated. Low-wind events E10 and E11 are shown in the upper panel, and moderate-wind events are shown in the lower panel (E1, E13, E18 and E19).

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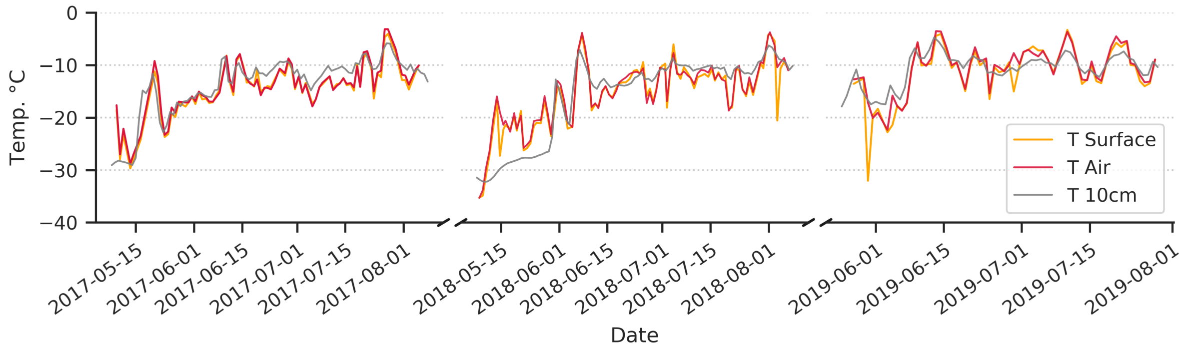

Figure A6. Daily mean air, surface and subsurface temperature time-series for 2017, 2018 and 2019.

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