Authors replay to the interactive comment on "Past surface temperatures at the NorthGRIP drill site from the difference in firn diffusion of water isotopes" by S. B. Simonsen et al.

We like to thank the reviewers for their helpful comments and constructive suggestions. In response we have revised the manuscript to become a more understandable introduction of our new method to reconstruct past surface temperatures from the difference in diffusion between different stable water isotopes.
In the following we will first address the comments by the two reviewers, highlighted in italic. After the reply to the two reviewers, we will list suggested corrections to the discussion manuscript (DMS).

Reply to Anonymous Referee #1

<u>General Comments:</u>
The consequence of the choices of a densification model, or the accurate knowledge of the accumulation are not discussed quantitatively.

We agree, that the error propagation of the basic approximations and choices are not discussed quantitatively. As stated in the DMS, the error sources of the modeling choices are hard to assess. We believe, a full error propagation study is not possible, due to the fact that the errors are dependent on each other. We will try to explain and expand on our knowledge of the error sources and come with additions to the DMS in the following to help the reader better understand the limitations of our temperature reconstruction.

The error sources mentioned by both of the referees can be divided into four categories; flow model, firn model, close-off depth and accumulation record. We have made a new set of model runs to assess the relationship between accumulation, temperature and differential diffusion based on the different assumptions. We will use these models to look at the individual components mentioned by the referees.

<u>Flow model:</u> As suggested by the referee, we have now modeled the temperature, accumulation and differential diffusion relationship, using the simple flow model presented by Grinsted and Dahl-Jensen 2002 (GDJ), see Figure 1. It is clearly seen how the GDJ-model is lacking the resolution for the GICC05 accumulation. As seen in Figure 2, is the reconstruction based on the GDJ flow model, is more flat in its reconstructed surface temperature, cold periods become warmer and warm periods colder. This may be related to the low resolution of the GDJ accumulation.

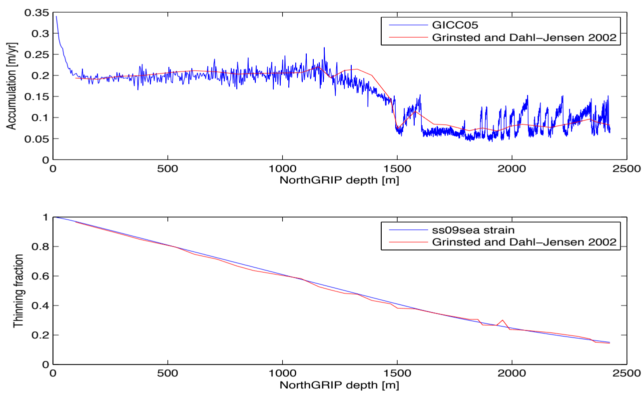

Figure 1: The accumulation used in the DMS and the one presented by Grinsted and Dahl-Jensen 2002

<u>Firn model:</u> Clearly the choice of the firn model is the biggest source of uncertainties in reconstructing past surface temperatures from the difference in stable water isotope diffusion, besides from the error associated with fitting the slope of the power spectral densities (PSD). However, the validation of the introduced error by the firn model choice is not directly possible. Based on present day conditions we have chosen the simplest model known to us to eliminate the error propagation of over fitting parameters. For present day conditions the Herron-Langway model (HL) can easily be tuned to fit the observed density profile of the NorthGRIP drill site [Simonsen 2008, fig. 3.1]. The differential diffusion has now been estimated using an isothermal version of the Arthern et al. 2010 parameterization of the HL-model, to see what effect a different parameterization will have on the reconstructed surface temperature. The new surface temperature reconstruction is generally warmer than the solution shown in the DMS, as seen in figure 2.

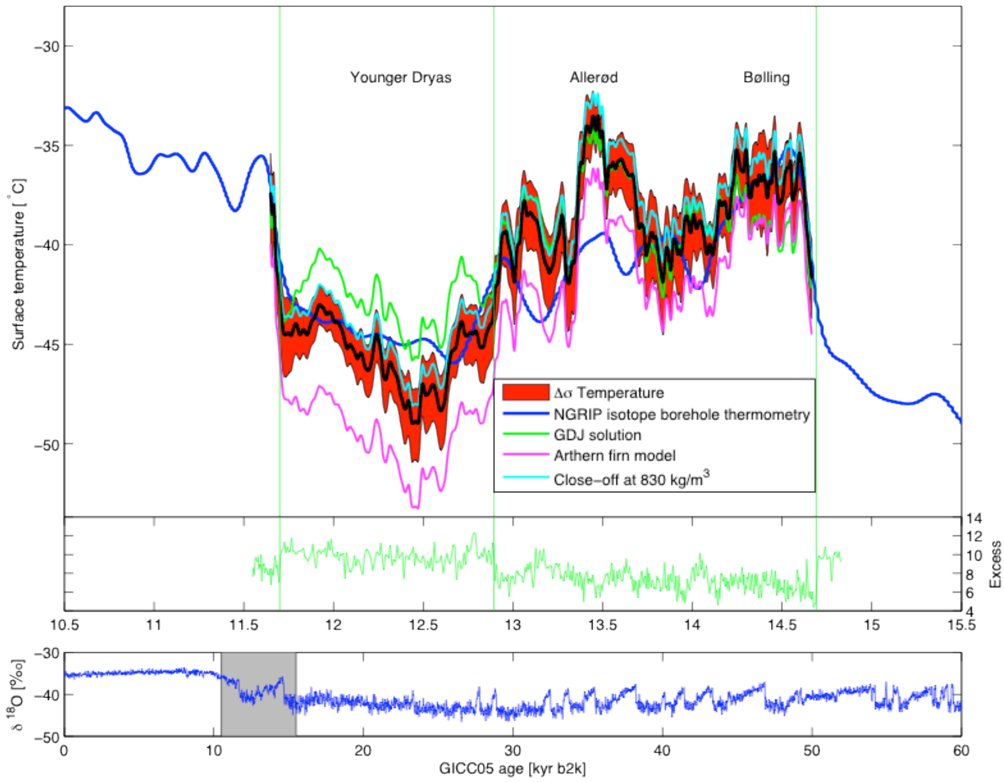

Figure 2: Suggested figure to replace figure 4 in DMS.

<u>Close-off depth:</u> To estimate the effect of changing close-off depth during rapid climate transitions, we have also modeled the accumulation, temperature and differential diffusion relationship using an upper limit estimate of the close of density (830 kg m^{-3}). The temperature solution is generally colder than what was presented in the DMS, however well within the error estimate of the fitted slope in the PSD.

When looking at rapid climate change the steady-state temperature and accumulation assumption might be a concern for the estimated thickness of the firn column. However, the running mean estimator for the "measured" differential diffusion will suppress errors induced by assuming steady state.

<u>Accumulation:</u> The annual layer thicknesses are well constrained by the dating of the NorthGRIP ice core, from counting of annual layers by the GICC05 time scale [Andersen et al. 2006, Svensson et al. 2006, Svensson et al. 2008]. Based on that we consider the error introduced by the thinning model to be more significant.

A simple way of summing the errors would be to assume individual independence. The assumption-introduced differences in the estimated surface temperatures are not independent of each other and thereby a root mean square addition of them would not give a good estimate of the error in the temperature reconstruction based on differential diffusion.

Based on the errors presented above we suggest to replace figure 4 in the DMS, with the shown above figure 2. Based on the new figure and the discussion above we suggest making the following change to MS in section 4.1 :

" ...time of the reconstruction. The error due to measuring uncertainties are well within the error of the fitted differential diffusion length and may be neglected in the temperature reconstruction as long as the white noise tail is not part of the fitted area.

To assess the bias of assumptions made to produce the reconstructed surface temperature shown in Fig. 4, the reconstruction have also been made using different

approaches for modeling the dependency of the differential diffusions on temperature and accumulation. Despite not all being fully realistic, the three scenarios are also shown in Fig. 4. The three approaches are; (1) Assuming flow and accumulation history derived by the GDJ-model. (2) Another parameterization of the Herron-Langway densification model based on an isothermal version of the Nabarro-Herring type creep parameterization by Arthern et al. 2010. (3) Assuming the pore close of at 830 kg per m³. These three scenarios cannot be seen as a real confidence interval for the reconstructed surface temperature by differential diffusion, but are showing the effect of the model assumptions.
The temperature profile (in black) in Fig. 4 is believed to be the surface temperature during the period as implied by the differential diffusion of the two stable water isotopes. "

Based on the revision of the figure the caption to figure 4 should also be revised. We suggest:
"Top panel: (Black curve) The temperature reconstruction based on the differential diffusion with a window of N=200, which is moved ΔN =11. (Red shading) The confidence interval of the fitted PSD. (Green curve) Surface temperature reconstruction using flow parameters by DGJ. (Magenta curve) Surface temperature reconstruction using parameterization of the Herron-Langway firn model by Arthern et al. 2010. (Cyan curve) Surface temperature reconstruction using a close-off density of 830 kg per m³. For comparison the Isotope borehole thermometry are also show in blue. Middle panel: The deuterium excess record for the period. Major climatic shifts are marked with vertical green lines both on the top and middle panel. Lower panel: The $\delta^{18}O$ record of the NorthGRIP ice core on the GICC05 timescale, for the last 60 kyr. All times are on the GICC05 time scale."

Specific Comments:
section 2.1 line 15, figure 1.c: I am asking for clarification: If the Z_c is different below 50m depth for the cases with and without seasonal cycle, is it just an offset due to what happens above? The seasonal cycle in temperature is not really noticeable below 50m, so adding in the seasonal cycle would not have a large effect.

The seasonal temperature cycle effect is largest close to the snow surface. Due to the exponential nature of the relationship between the saturation vapor pressure and temperature the final diffusion length at the close-off is increased. As seen by comparing the solid lines and dotted in DMS Fig. 1c.

section 2.1, p. 925, line 19, equation 8: Can you give a reference for this equation?

The equation is from [Johnsen et al. 2000], the reference will be added to the MS. This formulation is in very good agreement with eq. 2 in Murphy and Koop (2005)

section 2.2, p 927, line 16: '38ky b2k' b2k is not a widespread acronym and should be spelled out at least once

The b2k refers to before year 2000, and this clarification will be added at page 927 line 16

section 2.2, p. 927, line 15: you refer to fig 2, but I think you meant fig. 3. There are other places where you refer to the wrong figure 2/3, for instance page 932 line 14.

Correct, the sentence at page 927, line 15 should be referring to figure 3 and not 2. At page 932 the fig 3 should be fig 2.

section 4, p. 931, line 15-20: It would be interesting to use a few of the various ice flow models you mention, and see how they affect your results quantitatively. At least, you should justify why you chose to use ss09sea (I presume it is the most up to date).

See the reply to the general comment and the reply to referee #2 (general comment)

section 4, p. 932, line 14. I think you mean figure 2, not 3.

Correct, it should be figure 2 and not 3.

section 4, general: The differential diffusion in the firn depends a lot on the densification on the firn, *and the depth of pore close off. The paper only comments lightly on the densification model used, and the parameterisation used for pore close off. (section 4, page 930-931). The uncertainty in our knowledge on the pore close off depth may give a large error in the determination of the differential diffusion length, and it would be good to give some numbers for it, even with a very crude estimate of 2 different parameterisations, or 2 different versions of the accumulation/strain rate, or by adding a 10% error (or something else realistic) in the accumulation rate.*

See the reply to the general comment.

Section 5: It is indeed surprising that the Allerod does not match the d18O data. Have you looked at what the noble gas thermometer d15N/d40Ar says? It would alert you on a potential bias due to a very shallow, or abruptly changing lock-in zone in the same ice core your data come from.

As mentioned in the DMS the accurate accumulation record given by the GICC05 does not support the temperature increase. A rapid change in the close-off might be the reason for the mismatch between the two temperature reconstructions. To our knowledge have no high-resolution measurements been presented, which are able to shed light on the Allerød warming. We would be glad to add such knowledge to the discussion if provided.

figure 1a: The dotted line is barely readable, and it does not add much to your point. I suggest you get rid of it.

The dotted line is removed

figure 1c: Are you sure the wiggles are real and not due to the sampling of your model?

This diffusivity is highly temperature dependent by the exponential nature of the saturation vapor pressure described in eq. 8. Therefore, the wiggles are a result of changing temperature in the firn column, under conditions with constant accumulation rate.

figure 3: Maybe you could add an error bar envelope on your diffusion lengths, or delta diffusion lengths, mirroring what you did for figure 4.

An error bar envelope on this figure will not help the understanding of the errors involved by estimating past temperatures from differential diffusion. This figure suits the purpose of showing how the different diffusion parameters are affected by a known temperature history, and not judging the correctness of this reconstruction.

figure 4, page 942: - It would be useful to write on the figure (or initial), the Youger Dryas, Bolling and Allerod periods. - The NGRIP isotope borehole thermometry curve does not have the same spectral content (it is more smoothed) as your new data. Since you have d18O data, maybe you could produce a curve with the same spectral content as your data. It would make the comparison more fair. If it makes the figure too busy, maybe we can find a happy medium. I find it hard to compare the 2 records between e.g. 12 and 13 ka.b2k with this much smoothing.

The addition of time epochs will be added to the figure. See the here-proposed changes to figure 4 of the DMS (Shown here in figure 2).

In principle the isotope borehole temperature reconstruction can be as detailed as the isotope record itself. However, we prefer the smoothed version, since the reconstruction is based on the isotope slope and are not able to account for all of the spectral information which we believe is present in the transition.

<u>Technical Corrections:</u>

Abstract line 5: '2 stable water isotopes 18O and D': 2 pairs of stable isotopes, 18O/16O and D/H.

To be clear on the definition we suggest:

"two stable water isotopologues $^{2}H^{1}H^{16}O$ and $^{1}H_2{}^{18}O$."

All other technical corrections will be added to the manuscript.

Reply to Anonymous Referee #2

<u>*General comments*</u>

- May the difference in the Allerod period be due to uncertainties in reconstructing past snow accumulation changes (layer thickness) in a climate period characterized by fast changes in atmospheric circulation?

The difference might be due to uncertainties in the accumulation record and the associated strain history. However, the signal of a warming is also clearly seen in the raw differential diffusion record (figure 3). In the different model runs from the reply to referee #1's general comment, the signal is also a feature. We believe, there is a temperature increase in this period, however we cannot rule out the possibility of change in atmospheric circulation at the time of rapid climate changes. From the solution range seen in Figure 2, this warm Allerød is also seen.

- In the text there is some confusion in the timescale used (below) and the differences between GICC05 and ss09sea timescales

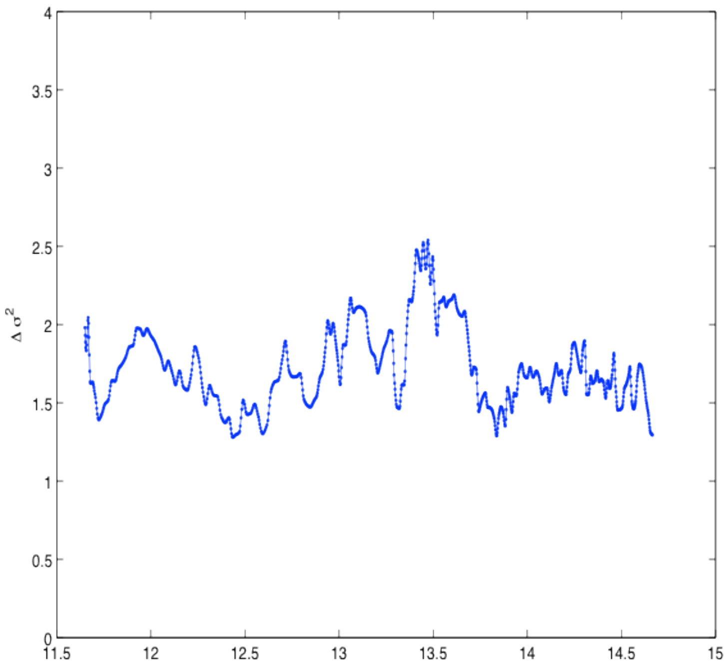

Figure 3: The estimated differential diffusion depth scale. Notice the increase in differential diffusion around the Allerød epoch.

To clarify the difference in the wording in the DMS between the ss09sea and the GICC05, we will start to explain it here and then suggest an addition to the manuscript.

The GICC05 is the official counted time scale for the NorthGRIP ice core, and all plots with a time axis in the DMS are shown on GICC05. The ss09sea with basal melt is a modeled time scale for the NorthGRIP ice core, however the version used in the DMS has been fitted to match the GICC05. Being a modeled time scale the ss09sea also gives a modeled strain history for the ice core. Therefore, when talking about the ss09sea in the DMS we are referring to the modeled strain history and not the ss09sea time scale itself. We can see this might give rise to some confusion in understanding the DMS and we suggest rephrasing the paragraph between l. 11-20 page 931 in the following manner:

"A number of ice flow models have been developed for the NorthGRIP site, among them are Grinsted and Dahl-Jensen (2002) (In the following this model will be referred to as the GDJ-model) and Johnsen et al. (2001). Such flow models can provide both the time scale and strain history in relation to the depth of the ice core. For the NorthGRIP site, annual layer counting has provided the most accurate time scale, the GICC05 Greenland Ice Core Chronology 2005 (GICC05) (Andersen et al., 2006; Svensson et al., 2006; Svensson et al., 2008). The GICC05 dates the NorthGRIP ice core throughout the last 60 kyr. In the following a version of ss09sea (Johnsen et al. 2001) corrected to fit GICC05 will provide the strain history for the NorthGRIP ice core. Applying the strain history from ss09sea to the observed layer thickness in GICC05 provides us with the annual accumulation record needed for estimating past temperatures from the diffusion record of the NorthGRIP isotope series."

- Have the high-resolution isotopic data been corrected for past _18O seawater changes?

The high-resolution isotope data have not been corrected for seawater changes. The differential diffusion length does not depend on the absolute isotopic signal. A

change in the isotopic content of the seawater would be seen as a low frequency signal in the PSD, which already is neglected in the estimation of the differential diffusion length estimate. As a result of the above we do not apply any corrections on the isotopic records due to changes in the ocean water and to eliminate additional error sources.

- Since this method is highly dependent on accumulation rate, the feasibility of applying this method to other ice core sites (Antarctica for example) and the limits of the method should be discussed.

The accumulation bias and the application of the method should be discussed. Regarding Antarctica the low accumulation over the east plateau will allow for reconstructions where we do not need to account for the annual temperature signal. On top of that for the special case of ice cores like Dome C and Vostok the transition is located at about 600 m depth. The ice flow models and the dating for this shallow depth will probably perform in a satisfactory way. So low accumulation results into low resolution and thus counting is not possible but because of this some interesting climatic events are found at a depth that is far from the kink height and the bedrock. This also means that the ice diffusion is less of a problem because the ice can hardly see the warm temps of the bedrock. On the other hand we are looking forward to the results from the WAIS divide core, which has high accumulation and present a chronology, very much equivalent to NGRIP.

We suggest the following final remark to the discussion section.

"Our method for reconstructing past surface temperatures from the difference in the diffusion for stable water isotopes is highly dependent on accurate knowledge of past accumulation and strain histories. Therefore, the method is applicable in locations, such as Greenland, where interannual changes in impurity content makes it possible to date the ice core with great precision from annual layer counting. In locations with lower accumulation the success of the method becomes reliable on the accuracy of the model strain and accumulation history. However, at low accumulation sites interesting climate transitions may be located at shallower depths and may not be as vulnerable to flow features as the deep transition in the NorthGRIP ice core. "

<u>*Detailed comments:*</u>

Page 923, line 5: There is also another method that has been used by Masson-Delmotte et al. (2005) in the GRIP ice core by considering the deuterium excess record and so the effect of changes in moisture source temperature and seasonality effects. Please, add something about this.

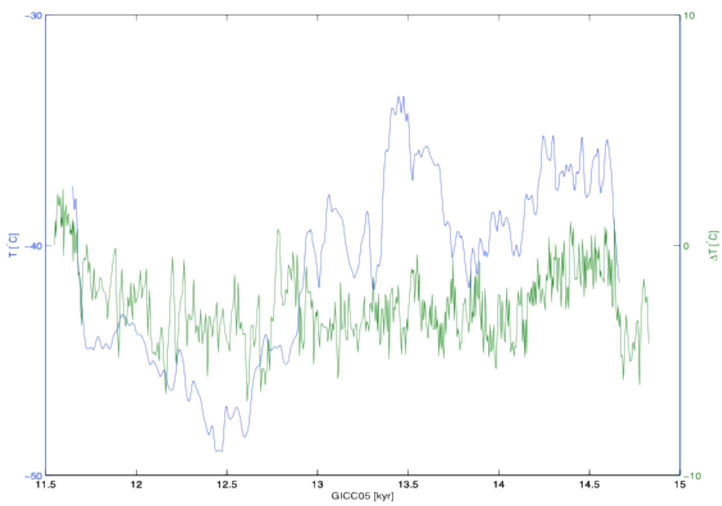

Figure 4: In blue the reconstruction based on differential diffusion and in green the anomalies based on Masson-Delmotte (2005)

Based on eq. 3 in the supplementary material of Masson-Delmotte et al. (2005), we have calculated the anomalies of the surface temperature at the site, figure 4. The method does not show the series of rapid climatic changes over the period, which otherwise is known for its rapid climate transitions. Given this, and the fact that the method was designed for Holocene (i.e. not general) conditions, we do not find it relevant to add this reconstruction to the paper to avoid adding additional plots to an already busy graph.

Page 923 line 23: may you add something (very short) about the definition of firn? it will help those readers not used to glaciological terms.

> ***In order not to disrupt the argument about vapor diffusion with a definition of the firn column, we suggest to add a footnote at "firn column" (page 923 l. 23);***
> ***"Firn can be defined as snow which have survived one melt season without being transformed into ice [Paterson 2002]. Here we define the firn column as the transformation stage of snow into ice, where an interconnected network of pores makes the diffusion of stable water isotopes possible throughout the vapor phase."***

Page 927, line 16: may you define b2k?

> **Added before year 2000 (b2k)**

Page 931, lines 2-3: See my comments above regarding the effects related to accumulation rate changes and strain rate. Probably, these effects are less important for NorthGRIP where the accumulation rate changes in the past are better defined. However, when ice flow models coupled with firn densification models are used for dating an ice core, where the inputs parameters like accumulation rate and temperature are deduced from the isotopic profiles, can this new method be used? May you provide some comments on this?

> ***See the suggested addition to the final remark of the discussion.***

Page 931 lines 11-20: it is not very clear which is the difference between this new version of ss09sea timescale and GICC05. And which are the implications for the accumulation rate record?

> ***See the reply to the general comment by referee #2***

Page 932, line 14: is Fig 2 instead of Fig3?

> ***Thanks for noticing, will be changed in revised manuscript.***

Page 933, line 6: change temperate to temperatures.

> ***Correction made to the manuscript***

Page 933, line 9: I would say that the temperatures seem even higher than during the Bolling period! The resolution of the two data sets (I mean, differential diffusion T data and borehole isotope T data) in figure 4 does not seem similar: : :. Cannot the borehole T be calculated from the new high res data? And, possibly, what about the Tsite reconstruction taking into consideration deuterium excess (see Masson-Delmotte et al., 2005)?

> ***Defining the Bølling as the peak in the d18O about 14.5 kyr and Allerød as the flat part in the d18O between Bølling and Younger Dryas (An addition of the epochs to figure 4, have been suggested by referee #1.), the most pronounced difference between the isotope borehole thermometry and the differential diffusion temperature are in the middle of what we just defined as the Allerød period. The differential diffusion method is based solely on the temperature of the firn and thus is not influenced by the temperature at the moisture source or the influence of deuterium excess on the individual isotopic content.***
> ***Regarding Masson-Delmotte (2005), see the reply to previous discussion of the Temperature anomaly.***

Page 933, line 16: what about the uncertainties in accumulation rate in a climate period characterized by fast climate changes?

> ***See reply to general comment by referee #1.***

Page 934, line 21-22: perhaps the authors may add something about the new laser spectroscopy methods allowing for high-resolution measurements.

> ***Suggest to add:***
> ***"… diffusion paleothermometry. Recently, online water isotope measurements of ice cores with the use of melter systems and infrared spectroscopy have been developed [Gkinis et al. 2011]. These methods have the potential to yield measurements of very high resolution that can be beneficial for the type of temperature reconstructions we present here. Therefore the method presented …"***

Page 934, line 23-to the end: in the conclusions paragraph some discussion on the feasibility of applying this method to other ice core sites as well as on the limits of the method should be added.

Suggest to add at the end of the conclusion:

"... firn densification. The method present here is only applicable for reconstructing the temperature signal before the ice self-diffusion becomes a dominant factor and cannot be corrected for."

Figure 1: This figure is not very readable. In the captions, please change doted to dotted.

The dotted line is removed from the figure, as suggested by referee #1

Figure 2: the x axis should be "Surface Temperature (_C)".

Added to the revised manuscript

Figure 3: The legend and the curve colours of the upper part figure should be changed : : :.. there are two reds curves: : : In the figure caption it should be added a comment to explain the temperature record (borehole isotope temperature: : :.) reported in the bottom part of the figure

The ice diffusion curve has been changed to gray.

We suggest to change the caption to:

"Modeled diffusion lengths along the NorthGRIP ice core, based on NorthGRIP isotope borehole thermometry (shown in the lower panel). Also shown for reference is the δ18O record for NorthGRIP. As seen in the top panel, the modeled differential diffusion lengths are almost not seen in the interstadials in the Last Glacial. For the modeling of the diffusion length of δ17O the fractionation constants reported by Barkan and Luz (2007) are used."

References

Arthern, R. J., Vaughan, D. G., Rankin, A. M., Mulvaney, R., & Thomas, E. R. (2010). In situ measurements of Antarctic snow compaction compared with predictions of models. J. Geophys. Res. ,115 (F3), F03011–. AGU. doi:10.1029/2009JF001306

Gkinis, V., Popp, T. J., Blunier, T., Bigler, M., Schüpbach, S., & Johnsen, S. J. (2011). Water isotopic ratios from a continuously melted ice core sample. Atmospheric Measurement Techniques Discussions , 4 (3), 4073–4104. doi:10.5194/amtd-4-4073-2011

Murphy, D. M., & Koop, T. (2005). Review of the vapour pressures of ice and supercooled water for atmospheric applications. Quarterly Journal of the Royal Meteorological Society , 131 (608), 1539–1565. doi:10.1256/qj.04.94

Proposed correction

Page 922, line 5: revised "two stable water isotopologues $^2H^1H^{16}O$ and $^1H_2{}^{18}O$."
Page 922, line 9-10: revised "…surface temperatures. It results in a diffusion length longer than if the firn was isothermal."
Page 923, line 23: Added footnote: "Firn can be defined as snow which have survived one melt season without being transformed into ice [Paterson 2002]. Here we define the firn column as the transformation stage of snow into ice, where an interconnected network of pores makes the diffusion of stable water isotopes possible throughout the vapor phase."
Page 925, line 20: Added reference Johnsen et al. 2000
Page 927, line 15: revised fig. 2 to fig. 3
Page 927, line 16: Added before year 2000 (b2k)
Page 931, line 11-20: revised "A number of ice flow models have been developed for the NorthGRIP site, among them are Grinsted and Dahl-Jensen (2002) (In the following this model will be referred to as the GDJ-model) and Johnsen et al. (2001). Such flow models can provide both the time scale and strain history in relation to the depth of the ice core. For the NorthGRIP site, annual layer counting has provided the most accurate time scale, the GICC05 Greenland Ice Core Chronology 2005 (GICC05) (Andersen et al., 2006; Svensson et al., 2006; Svensson et al., 2008). The GICC05 dates the NorthGRIP ice core throughout the last 60 kyr. In the following a

version of ss09sea (Johnsen et al. 2001) corrected to fit GICC05 will provide the strain history for the NorthGRIP ice core. Applying the strain history from ss09sea to the observed layer thickness in GICC05 provides us with the annual accumulation record needed for estimating past temperatures from the diffusion record of the NorthGRIP isotope series."
Page 932, line 14: revised fig. 3 to fig. 2
Page 932, line 26 to end of section 4.1: revised " …time of the reconstruction. The error due to measuring uncertainties are well within the error of the fitted differential diffusion length and may be neglected in the temperature reconstruction as long as the white noise tail is not part of the fitted area.
To assess the bias of assumptions made to produce the reconstructed surface temperature shown in Fig. 4, the reconstruction have also been made using different approaches for modeling the dependency of the differential diffusions on temperature and accumulation. Despite not all being fully realistic, the three scenarios are also shown in Fig. 4. The three approaches are; (1) Assuming flow and accumulation history derived by the GDJ-model. (2) Another parameterization of the Herron-Langway densification model based on an isothermal version of the Nabarro-Herring type creep parameterization by Arthern et al. 2010. (3) Assuming the pore close of at 830 kg per m^3. These three scenarios cannot be seen as a real confidence interval for the reconstructed surface temperature by differential diffusion, but are showing the effect of the model assumptions.
The temperature profile (in black) in Fig. 4 is believed to be the surface temperature during the period as implied by the differential diffusion of the two stable water isotopes. "
End of section 5: Added: "Our method for reconstructing past surface temperatures from the difference in the diffusion for stable water isotopes is highly dependent on accurate knowledge of past accumulation and strain histories. Therefore, the method is applicable in locations, such as Greenland, where interannual changes in impurity content makes it possible to date the ice core with great precision from annual layer counting. In locations with lower accumulation the success of the method becomes reliable on the accuracy of the model strain and accumulation history. However, at low accumulation sites interesting climate transitions may be located at shallower depths and may not be as vulnerable to flow features as the deep transition in the NorthGRIP ice core. "
Page 934, line 23: Added "… diffusion paleothermometry. Recently, online water isotope measurements of ice cores with the use of melter systems and infrared spectroscopy have been developed [Gkinis et al. 2011]. These methods have the potential to yield measurements of very high resolution that can be beneficial for the type of temperature reconstructions we present here. Therefore the method presented …"
End of section 6: Added "… firn densification. The method present here is only applicable for reconstructing the temperature signal before the ice self-diffusion becomes a dominant factor and cannot be corrected for."

Acknowledgements: We have added an acknowledgement to the NorthGRIP members for providing the data:
""… Climate. NGRIP is directed and organized by the Ice and Climate research group, Niels Bohr Institute, University of Copenhagen. It is supported by funding agencies in Denmark (FNU), Belgium (FNRS-CFB), France (IPEV and INSU/CNRS), Germany (AWI), Iceland. (RannIs), Japan (MEXT), Sweden (SPRS), Switzerland (SNF) and the USA (NSF, Office of Polar Programs). NCAR/EOL …
Figure 1a: the dotted line are removed and the sentence "The doted line indicates the temperature, a layer experiences as it moves down into the firn matrix given stable accumulation and temperature conditions" is removed from the caption.
Figure 2: Changed the x axis to be "Surface Temperature (deg C)".
Figure 3: ice diffusion changed to be depictured in gray. Caption revised "Modeled diffusion lengths along the NorthGRIP ice core, based on NorthGRIP isotope borehole thermometry (shown in the lower panel). Also shown for reference is the δ18O record for NorthGRIP. As seen in the top panel, the modeled differential diffusion lengths are almost not seen in the interstadials in the Last Glacial. For the modeling of the diffusion length of δ17O the fractionation constants reported by Barkan and Luz (2007) are used."
Figure 4: Figure revised and caption revised "Top panel: (Black curve) The temperature reconstruction based on the differential diffusion with a window of N=200, which is moved ΔN

=11. (Red shading) The confidence interval of the fitted PSD. (Green curve) Surface temperature reconstruction using flow parameters by DGJ. (Magenta curve) Surface temperature reconstruction using parameterization of the Herron-Langway firn model by Arthern et al. 2010. (Cyan curve) Surface temperature reconstruction using a close-off density of 830 kg per m^3. For comparison the Isotope borehole thermometry are also show in blue. Middle panel: The deuterium excess record for the period. Major climatic shifts are marked with vertical green lines both on the top and middle panel. Lower panel: The $\delta^{18}O$ record of the NorthGRIP ice core on the GICC05 timescale, for the last 60 kyr. All times are on the GICC05 time scale."