

## Response to the reviewers

We thank both reviewers for their constructive comments. Please find below detailed answers.

### Anonymous Referee #1

1. The authors should also indicate how the data will be made available after manuscript has been published.

**After publication the data will be available from the data base PANGAEA**  
<http://dx.doi.org/10.1594/PANGAEA.849161>.

2. Section 2: Given that two co-authors were also co-author on the recent paper presenting the stacked ice core record from the NEEM shallow ice paper (Masson-Delmotte et al. 2015) I find it odd not to include this nearby isotope record in this study. Given the high signal-to-noise ratio of that stacked core it might make sense to compare the individual NGT cores with this ice core.

**We decided not to include the NEEM data, because of the covered time period. The NEEM (shallow) record covers the most recent (300) years. Our focus is on the last millennium. The core B26 was drilled only view kilometers from the NEEM site and covers a much longer time period. However, of course we include the NEEM record in the discussion of our results (e.g. in the section “3.3 The northern Greenland  $\delta^{18}O$ -stack and its paleoclimatic significance”)**

3. Page 2346 L 15-19: It is unclear to me how the authors have taken into account layer thinning when assigning the depth-age model. Please explain in details the model used.

**Layer thinning was not taken into account as the cores were drilled only in the upper part of the ice sheet. We add this information to the manuscript.**

**For the ice core dating we only picked the depth of the time-marker horizons. Between two horizons we assume the accumulation rate to be constant.**

**Compared to densification thinning effect is of second order at the top 100 m.**

**E.g. if the Greenlandic ice sheet is about 3000 m 100 m is about one thirtieth. In about 1000 years the mistake in the accumulation rate is about 2 % which means that we have 102 instead of 100 mm.**

4. P2347 L3: What is the dating uncertainty for the period between 1100-1500 years? Later (p. 2349) the authors decide apply a running mean of 5 years – it is unclear to me why 5 years were chosen and not 10 years given that the uncertainty is estimated to be 10 years. I suggest that the authors discuss and quantify the effect of this dating uncertainty on the correlation coefficients discussed on page 2349. Please consider to use a 11-year running mean to filter out the solar cycle instead.

**There is no error for our Depth-Age Model (well dated volcanic horizons). But there is a maximum of 10 years difference between annual layer counted NGT records and our dating assumption (See table 2).**

**We will show 11-years running means instead of 5 years to better take into account the potential dating uncertainty.**

**For 11-year running means about 50% of the records have correlation coefficients higher 0.3 (5-year running mean 25%).**

5. P. 2347 L15-24: Please explain the model used to account for thinning.

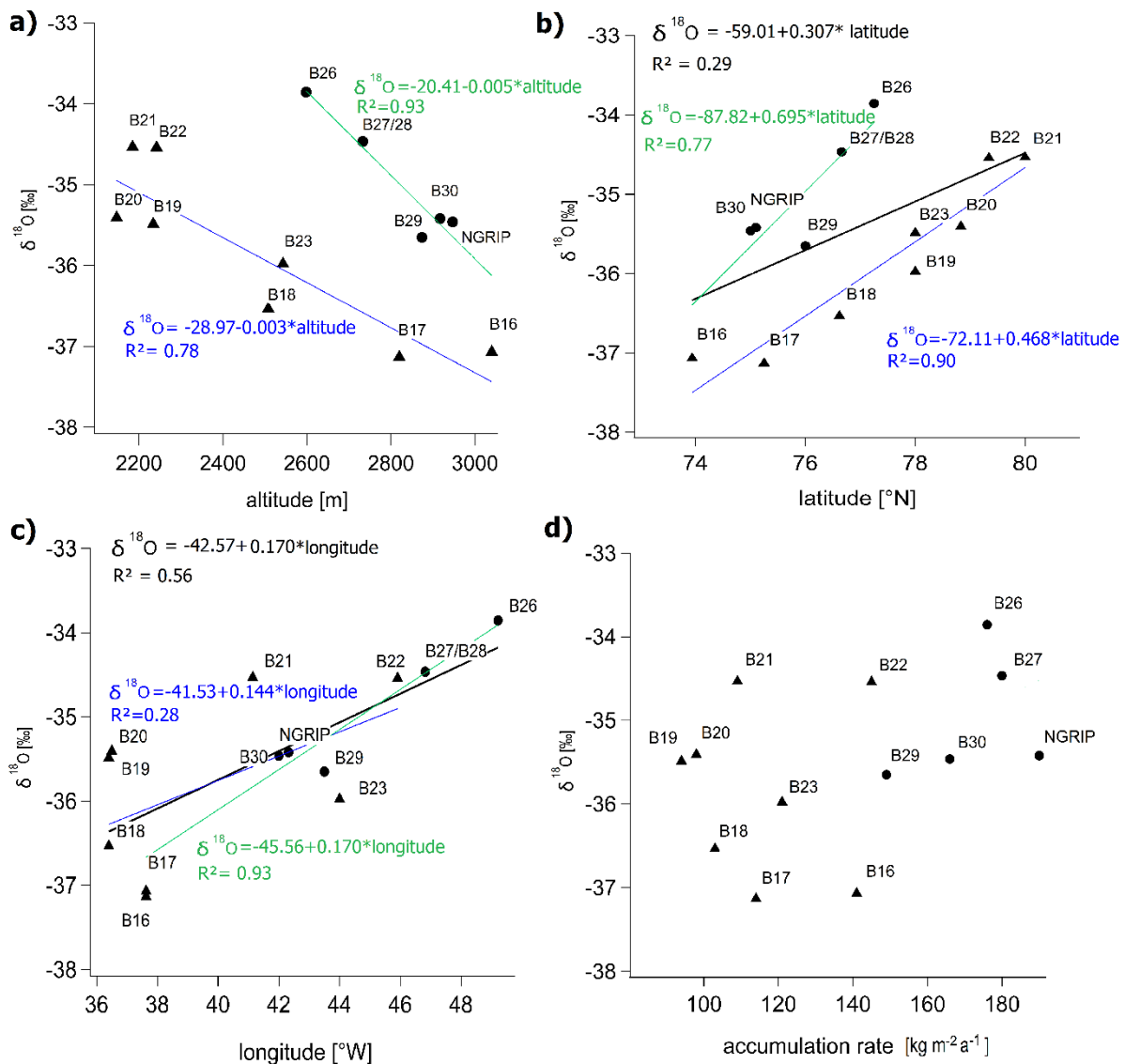
**Thinning was not taken into account. Please see point 3**

6. P. 2348 L3-6: Given that you are using mean annual isotope values from ice cores with very low accumulation you will need to argue why diffusion does not alter the mean annual isotopic value. I would suggest that the best approach to do this would be to calculate the maximum diffusion length found at each site and compare this with the mean annual layer thickness.

**Following Johnsen et al. 2000 the maximal diffusion length is 9 cm, which is slightly smaller than the annual layer thickness. Diffusion might be affecting the absolute difference in isotope content of neighboring years but the mean over 11 or 30 years will not be affected. We add this information to the manuscript in the end of section “3.1 Depth-age models and snow accumulation rates”.**

7. P2349 L3-11: You need to remove the linear regressions from the figures, which are not statistical significant. Showing these fits does not make sense if they are not statistical significant. I suggest that you carry out a multivariable linear regression as well. I don't believe that showing the linear regression between the isotopic value and the longitude reveal any useful information. Instead I suggest that you use a relevant metric instead of the longitude. For example you could use the distance between the ice core site and the ice divide as a relevant metric, which is more physical appropriate than the longitude.

**We agree to remove the insignificant regression lines. Instead we add statistically significant fits for group I ("east") and group II ("divide") to show the differences on and east of the main ice divide. We think it is necessary to show all these plots to make clear, that it is not an easy situation in northern Greenland to see the relationships because of the canceling out of different effects. If you go northward (lighter d18O values) you also go downward (heavier d18O values). Multilinear regression was performed as well and the results are discussed in the manuscript.**



8. P 2350 L5-9: I'm pretty sure that the pattern, which you show in Figure 5 is called the EOF while the temporal component of the EOF/PC analysis is called the PC. Under all circumstances you should give error bars on the to show that the first two EOF/PC components are independent of each other. Secondly you should also show the temporal component of the first 2 PC's

**Because we do not see any extra information and to shorten the manuscript for better readability we will remove the figure showing the EOFs and most parts in the text dealing with the PCA. At the end**

of the section “Regional variability of  $\delta^{18}\text{O}$  in northern Greenland” we only say that there are two EOFs above the noise level while EOF1 has homogenous and EOF 2 and bipolar (east-west) pattern.

9. P2351 L3-6: As argued above it would make sense to also compare the your NG-stack with the NEEM stack.

**We found a strong correlation of the NEEM-stack to our NG-stack ( $r = 0.8$  for 30-year running mean). And added this to the discussion in the manuscript.**

10. P2352 L1-14: What is the argument for not using the isotope-temperature relationship derived by Masson-Delmotte et al. 2015 for present day conditions, but instead use isotope-temperature relationship for glacial-interglacial conditions?

**We do not use gradients derived from deep borehole temperatures at one site (glacial-interglacial conditions) the gradient we use (0.67) was derived from special isotope-temperature surface relationship studies for present day conditions which therefore can be used for our Holocene dataset. If using the NEEM gradient of  $1.1 \pm 0.2$  ‰ per °C the temperature range is:  $-1.3^\circ\text{C}$  to  $2.28^\circ\text{C}$  which is slightly smaller than the results with the Dansgaard/Johnsen gradient. The gradient derived by Masson-Delmotte et al. 2015 can provide a more correct gradient in time while the gradient, which was valid for 2007-1979 AD, is also usable for other periods of strong warming, but not in space.**

**We will show these results additionally to the other calculated results in section “3.3 The northern Greenland  $\delta^{18}\text{O}$ -stack and its paleoclimatic significance“.**

11. P2355 L6-12: Please consider the fact that for the cores located to the east you likely have higher fraction of winter accumulation compared to summer accumulation. This likely means that variations in amount of summer accumulation would increase the noise, and thereby decrease the inter-core correlation. You could also consider using an 11-year running mean, as you have indicated earlier that uncertainties for some part of the cores were 10 years.

**Yes, a changing seasonal distribution can be an additional source of noise. We therefore focus the interpretation on the running mean data. However, it is not possible to assess the seasonal accumulation from our data.**

12. P2356 L 3-8: You need to support your statement about the spatial pattern of temporal variability with some kind of analysis.

**We calculated the dominant frequency in 11-year running mean records of the individual cores. B18-B21 but also B29 show longer periods (117-248 a) than B16-B17 and B22-B30 (besides B29) (81-39 a)**

13. P2356 L24-27: It is not clear to me how you based on Figure 4D, which does not show a significant correlation between  $d^{18}\text{O}$  and accumulation can draw the conclusion that your data are consistent with the hypothesis that the foehn effect causes an anti-correlation between  $d^{18}\text{O}$  and the accumulation rate.

**We will remove the regression line between accumulation and  $d^{18}\text{O}$  in figure 4 and also the discussion about foehn effect in the manuscript.**

14. P 2357 L 12-21: You need to explain the model parameters, which you tune and how you set up the model to simulate your data. Otherwise I suggest removing this section.

**We removed most parts of this section. We will only give the information that multilinear regression is necessary to clarify the correlation to the  $d^{18}\text{O}$  values because due to the topography there are several processes that are cancel out each other in northern Greenland e.g. the effect of altitude and latitude.**

15. P2357 L28-P2358 L2: It is hardly surprising that you have a high correlation between PC1 and the NG stack as you use the same dataset to produce both records. You might also want to clarify that you refer to the temporal component of EOF/PC1 and not the spatial component shown in the figure. As mentioned above I strongly suggest that you show both the spatial and temporal component of the EOF/PC analysis.

**Because we shortened the PCA part in the manuscript e.g. removed the EOF plot and cannot attribute the PCs to any forcing factor we will not show the individual PCs.**

16. P2358 L1-2: I understand where your 22% comes from – however I do not think that

it is correct to claim that only 22% of the NG-stack variability is caused by a regional climate signal. One could make the claim that by making the NG-stack you smooth out most of the influence from deposition noise hence all the variability in the NG-stack is caused by climate one way or the other. When reading your sentence I am left with the answer 'what is the remaining 78% variability in the NG stack?'

**See point 8.**

17. P2358 L11-13: This is a circular argument – you calculate the PC's based on the same cores, which make up the stack.

**We removed this argument.**

18. P2359 L 1-4: What is the correlation for SON and DJF? What are the p-values?

**The r values for SON and DJF are smaller (see table 5). DJF is only significant ( $p < 0.05$ ) for Illulisat and the merged southern record. For SON we calculate  $r = 0.5-0.31$ . We added the information to the text of the manuscript.**

19. P2359 L10-13: Please quantify the similarities with the stack of Masson-Delmotte et al. 2015.

**We find similarities in the identification of the depleted or most enriched events as described p.2359. We correlate both records and find a strong and statistically significant correlation with  $r = 0.54$  (annual values) and  $r = 0.82$  (30 year running mean). We added this information in the discussion part.**

20. P2359 L22-23: Wouldn't it be possible to reach this conclusion base on the PC1 and PC2 instead of having to separate the cores into subjectively chosen groups?

**See point 8.**

21. P2361 L10-13: To support this hypothesis you might want to consider comparing your Stack I (the cores to the east of the divide) with the LOMO-core, as you have argued for these cores to be dominated by a winter precipitation signal.

**The correlation for 30 years running means between the Lomo-core and the stack I ("east") shows a correlation coefficient of  $r = 0.2$  whereas stack "divide" has negative correlation ( $r = -0.12$ ). This can be a first hint that there is more winter snow in the northeastern part of northern Greenland.**

**For the other arctic records we also compare to the stacks "east" and "divide".**

**Dye3 and AN show comparable r values as for the NG-stack, the correlation between Agassiz core and stack "east" ( $r = 0.53$ ) is slightly better than stack "divide" ( $r = 0.47$ ). However the NG-stack has strongest correlation at each site. Only for Lomo we found differences in the strength of correlation. We add this information to the manuscript in section 3.4.**

22. P2363 L1-17: The analysis of the response from volcanic eruptions on the isotopic signal presented in this section need to be supported by a statistical analysis otherwise I suggest to remove this section.

**We removed this part for a clearer structure and to shorten the length of the paper.**

23. P2365 L13-19: to support your hypothesis that the year 1420-event is related to sea ice decline you will need to argue why you do not have a positive anomaly in the d18O record for year \_1590 and year \_1700 where sea ice is at a significantly lower level than at 1420.

**We change the wording in the text to weaken the statement.**

**As the shown sea-ice record is an arctic-wide reconstructed record and the used data older than in-situ observations, the interpretation has to be seen with the necessary respect.**

24. P2366 L23-25: This sentence needs to be restructured. You need to point out that you are referring to mean annual d18O values (I presume this is the case). You need to point out that you mean that 12% of the spatial variability is due to ice sheet topography. As argued above it is hard to understand how 78% of a stacked ice core record can be due to random noise not related to the climate. As shown by White et al. 1997 a significant part of a single core compare to a stacked record is noise – however they estimate \_40% common variability between the individual cores and the stacked record. It does seem that you are mixing temporal and spatial variability together here. Please correct appropriately.

**We make clearer that we are discussing spatial variability. However, we shortened the length of the PCA section drastically to shorten the papers length and to achieve a better readability.**

### Minor revision

P2343 L15: Add reference Merlivat and Jouzel 1979 -> **done**

L16: Add reference Jouzel and Merlivat 1984-> **done**

L21: Add reference Fisher et al. 1985-> **done**

L22: Add reference Pinzer et al. 2012, Steen-Larsen et al. 2014, Johnsen et al. 2000-> **done**

L24: Add reference White et al. 1997, Masson-Delmotte et al. 2015-> **done**

P2345 L21: Please provide detailed information about which cores and which part of the core were samples with what resolution.

**Samples were cut with 1-5 cm depth-resolution as given in the manuscript. Most of the ice was sampled with 2-2.5 cm resolution. Only at the upper most parts of the core samples were cut with lower depth-resolution (up to 5 cm). For some meters of special interest a resolution of 1 cm was used. We added this more detailed information to the manuscript.**

P2348 L14: Please explain that the calculated SD is the standard deviation of the mean annual isotope values (I presume this is the case) -> **done**

P 2349 L17-20: You might want to compare the inter-core correlation coefficients with those derived by White et al. 1997 and Masson-Delmotte et al. 2015

**The cores in the surroundings of the deep cores at NEEM and GRIP had been drilled in closer distance to each other than the NGT cores. Therefore, they find higher correlations with  $r \sim 0.54$  (Delmotte et al. 2015) and  $r = 0.41-0.55$  (White et al. 1997).**

**Added the given information to the manuscript.**

P 2357 L 15: Change enormous to significant-> **done**

P 2358 L 28: may be - > maybe-> **done**

P2364 L 11: Change 'the temperature records' to 'the isotope records'-> **done**

## Anonymous Referee #2

1. As already mentioned the paper suffers from a poor structure and as a consequence it is far too long. There is a lot of unnecessary repetition. One way of avoiding this would be to combine "Results and Discussion". I also suggest removing Fig 6 since it is included in Fig 8. I also wonder if it is necessary to show all the plots? For instance, can Fig 7 be left out?

**We add figure 8 (sub-stacks) to 6 and left out figure 7 (residuals).**

**We shortened the paper length by combining "discussion" and "results to avoid unnecessary repetitions.**

2. I lack meteorological information which is the fundamental background for interpreting d18O so a section on this would be an important part of improving this paper. Some of this information is included in other parts of the paper (mainly in the discussion part) but I think that the paper would benefit from having it all collected in one section in the beginning.

**We add information in the introduction to a give short overview about the most important meteorological facts for the d18O values in northern Greenland. Furthermore we add the results of 15m firn temperature measurements to table 4.**

3. I also lack a proper "background and previous work".

**We add information on previous d18O NGT work and describe the scientific activity in northern Greenland in the introduction**

For instance there are several comments in the paper to how northern Greenland is different from Southern Greenland but few (if any?) specific examples. Please include some of these with proper references.

**In the introduction part we already described that northern Greenland differs significantly from the south in terms of lower air temperatures and lower snow accumulation rates. We describe the meteorological characteristics of northern Greenland now more in detail.**

For people not working with Greenland even terms like "southern Greenland" and "northern Greenland" need to be specified.

**We separate the Greenlandic ice sheet at summit in north and south and will specify that now in the text.**

4. My main concern with this paper is that the accumulation records are not given the space and consideration for the results that I think it should have. I understand that some of the accumulation data has been published before but I think that these data has to be viewed in connection with the d18O data.

**For results on the mean accumulation rate data see Weißbach et al. 2015**

**DOI 10.1007/978-3-319-13865-7\_21**

**The accumulation rate at the different drill sites was over the last 1000 years rather constant. We observe no stat. significant correlation between the mean accumulation rate and the d18O values (see figure 4). On annual resolution we would expect that the accumulation rates are following the d18O characteristics.**

Some of the questions that come to my mind that I do not find an answer for in the paper are: -  
What is the seasonal distribution of snowfall in Greenland?

**With the given data we cannot answer this question. Due to the dating assumptions and sampling resolution we do not have seasonal resolution.**

In Table 5 the seasonal impact of temperature on the d18O is investigated but the seasonal distribution of accumulation is not really discussed anywhere. - What does the long term (stacked) accumulation record look like for this area? Maybe some insight could be revealed from combing this with the d18O record for instance in Fig 8. I also wonder what the accumulation records from these cores look like over time?

**Because of the dating assumptions we do not have "real" annual resolution. For that reason we do not focus on the annual accumulation rates or their influence to  $\delta^{18}\text{O}$ .**

Is there was any GPR data collected in connection with the cores that would indeed provide information to the questions asked; how representative single ice cores can be for a specific area. I

suggest to look at the literature from similar studies done in Antarctica where there are exactly the same concerns with low accumulation as in Northern Greenland.

**GPR data is a totally different topic. Because we do not focus on the accumulation rates we decided not to include this data to our paper.**

**There was a traverse from NGRIP to NEEM with GPR. The results are given in the Diploma thesis of Radzic 2008 (unpublished).**

5. The paper claims to provide a “new climate record” but it is not so clear what if there was a previous climate record- and if it was what it looked like. Like many things in this paper it might be buried in the text but it is not easy to find.

**There is no “old” stacked record for northern Greenland. Only single NGT records are published (Schwager 2000, Fischer et al. 1998). The collection of NGT cores and the generation of the stack(s) offer us for the first time the possibility to have a representative stack for northern Greenland. Before, there were stacks for smaller areas at NEEM e.g. Masson-Delmotte et al. 2015 or Summit e.g. White et al.1997.**

6. Results absolutely need some kind of error analysis both on the dating and the stacked record. **There is no dating error due to our dating assumptions. If there was a prior dating with annual layer counting we give the maximum difference between both dating methods in table 2.**

7. Regarding about the AMO impact in Greenland I suggest looking at this paper in addition to what is presented: Chylek, P., C. Folland, L. Frankcombe, H. Dijkstra, G. Lesins, and M. Dubey (2012), Greenland ice core evidence for spatial and temporal variability of the Atlantic Multidecadal Oscillation, Geophys. Res. Lett., 39, L09705, doi:10.1029/2012GL051241.

**We add information about AMO studied from  $\delta^{18}O$  in ice cores and its temporal and spatial relevance in Greenland. However the AMO influence is reduced in the north we see the AMO as possible explanation for the periodic oscillation between 1100 and 1600 AD.**

Some minor specific comments

Abstract: The first paragraph is including many unnecessary numbers which are not informative. I suggest to rewrite the abstract. **We remove some of the given numbers and shortened the abstract.**

Material and methods: l. 20 please add reference to this method. **Done. Kaufmann et.al 2008**

The expression “very low accumulation” is used on many places in the text without defining it. **Very low means 100 mm/a or less.**

The language is generally acceptable but there are a number of typos that eventually needs to be fixed; as an example p 2352, l. 13: should be “firm” instead of “firn”. **Done**

1 **Spatial and temporal oxygen isotope variability in northern**  
2 **Greenland – implications for a new climate record over the**  
3 **past millennium**

4

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12



1 **Abstract**

2 We present for the first time all 12  $\delta^{18}\text{O}$  records obtained from ice cores drilled in the framework  
3 of the North Greenland Traverse (NGT) between 1993 and 1995 in northern Greenland,  
4 ~~between 74 to 80 °N, 36 to 49 °W and 2000 to 3200 m a.s.l.~~ The cores cover an area of 680 x  
5 317 km, ~~~200 000 km<sup>2</sup> or 10 % of the area of the~~ Greenland ice sheet. Depending on core length  
6 (100-175 m) and accumulation rate (90-200 kg m<sup>-2</sup> a<sup>-1</sup>) the single records reflect an isotope-  
7 temperature history over the last 500-1100 years.

8 ~~Lowest  $\delta^{18}\text{O}$  mean values occur north of summit and east of the main divide as a consequence~~  
9 ~~of Greenland's topography. The  $\delta^{18}\text{O}$  signal in northern Greenland is influenced by~~  
10 ~~temperature, accumulation and the topography of the North Greenland ice sheet between 72~~  
11 ~~and 80 °N. About 12 % of the variability can be attributed to the position of the single drill sites~~  
12 ~~in relation to the ice sheet topography.~~

13 ~~Lowest  $\delta^{18}\text{O}$  mean values occur north of summit and east of the main divide.~~ In general, ice  
14 cores drilled on the main ice divide show different results than those drilled east of the main ice  
15 divide that might be influenced by secondary regional moisture sources.

16 A stack of all ~~12~~ NGT records and the NGRIP record is presented with improved signal-to-  
17 noise ratio. ~~Compared to single records,~~ this stack represents the mean  $\delta^{18}\text{O}$  signal for northern  
18 Greenland that is interpreted as proxy for temperature. Our northern Greenland  $\delta^{18}\text{O}$  stack  
19 indicates ~~isotopically distinctly~~ enriched  $\delta^{18}\text{O}$  values ~~periods compared to their average~~ during  
20 medieval times, about 1420±20 AD and from 1870 AD onwards. The period between 1420 AD  
21 and 1850 AD ~~was isotopically~~ has depleted  $\delta^{18}\text{O}$  values compared to the average for the entire  
22 millennium and represents the Little Ice Age. ~~The  $\delta^{18}\text{O}$  values of the~~ The 20<sup>th</sup> century ~~are~~ has  
23 ~~isotopic values higher than the 1000 years mean and is comp arable~~ comparable to the medieval  
24 period but are lower than that about 1420 AD.

25  
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## 1 1 Introduction

2 During the past decades the Arctic ~~region~~ has experienced a pronounced warming exceeding  
3 that of other regions (e.g. Masson-Delmotte et al., 2015). To set this warming into an historical  
4 context, a profound understanding of natural variability of past Arctic climate ~~of the Arctic~~ is  
5 essential. To do so, studying climate records is the first step. However, meteorological  
6 measurements in the Arctic are only available for relatively short time periods; only a few time  
7 series start already in the 19<sup>th</sup> century. Hence, proxy data from climate archives such as ice  
8 cores from the polar ice caps are ~~necessary~~essential.

9 Studying the climate of the past centuries allows us to compare the instrumental data with proxy  
10 records and therefore to assess the quality of the proxies for climate reconstructions.

11 Stable water isotopes (here  $\delta^{18}\text{O}$ ) in ice cores are commonly used to derive paleo-temperatures  
12 (e.g. Fischer et al., 1998c; Johnsen et al., 2000; Steffensen et al., 2008). They are largely  
13 controlled by equilibrium and kinetic fractionation processes during evaporation at the ocean  
14 surface, along the poleward air-mass transport and condensation of precipitation, depending on  
15 temperature and moisture conditions (Dansgaard et al., 1969; Jouzel and Merlivat, 1984;  
16 Merlivat and Jouzel, 1979).

17 The isotope ratio is not only driven by local temperature, but is affected by several factors like  
18 moisture sources and their proximity to the deposition site, the topography of the ice sheet and  
19 the seasonality of precipitation (Fisher et al., 1985). In addition the isotope signal is altered by  
20 post-depositional processes like wind-induced redistribution of snow, temperature gradient  
21 metamorphism and diffusion (Johnsen et al., 2000; Pinzer et al., 2012; Steen-Larsen et al.,  
22 2014). Stacked records are used to compensate for effects due to local to regional differences  
23 and to improve the signal-to-noise ratio (Fisher et al., 1985; Masson-Delmotte et al., 2015;  
24 White et al., 1997).

25 To date, most ice core studies on the Greenland ice sheet were carried out point wise (e. g. Dye  
26 3, GRIP, GISP2, NGRIP), which poses the question: How representative is one single long ice  
27 core record to derive a comprehensive record of past climate? A study of ice cores from  
28 southern Greenland revealed that winter season stable water isotopes are largely influenced by  
29 the North Atlantic Oscillation (NAO) and are strongly related to southwest Greenland air  
30 temperatures. On the other hand, summer season stable water isotope ratios show higher  
31 correlations with North Atlantic sea surface temperature conditions (Vinther et al., 2010). In  
32 particular, northern Greenland has been little investigated so far. ~~The summit in Greenland's~~  
33 center is the highest site and separates Greenland in a northern and southern part, even though

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1 ~~†~~ Northern Greenland differs significantly from the south in terms of lower air temperatures  
 2 and lower snow accumulation rates (Fischer et al., 1998c). Thus, the results from southern  
 3 Greenland are not directly transferable to the northern part.  
 4 Northern Greenland's climate is influenced by different effects than the southern part. One  
 5 example is the NAO effect which is present in southern and western part of Greenland and is  
 6 discussed to be reduced in northern Greenland (Appenzeller et al., 1998).  
 7 The cyclones causing the precipitation over northern Greenland originate in the Baffin Bay and  
 8 bring dry and cold air masses from the central Arctic to north Greenland (Chen et al., 1997).  
 9 The dominant westerly winds are blocked by the ice divide, while the north eastern part has very  
 10 low accumulation rates below  $100 \text{ kg m}^{-1} \text{ a}^{-1}$ .  
 11 The topographic situation in northern Greenland is special for  $\delta^{18}\text{O}$  studies. In northern  
 12 Greenland going northward also means do go downward (lower altitudes).  
 13 For a correct estimate of mass balances as well as the response to the ongoing climate change,  
 14 knowledge of accumulation rates and the spatial distribution of  $\delta^{18}\text{O}$  as a temperature proxy are  
 15 important for the entire Greenland ice sheet. However, due to northern Greenland's remoteness  
 16 its recent past climate has, up to now, only been little investigated.  
 17 Even in the 1990s little was known about northern Greenland. Only few studies were performed  
 18 before Alfred-Wegener Institute (AWI) North-Greenland-Traverse (NGT) started in 1993.  
 19 There was a traverse of Koch and Wegner in 1913 (Koch and Wegner, 1930), of Benson in  
 20 1952-53 (Benson, 1962), and the British North Greenland Expedition in 1958 (Bull, 1958)  
 21 which studied the accumulation rate in northern Greenland. But there had been no stable water  
 22 isotope studies in the central part of northern Greenland before. Fischer et al. (1998c) and  
 23 (Schwager, 2000) present the first results from  $\delta^{18}\text{O}$  values of some of the NGT records.  
 24  
 25 Using the updated accumulation rates ~~-of the updated of the~~ (compared to Friedmann et al.,  
 26 1995; Schwager, 2000) ~~NGT-Alfred-Wegener Institute (AWI) North-Greenland-Traverse~~  
 27 ~~(NGT) data~~, it was possible to show that the area of lower accumulation rates is much larger  
 28 than expected before, which has a huge influence on the outlet glaciers (Weißbach et al., 2015).  
 29 The NGT ice cores offer for the first time the possibility to study the spatial and temporal  
 30 variability of stable oxygen isotope records from northern Greenland. Furthermore, they allow  
 31 the analysis of the common spatial stable water isotope signal in northern Greenland by stacking  
 32 the individual records to significantly reduce the isotopic noise that is present in a single ~~data~~  
 33 record due to local peculiarities.

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1 The main objectives of this study are 1) to investigate the spatial variability of  $\delta^{18}\text{O}$  in northern  
2 Greenland using this new set of  $\delta^{18}\text{O}$  data and to evaluate the influence of isotopic noise on a  
3 single record, 2) to assess whether stable water isotope records from sites with low  
4 accumulation rates can be interpreted as climate signals, 3) to present a new robust stacked  $\delta^{18}\text{O}$   
5 record for northern Greenland covering the past millennium, and 4) to interpret this record in  
6 terms of paleoclimate with respect to temporal variability and relation to large-scale climate  
7 information from other proxy records.

## 9 2. Material and Methods

### 10 4.1 (Appenzeller et al., 1998; Benson, 1962; Bull, 1958; Chen et al., 1997; Johnsen et 11 al., 1989; Koch and Wegener, 1930; Taylor et al., 1993; Weidick, 2001) Material 12 and Methods

13 The ice cores presented here were drilled during the NGT from 1993 to 1995. In total, 13 ice  
14 cores (B16-B23, B26-B30) from 12 different sites (Table 1, Fig. 1) were drilled along the  
15 traverse route. The ice cores cover the last 500-1000 years. The drillings were accompanied by  
16 extensive surface snow studies (e.g. Schwager 1999,2000).

17 B21 and B23 as well as B26 to B30 are located on ice divides (Fig. 1) while B16-B20 were  
18 drilled east of the main ice divide. The NGRIP core (North Greenland Ice Core Project  
19 Members 2004) was drilled 14.5 km northwest of B30 following the main ice divide and is  
20 therefore included in this study.

21 Before analyzing the stable water isotopes, a density profile of each core was measured. To do  
22 so, the single core segments (approximately 1 m long) were weighed in the field. Additional  
23 higher-depth resolution density records were determined using gamma-absorption  
24 measurements in the AWI cold lab (Wilhelms, 1996). Finally, in 2012 density of the first 70 m  
25 of the three cores B19, B22 and B30 was analysed by X-ray computer tomography (X-CT,  
26 Freitag et al., 2013).

27 An exponential function fitted to the data taking into account all three types of density data with  
28 same respect was used to calculate water equivalent (w. eq.) accumulation rates and to  
29 synchronize the cores.

30 Selected parts of B30 were also analyzed for electrolytic conductivity using high resolution  
31 continuous flow analysis (Kaufmann et al., 2008).

32 For the isotopic measurements the ice was cut in samples of 1-5 cm depth resolution,  
33 corresponding to 2-10 samples per year. Most of the ice was sampled with 2-2.5 cm depth

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1 resolution. Only at the uppermost parts of the core samples were cut with lower depth resolution  
2 (up to 5 cm). For some meters of special interest a resolution of 1 cm was used. After melting  
3  $\delta^{18}\text{O}$  was determined using mass spectrometers type Delta E und S from Finnigan MAT in the  
4 AWI laboratory with uncertainties less than 0.1 ‰ as determined from long-term  
5 measurements. The cores B27 and B28 were drilled at the same site. Parts of the core B27  
6 (8.25-11.38 m water equivalent (w. eq.)), corresponding to AD 1926-1945) got lost, and were  
7 replaced by the record from B28. For the other parts, the mean of both dated cores was  
8 calculated to generate one isotope record for this site.

9 Six of the NGT cores (B16, B18, B20, B21, B26 and B29) were already dated up to a certain  
10 depth by annual layer counting (using density, major ions or  $\delta^{18}\text{O}$ ) in prior studies (e.g. Fischer  
11 and Mieding, 2005; Fischer et al., 1998a; Fischer et al., 1998b; Schwager, 2000). Depending  
12 on the availability of data and differences in snow accumulation rates the dating quality of these  
13 cores varies between 1 and 5 years accuracy. For the other NGT cores annual layer counting  
14 was not possible due to the very low accumulation rates ( $<100 \text{ [kg m}^{-2} \text{ a}^{-1}\text{]}$ ). To achieve the  
15 same dating quality for all NGT cores for better comparison and to apply the dating on the  
16 whole core length, we used a new dating procedure for all cores. From density corrected (w.  
17 eq.) high resolution electrical conductivity profiles (Werner, 1995; Wilhelms, 1996) and  $\text{SO}_4^{2-}$   
18 -concentration profiles for B16, B18, B21 (Fischer et al., 1998a, b), B20 (Bigler et al., 2002)  
19 and electrolytic conductivity profile (B30), distinct volcanic horizons were identified and used  
20 as match points to synchronize the cores (Table 2). Some of the volcanic eruptions show a more  
21 pronounced signal in the Greenlandic ice than others. Thus not all eruptions could be identified  
22 in every record.

23 Between match points, the annual dating was assigned assuming a constant snow accumulation  
24 rate. If a volcanic match point could not be clearly identified in an ice core, the next time marker  
25 was used to calculate the mean accumulation rate. Below the deepest volcanic match point, the  
26 last calculated accumulation rate was extrapolated until the end of the core. As the cores were  
27 drilled only in the upper part of the ice sheet (up to 100-175 m depths) layer thinning was not  
28 taken into account.

## 29 **2.3 Results and discussion**

### 30 **2.3.1 Depth-age models and snow accumulation rates**

31 The last millennium was a volcanically active time (Sigl et al., 2013). The volcanic aerosols  
32 deposited on the Greenland ice sheet can be used as time markers. The depths of peaks in

1 conductivity and sulfate concentration attributed to certain volcanic horizons are given in Table  
2 2 as used for our dating approach.

3 During the last 500 years, the time period between two detectable eruptions at NGT sites does  
4 not exceed 100 years for all the cores. This leads to a dating uncertainty for each core smaller  
5 than 10 years compared to the annually counted timescales (Mieding, 2005; Schwager, 2000),  
6 minimal at the matching points. The three youngest volcanic reference horizons (Katmai,  
7 Tambora and Laki), the eruption from 1257 AD (Samalas, Lavigne et al., 2013), and 934 AD  
8 (Eldgia) were found in all cores, whereas the other eruptions could not be clearly identified in  
9 every ice core. We could not find a common pattern (e.g. distance, strength of the eruption)  
10 whether or not volcanic horizons could be observed in all records.

11 This already indicates a high spatial variability within the study region related to significant  
12 influences of local to regional peculiarities (e.g. wind drift or sastrugi formation). An overview  
13 of the resulting mean accumulation rates for the entire core lengths for all NGT drilling sites as  
14 well as the respective ranges are given in Table 3. According to our dating, the cores reaching  
15 furthest back in time are B18, B19 and B20, covering more than the last 1000 years. These  
16 northeasterly cores have the lowest accumulation rates with values below  $100 \text{ kg m}^{-2} \text{ a}^{-1}$  (B19:  
17  $94 \text{ kg m}^{-2} \text{ a}^{-1}$ , B20:  $98 \text{ kg m}^{-2} \text{ a}^{-1}$ ), whereas the highest mean accumulation rate is found for  
18 B27/28 in the southwest of our study region with  $180 \text{ kg m}^{-2} \text{ a}^{-1}$ . Generally, the accumulation  
19 rate decreases from the sites located on the main ice divide in the south west of the study area  
20 to the north east.

21 The observed range of accumulation at one single site is highest for the southwestern cores  
22 (B30 and B29) ranging between  $137$  and  $161 \text{ kg m}^{-2} \text{ a}^{-1}$  (B29). Lowest values are found for the  
23 cores east of the main ice divide (e.g. B17, B18 and B19) ranging between  $113$  and  $119 \text{ kg m}^{-2}$   
24  $\text{a}^{-1}$  (B17).

25 The length of the records varies depending on accumulation rate and total length of the core.  
26 The longest records are from B19 (back to 753 AD) and B20 (back to 775 AD). The following  
27 comparisons of the individual records refer to the longest common time window (1505-1953  
28 AD). Although diffusion is known to change isotopic values in the snow, in this study the data  
29 were not corrected for diffusion effects because the very low accumulation rates would hamper  
30 this calculation. While diffusion length is in the range of annual layer thickness, diffusion might  
31 be affect the absolute difference in isotope content of neighboring years but the mean over 11  
32 or 30 years will not be affected.

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## 1 **2.23.2 Regional variability of $\delta^{18}\text{O}$ in northern Greenland**

2 Annual mean  $\delta^{18}\text{O}$  records of the NGT cores are displayed in Fig. 2. Table 4 summarizes the  
3 main  $\delta^{18}\text{O}$  characteristics of each core.

4 The lowest mean  $\delta^{18}\text{O}$  values ( $\sim -37\text{‰}$ ) ~~of about  $-37\text{‰}$~~  in northern Greenland (B16-B18) and  
5 maybe the lowest in Greenland are found east of the main ice divide and north of the summit,  
6 but not at the summit as might be expected. This is in contrast to the findings of Ohmura (1987),  
7 who suggested for this region temperatures similar to summit.

8 Generally, the cores located east of the main ice divide show lower mean  $\delta^{18}\text{O}$  values than those  
9 located on the ice divide (Fig. 3a). For instance, ~~B30~~B29, and ~~B29~~B30 are on similar altitude  
10 and latitudes as B16 and B17 but show significantly heavier values (Fig. 3a).

11 Fig. 4 indicates that accumulation, latitude and altitude may have minor impact on the  $\delta^{18}\text{O}$   
12 values here. One possible explanation would be additional moisture isotopically depleted  
13 during the transport from rather northern directions.

14 The cores more to the north (B19-B22) were drilled at lower altitude and therefore record  
15 different climate signals (i.e. from lower air masses) compared to the high altitude ice cores  
16 that, in turn, record a more smoothed signal of higher atmospheric layers. Similar effects were  
17 observed e.g. in Svalbard (Isaksson et al., 2005), even though in considerably lower altitudes  
18 compared to Greenland.

19 The maximum difference in mean  $\delta^{18}\text{O}$  values of individual ice cores is 3.3 ‰ (highest mean  
20  $\delta^{18}\text{O}$  in B26:  $-33.86\text{‰}$ , lowest mean  $\delta^{18}\text{O}$  in B17:  $-37.13\text{‰}$ ). The standard deviation (SD) for  
21 the annual mean values within each core in the common time window (1505 - 1953 AD) is  
22 lowest for B16 (0.99 ‰) and highest for B18 (1.44 ‰). We found no general relation between  
23 accumulation rate and standard deviation of the  $\delta^{18}\text{O}$  values for all individual cores, even  
24 though the northern cores with generally lower accumulation rates show higher standard  
25 deviations than the southern cores.

26 The correlation coefficients between the annual  $\delta^{18}\text{O}$ -records of individual ice cores are  
27 relatively small ( $r = 0.1$  to  $0.36$ ,  $p < 0.05$ ). This can be partly explained by the fact that the 13  
28 northern Greenland (NG) drilling sites (12 NGT and NGRIP) are up to 680 km apart from each  
29 other. In other studies where correlated cores are drilled closer together, at one drill site, they  
30 found higher correlation coefficients (e.g. at GRIP(White et al., 1997)  $r = 0.41-0.55$  (White et  
31 al., 1997) or at NEEM  $r \sim 0.54$  (Masson-Delmotte et al., 2015)). The strongest correlations are  
32 found for the cores from the southwest (~~B30~~B26~~B30) and the lowest for those from the  
33 northeast (B19, B20). There is a significant linear relationship between the distance between~~

1 the core sites and their annual  $\delta^{18}\text{O}$  correlation coefficient ( $r = -0.44$ ,  $p < 0.05$ ). However, it is  
2 not always true that the cores with smallest distance between them have the highest correlations.

3 For smoothed values (~~5-11~~ year running mean) the correlation coefficients between the  $\delta^{18}\text{O}$   
4 records are only slightly higher. Only ~~25-50~~ % of the combinations have coefficients higher  
5 than 0.3, and ~~15-14~~ % are lower than 0.1. This indicates an important influence of regional site  
6 to site differences.

7 Variability in  $\delta^{18}\text{O}$  is dependent on local (e.g. wind), regional (e.g. position on the ice sheet)  
8 and large-scale (e.g. circulation patterns) processes. Even adjacent cores may differ  
9 considerably according to snow drift (Fisher et al., 1985). One further reason for the rather  
10 ~~lower~~ correlations may be attributed to dating uncertainties. ~~As smoothing the data does not~~  
11 ~~increase the correlation coefficient significantly (still 50 %  $r < 0.5$  for 11 year running mean~~  
12 ~~values), we conclude that different regional influences on the  $\delta^{18}\text{O}$  values play a more important~~  
13 ~~role. All cores with the higher correlations (B23, B26, B27/28, B29 and B30) are located in the~~  
14 ~~same area in the western part of northern Greenland whereas all other cores are located more~~  
15 ~~to the east.~~

16 ~~In~~ From Fig. 2, we compare our individual NGT  $\delta^{18}\text{O}$  records to other published Central to  
17 North Greenland (GRIP, GISP2, NGRIP)  $\delta^{18}\text{O}$  time series. Prominent decadal-scale maxima  
18 and minima occurred mostly isochronally. However, specific events such as warm periods  
19 around 1420 AD or 1920-30 AD or a cold period in the 17<sup>th</sup> century are more pronounced in  
20 the NGT cores compared to summit records.

21 ~~In Fig.2 is also obvious that S~~ some records show faster changes between warmer and colder  
22 events (e.g. GRIP, B30 and B26), while others (e.g. B17-B21) remain longer at values higher  
23 or lower than their mean (Fig. 2). The longest warm period (compared to the mean of whole  
24 core length) is found in B19 (with 37 subsequent years warmer than the mean), while B17 has  
25 the longest cold period (28 subsequent years colder than mean). GRIP, B26, and B27/28 show  
26 a higher frequency with a maximum of about ten subsequent warmer or colder years. A  
27 frequency analysis on 11-year running mean smoothed data supports these findings. B18-B21  
28 and B29 show much longer main periods (117-248 a) than B16-B17 and B22-B30 (besides  
29 B29, 81-39 a).

30 In general, the first half of the last millennium was characterized by longer warm or cold  
31 anomalies than the second half and -

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1 ~~The east to west difference is also detectable in the temporal variability of the annual  $\delta^{18}\text{O}$~~   
2 ~~values. Records~~ with more rapid fluctuations are from summit and the main ice divide,  
3 while those cores drilled east of the divide have longer periods of positive or negative  
4 anomalies. We conclude that east of the divide, the climate conditions are not as ~~variable~~  
5 ~~and variable and~~ therefore the annual  $\delta^{18}\text{O}$  signal is of greater persistence.

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6 ~~The PC1 has negative loadings on all the time series and therefore represents a homogenous~~  
7 ~~regional scale pattern even though the loadings for the cores on the ice divide are higher. In~~  
8 ~~contrast, PC2, as the second strongest influence, shows a pronounced east-west difference (Fig.~~  
9 ~~5). A similar pattern with distinct differences between the main ice divide region and the eastern~~  
10 ~~region can also also be found in several other aspects.~~

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12 ~~We found lighter  $\delta^{18}\text{O}$  values in the southern and eastern part of northern Greenland in contrast~~  
13 ~~to the general speculations of Dansgaard (1954), who expected lighter values northward. The~~  
14 ~~east-to-west difference is also expressed by the dependency of  $\delta^{18}\text{O}$ -values on longitude (Fig.~~  
15 ~~4). This is in line with results from Box (2002), who found that there is often an opposite trend~~  
16 ~~in air temperatures in east and west Greenland. The antiphase of temperature records from east~~  
17 ~~and west Greenland is may be explained by the importance of different weather regimes (e.g.~~  
18 ~~Ortega et al., 2014).~~

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19 The range in  $\delta^{18}\text{O}$  in the different cores is different, too. Cores drilled in the northeast that are  
20 characterized by the lowest accumulation rates have the highest standard deviations (SD) in  
21  $\delta^{18}\text{O}$ , which can be partly explained by the fact that a smaller number of accumulation events  
22 scatters easier.

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23 ~~Taking all these aspects together, we argue that the main ice divide has a large influence on the~~  
24 ~~spatial  $\delta^{18}\text{O}$  pattern representing temperatures.~~

25 ~~We investigated the relationship between the altitude, latitude and longitude of the drilling sites~~  
26 ~~and the mean  $\delta^{18}\text{O}$  values (Fig. 4a, b, c), which are when considering all records, statistically~~  
27 ~~significant ( $p < 0.05$ ) only for longitude and latitude. Regarding their snow accumulation rate~~  
28 ~~we differentiate two groups: I) cores with accumulation rates lower than  $145 \text{ kg m}^{-2} \text{ a}^{-1}$  mainly~~  
29 ~~located east of the main ice divide (B16-B21 and B23) and II) cores with higher accumulation~~  
30 ~~rates (B22, B26-B30 and NGRIP). We find heavier  $\delta^{18}\text{O}$  ratios for sites with higher~~  
31 ~~accumulation rates (Fig. 4d). The relationship is weak but becomes stronger for higher~~  
32 ~~accumulation rates. Buchardt et al. (2012) noted that the relationship between accumulation~~  
33 ~~rate and  $\delta^{18}\text{O}$  is not distinct for Greenland. Furthermore Buchardt et al. (2012) found that the~~

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1 sensitivity of  $\delta^{18}\text{O}$  changes to accumulation rate is smallest in northeast Greenland (North  
2 Central and North 1972), which is in agreement with our findings.

3 ▲  
4 Among the factors influencing the mean isotopic composition, the longitude has the strongest  
5 impact ( $R^2 = 0.56$ ) which become clearest looking only at the data of group I ( $R^2 = 0.93$ ). Figure  
6 4 c) shows the clear east-to-west gradient in the mean  $\delta^{18}\text{O}$  values in northern Greenland.

7 In contrast, the effect of the altitude is rather low ( $R^2 = 0.13$ ) and not statistically significant. If  
8 separating between group I (“East”) and group II (“Divide”), there is a strong altitude effect ( $R^2$   
9 = 0.93 and 0.78) in the data, too.

10 These patterns may be explained by different atmospheric circulation conditions allowing  
11 additional moisture from other sources to reach the region east of the ice divide. This is  
12 supported by the finding of Friedmann et al. (1995) who suppose based on data from B16 to  
13 B19 that northeast Greenland receives more moisture from local sources as the Greenlandic  
14 Sea, Atlantic Ocean and the Canadian Wetland, in particular during summer.

15 ▲  
16 Buchardt et al. (2012), noted that the relationship between accumulation rate and  $\delta^{18}\text{O}$  is not  
17 distinct for Greenland. They see the “foehn effect” (dry warm wind in the lee of the ice divide)  
18 as one reason. The foehn effect causes an anticorrelation between  $\delta^{18}\text{O}$  and accumulation rate,  
19 which is not seen in central Greenland but on the lee side east of the ice divide in southern  
20 Greenland, as also visible for our data in Fig 4d. Furthermore, Buchardt et al. (2012), find that  
21 the sensitivity of  $\delta^{18}\text{O}$  changes in accumulation rate is smallest in northeast Greenland (North  
22 Central and North 1972), which is in agreement with our findings.

23 From the regression functions, we find that in northern Greenland  $\delta^{18}\text{O}$  values decrease from  
24 north to south and west to east as well as from higher to lower altitudes (Fig. 4). We found  
25 lighter  $\delta^{18}\text{O}$  values in the southern and eastern part of northern Greenland in contrast to the  
26 general speculations ideas of Dansgaard (1954), who expected lighter values northward. That  
27 we do not find the lightest values north is a consequence of different factors in northern  
28 Greenland that out balance each other. More to the north, where we would expect lighter  $\delta^{18}\text{O}$   
29 values, the altitude in northern Greenland is decreasing which causes heavier  $\delta^{18}\text{O}$  values (Fig.  
30 1). As Johnsen et al. (1989) did, multiple linear regression becomes necessary.

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1 ~~Johnson et al. (1989) found a regression slope of  $\delta^{18}\text{O}$  with respect to latitude  $\delta(\delta^{18}\text{O})/\delta(\text{latitude})$~~   
2  ~~$= -0.54 \text{‰/degree}$  and with respect to altitude  $\delta(\delta^{18}\text{O})/\delta(\text{altitude}) = -0.006 \text{‰/m}$  for large areas~~  
3 ~~of Greenland.~~

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4 ~~The multiple linear regressions show enormous uncertainties of the elevation and latitude~~  
5 ~~relationship. Using the parameters given by Johnson et al. (1989), it is not possible to calculate~~  
6 ~~certain  $\delta^{18}\text{O}$  relationships to altitude and geographic position from northern Greenland's ice~~  
7 ~~cores. However, using different tuning factors for the Johnson model, it was possible to~~  
8 ~~accomplish almost equal  $R^2$  ( $\approx 0.8$ ) for northern Greenland's  $\delta^{18}\text{O}$  values compared to the~~  
9 ~~Johnson et al. (1989) results. Applying this approach to our data, we find  $\delta(\delta^{18}\text{O})/(\delta(\text{latitude})) =$~~   
10  ~~$-0.30 (+/-0.40) \text{‰/degree}$  and  $\delta(\delta^{18}\text{O})/\delta(\text{altitude}) = -0.0035 (+/- 0.0024) \text{‰/m}$ . The regression~~  
11 ~~residuals are linearly related to longitude as well as accumulation rate (Fig. 7).~~

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12 ~~Generally, we found correlations to altitude, latitude and longitude but the out balancing effects~~  
13 ~~because of the special topography in northern Greenland have to be taken into account.~~

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17 ~~Regarding snow accumulation rate we differentiate two groups: I) cores with accumulation~~  
18 ~~rates lower than  $145 \text{ kg m}^{-2} \text{ a}^{-1}$  mainly located east of the main ice divide (B16 B21 and B23)~~  
19 ~~and II) cores with higher accumulation rates (B22, B26 B30 and NGRIP). We find heavier  $\delta^{18}\text{O}$~~   
20 ~~ratios for sites with higher accumulation rates (Fig. 4d). The relationship is weak but becomes~~  
21 ~~stronger for higher accumulation rates.~~

22 To study the regional-scale patterns of common variability of all annual  $\delta^{18}\text{O}$  records, we  
23 performed a principal component analysis (PCA). All calculations are done for the largest  
24 common time window of all cores (1505-1953 AD). Other time periods were used as well, and  
25 they show similar results.

26 Only the first two principal components (PC1 and PC2) are above the noise level. The first two  
27 eigenvectors of the isotopic time series explain 34.1 % of the total variance (PC1: 21.8 %, PC2:  
28 12.3 %). ~~The PC1 is similar to the mean of all records ( $r = 0.97$ ,  $p < 0.01$ ). It was not possible~~  
29 ~~to assign PC2 to any climatic relevant signal.~~ The other PCs are dominant in one or two records  
30 but are not significant for the total variance of the entire dataset. The loading patterns are  
31 mapped in Fig. 5 and show a homogeneous pattern for PC1 EOF1 and a bipolar (west-east) result  
32 for PC2 EOF2.

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1 ~~To summarize, The main ice divide separates the Greenland ice sheet into eastern and western~~  
2 ~~regions (Fig. 1). Cyclonic activity is most important for the precipitation over Greenland.~~  
3 ~~Cyclones forming over Hudson Bay or Baffin Bay and winds from the west or southwest~~  
4 ~~transport air masses to Greenland (Chen et al., 1997). The cyclonic influence decreases from~~  
5 ~~south to north and from west to east because of the blocking influence of the summit and the~~  
6 ~~main ice divide. Furthermore, we observe a stronger isotope-altitude relationship for the cores~~  
7 ~~on the ice divide ( $r = 0.96$ ). This may be explained by different atmospheric circulation~~  
8 ~~conditions allowing additional moisture from other sources to reach the region east of the ice~~  
9 ~~divide. This is supported by the finding of Friedmann et al. (1995) which suppose based on data~~  
10 ~~from B16 to B19 that northeast Greenland receives more moisture from local sources as the~~  
11 ~~Greenlandic Sea, Atlantic Ocean and the Canadian Wetland, in particular during summer.~~

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13  
14 ~~This justifies that for northern Greenland ice cores, the spatial differences in mean  $\delta^{18}\text{O}$  values~~  
15 ~~in northern Greenland can be largely explained by the influence of the topography of the ice~~  
16 ~~sheet on the regional climate system. The main ice divide influences the pathways of air masses~~  
17 ~~causing lower accumulation rates in the east.~~  
18 ~~geographic gradients in topography (i.e. altitude, latitude and longitude) and accumulation rate.~~  
19 ~~Thus, we assume that the temporal variability in a the NG stacked NG  $\delta^{18}\text{O}$  record represents~~  
20 ~~past temperature development.~~

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21 ~~We assume air temperature to be the main influence (PC1) on the  $\delta^{18}\text{O}$~~   
22 ~~values. There is a strong correlation of the PC1 (northern Greenland  $\delta^{18}\text{O}$~~   
23 ~~values) to the NG stack ( $r = -0.97, p \ll 0.01$ ). This leads to the conclusion~~  
24 ~~that 22% of the signal in the northern Greenland  $\delta^{18}\text{O}$  records can be~~  
25 ~~interpreted as a regional climate signal. This is supported by the fact that~~  
26 ~~Vinther et al. (2010) found for their PC1 from winter  $\delta^{18}\text{O}$  values from~~  
27 ~~southern Greenland's ice cores a strong correlation ( $r = 0.71$ ) to air~~  
28 ~~temperature data.~~

29 ~~The main divide influences the pathways of air masses, causing the "foehn~~  
30 ~~effect" and thus lower accumulation rates in the east. Thus we conclude~~  
31 ~~that the largest part of the spatial differences in  $\delta^{18}\text{O}$  values in northern~~

- 1
- 2
- 3

~~Greenland is caused by the influence the topography of the ice sheet on the regional climate system.~~

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### 2.3.3.3 The northern Greenland $\delta^{18}\text{O}$ -stack and its paleoclimatic significance

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Stable water isotope ratios in ice are widely used as a proxy for air temperature (Dansgaard, 1964; Johnsen et al., 1995; Jouzel et al., 1997b). ~~In this section, we will discuss the representativity of a single ice core  $\delta^{18}\text{O}$  record in northern Greenland and the influence of different aspects as changes in altitude, latitude, longitude or accumulation rate on the stable water isotope ratio.~~ The comparison to direct air-temperature observation data and proxy data allows to assess the quality of the proxy in terms of paleo-climatological interpretation.

To reduce the noise in the single  $\delta^{18}\text{O}$  records, we calculated a stacked record by averaging the 13 annual NG  $\delta^{18}\text{O}$  records in their overlapping time periods (NG-stack, Fig. 65). Before stacking, all records were centred and normalized regarding their common time window (1505-1953 AD). The SD of the NG-stack (0.44 for 1505-1953 AD) is less than half of the SD in annual  $\delta^{18}\text{O}$  records of the individual cores. Also Vinther et al. (2010) make clear that stacking is important to improve the signal-to-noise ratio in low accumulation rate areas. Local drift noise would account for half of the total variance in single-site annual series (Fisher et al., 1985).

As the NG-stack before 1000 AD is based on only four records (< 25% of the total core numbers), we decided to focus in the following only on the time period after 1000 AD.

As the NG-stack is a result of 13 ice cores over a large area we assume its regional representativity.

To investigate the relationship of the NG-stack with air temperature, we used monthly meteorological observations from coastal southwest Greenland sites and Stykkisholmur in Northwest Iceland available from the Danish Meteorological Institute (DMI-<http://www.dmi.dk>; 1784-1993 AD) and the Icelandic meteorological office (<http://en.vedur.is/>; back to 1830 AD), respectively. We selected only the Greenlandic temperature records longer than 200 years for our study even though they are in large distance (706-2206 km).

The correlation coefficients between the NG-stack and these air temperature records are shown in Table 5. Dating uncertainties are taken into account by comparing 5 year running means. The

1 NG-stack shows low but significant ( $p < 0.001$ ) correlations to the air temperatures at all sites  
2 (Tab. 5).

3 The strongest correlation with annual mean temperature was found for the merged station data  
4 at Greenland's southeast coast ( $r = 0.51$ ), and the temperature reconstruction for the North  
5 Atlantic Arctic boundary region of Wood et al. 2010 ( $r = 0.55$ ); the lowest was found for  
6 Qaqortoq ( $r = 0.39$ ) also in the south of Greenland (Tab. 5). For Stykkisholmur the correlation  
7 is in the range of the Greenlandic ones ( $r = 0.41$ ). Slightly higher correlations are obtained by  
8 comparing the NG-stack to seasonal data. Except for Ilulissat, winter months (DJF) show  
9 weaker correlations; spring (MAM) and summer (JJA) months show stronger correlations to  
10 the NG-stack.

11 Comparably low correlations between annual  $\delta^{18}\text{O}$  means and measured temperatures from  
12 coastal stations are also reported for the NEEM record (Steen-Larsen et al., 2011).

13 However, the rather low correlation coefficients might underestimate the real regional  $\delta^{18}\text{O}$ -  
14 temperature relations because of different reasons.

15 We expect that the most important reasons are the large distances and the difference in altitude  
16 (i.e. more than 2,000 m) between drill sites and the meteorological stations, which let them  
17 receive different atmospheric signals. The stations are located at the coast and are in turn also  
18 likely influenced by local factors as the occurrence of sea ice.

19 One other aspect might be the seasonality as argued by Steen-Larsen et al. (2011) for the NEEM  
20 site. The snow fall in northern Greenland maybe seasonally unevenly distributed. However, it  
21 is not possible to generate sub-annual data for northern Greenland ice cores due to low  
22 accumulation rates. We find a tendency to stronger correlation between the annual  $\delta^{18}\text{O}$  and  
23 summer (JJA,  $r = 0.35-0.51$ ) and spring (MAM,  $r = 0.36-0.62$ ) temperatures for most of the  
24 stations. This points to a higher proportion of summer snow in the annual accumulation in  
25 northern Greenland, too. SON has slightly weaker correlation coefficients ( $r = 0.31-0.5$ ) while  
26 DJF is only significant for Ilulissat and the merged southern station.

27 Also regional noise factors such as wind drift and sastrugi formation as well as uncertainties in  
28 ice core dating and the usage of very old observation data have to be taken into account.

29 In summary, we consider the northern Greenland  $\delta^{18}\text{O}$  stacked record as a reliable proxy for  
30 annual temperature for northern Greenland. The regional representativeness of the NG-stack is  
31 supported by the general similarity to the NEEM  $\delta^{18}\text{O}$  record (Masson-Delmotte et al., 2015)  
32 for the period 1724-1994 AD. We found a strong correlation between both records ( $r = 0.83$  for

1 30-year running mean). Even single events such as the highest values in 1928 AD and the 1810-  
2 1830 AD cooling occur in both records.

3  
4 Although the NG-stack record shows some correlation with temperature data from coastal  
5 Greenland sites, it remains an open question, how the NG-stack  $\delta^{18}\text{O}$  variations can be  
6 converted to absolute temperature changes within North-East Greenland during the last  
7 millennium.

8 For more than 30 years such conversion of isotopic time series of Greenland ice cores was  
9 based on a modern analogue approach taking the observed spatial isotope/temperature gradient  
10 of  $0.67 \pm 0.2 \text{ ‰ } ^\circ\text{C}^{-1}$  (Dansgaard, 1964; Johnsen et al., 1989) as a valid calibration for  
11 converting isotope records of Greenland ice cores into temperature changes (e.g. Grootes et al.,  
12 1993). The strong confidence of glaciologists into this approach came principally from two  
13 observations. 1) Over both polar ice sheets, the spatial correlation between modern isotope and  
14 annual mean temperature is very high and significant. 2) This empirical observation was  
15 theoretically understood as a consequence of a Rayleigh rainout system controlling the isotopic  
16 composition of meteoric water.

17 However, for the Greenland area this long time accepted approach has been challenged during  
18 the last decade. Two entirely independent analytic techniques, one based on the numerical  
19 interpretation of borehole temperatures (e.g. Dahl-Jensen et al., 1998) and the other based on  
20 the occlusion process of gases into the ice (e.g. Buizert et al., 2014; Severinghaus et al., 1998)  
21 allow a direct temperature reconstruction at least for some periods of the past. Consistently both  
22 methods point to much lower temporal  $\delta^{18}\text{O}$   $\text{T}^{-1}$  slopes ranging between  $0.4\text{-}0.3 \text{ ‰ } ^\circ\text{C}^{-1}$  (Jouzel  
23 et al., 1997a). Consequently they indicate a much higher temperature variability in Greenland  
24 during the last glacial period. For the period of the last 9000 years the Greenland average  
25 Holocene isotope-temperature relationship has been estimated to be  $0.44\text{-}0.53 \text{ ‰ } ^\circ\text{C}^{-1}$  again  
26 substantially lower as the modern spatial gradient (Vinther et al., 2009). However, as all these  
27 studies cover much longer time periods as compared to our NG-stack records, no firm  
28 conclusion can be drawn from these studies about an appropriate isotope-temperature  
29 relationship for the last millennium.

30 Along the NGT firn temperature measurements in about 15 m depth had been done (Tab. 4).  
31 But due to their small range of about 2 K difference it is difficult to reassess the general  
32 Greenland isotope temperature relationship from Johnsen et al. (1989) from the NGT data,  
33 solely. Schwager (2000) added data from Dansgaard et al. (1969) from along the EGIG traverse,  
34 which was also used in Johnsen et al. (1989), to expand the temperatures range to derive a more

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1 reliable isotope-temperature gradient. This calculated gradient of  $0.7 \pm 0.2 \text{ ‰ } ^\circ\text{C}^{-1}$  is within  
2 the gradient uncertainty range given by Johnsen et al. (1989). Using our updated NGT dataset  
3 we get the same results.

4 If we apply the spatial isotope/temperature gradient of  $0.7 \text{ ‰ } ^\circ\text{C}^{-1}$  from Schwager (2000) for  
5 the range of isotope variations ( $-1.43 \text{ ‰}$  to  $-2.54 \text{ ‰}$ ) of the NG-stack record, the isotope data  
6 would translate into temperature changes of  $-2.04 \text{ }^\circ\text{C}$  to  $3.59\text{--}6 \text{ }^\circ\text{C}$  ( $5.6 \text{ K}$ ) within the last  
7 millennium. However, applying instead a temporal gradient of  $0.48 \text{ ‰ } ^\circ\text{C}^{-1}$  as suggested by  
8 Vinther et al. (2009) results in possible temperature changes of  $-2.98 \text{ }^\circ\text{C}$  to  $5.23 \text{ }^\circ\text{C}$  ( $8.1 \text{ K}$ )  
9 within the last 1000 years. Using the most recent temporal glacial-interglacial isotope-  
10 temperature gradients reported by Buizert et al. (2014) would result in comparable temperature  
11 changes. If using the NEEM gradient of  $1.1 \pm 0.2 \text{ ‰ } ^\circ\text{C}^{-1}$  (Masson-Delmotte et al., 2015),  
12 which is valid for 2007-1979 AD in the area of NEEM, the resulting temperature range of the  
13 NG-stack is with  $-1.3$  to  $2.3 \text{ }^\circ\text{C}$  ( $3.6 \text{ K}$ ) a bit smaller than compared to the Johnsen or Schwager  
14 gradient.

15 Nevertheless, the resulting temperature ranges are larger than expected (e.g. Dahl-Jensen et  
16 al., 1998)-which is an additional argument not to calculate absolute temperatures from the NG-  
17 stack with the given gradients.

18 We conclude that any conversion of the NG-stack isotope record into absolute temperature  
19 variations during the last millennium is highly uncertain. Thus, for the following part of the  
20 manuscript, we will refer to NG-stack isotope anomalies as relative temperature changes in  
21 terms of “warmer” (i.e. isotopically enriched) and “colder” (isotopically depleted), only, but  
22 refrain from converting our ice core data into absolute temperature changes.

23 **→ discussion**

24 ~~As the NG stack is a result of 13 ice cores over a large area we assume its regional~~  
25 ~~representativity. From the PCA we know that the first two PC's are significantly correlated to~~  
26 ~~the NG stack, which supports the validity of the stack.~~

27 ~~A direct comparison of the  $\delta^{18}\text{O}$  and direct air temperature measurements is hindered by the~~  
28 ~~distance between drill sites and weather stations and results in relatively low correlations (Table~~  
29 ~~5). Comparably low correlations between annual  $\delta^{18}\text{O}$  means and measured temperatures from~~  
30 ~~coastal stations are also reported for the NEEM record (Steen-Larsen et al., 2011).~~

31 ~~However, the rather low correlation coefficients might underestimate the real regional  $\delta^{18}\text{O}$ -~~  
32 ~~temperature relations because of different reasons.~~

33 ~~We expect that the most important reasons are the large distances and the difference in altitude~~  
34 ~~(i.e. more than 2,000 m) between drill sites and the meteorological stations, which let them~~

1 receive different atmospheric signals. The stations are located at the coast and are in turn also  
2 likely influenced by local factors as the occurrence of sea ice. The difference in altitude is also  
3 one important fact causing the differences in GRIP and DYE3 borehole temperature data (Dahl-  
4 Jensen et al., 1998).

5 One other aspect might be the seasonality as argued by Steen Larsen et al. (2011) for the NEEM  
6 site. The snow fall in northern Greenland may be seasonally unevenly distributed. However, it  
7 is not possible to generate sub annual data for northern Greenland ice cores due to low  
8 accumulation. We find a tendency to stronger correlation between the annual  $\delta^{18}\text{O}$  and summer  
9 (JJA,  $r = 0.35-0.51$ ) and spring (MAM,  $r = 0.36-0.62$ ) temperatures for most of the stations.  
10 This points to a higher proportion of summer snow in the annual accumulation in northern  
11 Greenland, too.

12 Also regional noise factors such as wind drift and sastrugi formation as well as uncertainties in  
13 ice core dating and the usage of very old observation data have to be taken into account.

14 In summary, we consider the northern Greenland  $\delta^{18}\text{O}$  stacked record as a reliable proxy for  
15 annual temperature for northern Greenland. The regional representativeness of the NG stack is  
16 supported by the general similarity to the NEEM  $\delta^{18}\text{O}$  record (Masson-Delmotte et al., 2015)  
17 for the period 1724-1994 AD. Even single events such as the highest values in 1928 AD and  
18 the 1810-1830 AD cooling occur in both records.

19 To assess regional differences within northern Greenland, stacks of subsets of cores will be  
20 discussed in terms of interpretation as a temperature proxy. As illustrated in Fig. 4, we  
21 differentiate two different types of cores, cores drilled on the ice divide and cores drilled east  
22 of the ice divide. Accordingly, in Fig. 6-5 the overall northern Greenland  $\delta^{18}\text{O}$  stack used in this  
23 study is compared to a stack of the cores of lower accumulation rate drilled east of the main ice  
24 divide (B16, B17, B18, B19, B20, B21 and B23) ("~~group-stack Ieast~~") and a stack of those on  
25 the ice divide (B22, B26, B27, B29, B30 and NGRIP) ("~~group-stack Hdivide~~") (Fig. 8-5).

26 Even though there is a similar overall trend, the three records show differences in amplitude  
27 and timing of warm and cool events. The correlation between the two sub-stacks is rather low  
28 ( $r = 0.71$  of 30 year running means). In the 11<sup>th</sup> and 12<sup>th</sup> centuries, we observe a quasi-anti-  
29 correlation between ~~group-stack "I-East"~~ and ~~group-stack "H-Divide"~~. Even during ~~the~~-well-  
30 known climate events such as the Medieval Climate Anomaly (MCA, 950 - 1250 AD, Mann et  
31 al., 2009), the Little Ice Age (LIA, 1400 - 1900, Mann et al., 1998) and the Early Twentieth  
32 Century Warming (ETCW 1920 - 1940 AD, Semenov and Latif, 2012)(MCA, LIA, ETCW,  
33 marked in Fig. 6 and Fig. 8), there are significantly different  $\delta^{18}\text{O}$  patterns. For example, ~~group~~

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1 ~~II (ice divide) stack~~ “Divide” shows colder temperatures during 1000-1200 AD. Also, during  
2 the 16<sup>th</sup> century we notice substantial differences between the two sub-stacks. In ~~group-stack I~~  
3 ~~“East” (east, low accumulation rate)~~ events like the 1420 AD or the first part of the LIA show a  
4 higher amplitude.

5 The stack ~~of group I (east, low accumulation rate)~~ “East” has a higher correlation to the total  
6 NG-stack ( $r = 0.96$ ) compared to ~~group-II~~ stack “Divide” ( $r = 0.6768$ ) for the period 994-1994  
7 AD. Looking at the time period 1505-1993 AD with a high number of cores included in both  
8 sub-stacks, the correlation coefficients to the total NG-stack are almost equal (~~group-stack~~  
9 ~~I “East”~~:  $r = 0.95$ , ~~group-stack II “Divide”~~:  $r = 0.90$ ,  $p < 0.1$ ). Here, both records reflect the mean  
10 changes in  $\delta^{18}\text{O}$  for northern Greenland. Differences before 1505 AD may be artefacts of low  
11 core numbers even though regional differences in climate conditions cannot be ruled out.

12

13

14 We consider the NG-stack as a climate record ~~that confirms our interpretation of PC1, and~~  
15 displays the overall climate variation independent of local influences as topography or  
16 accumulation rate. In contrast, results from studies with only one record become ~~uncertain~~  
17 ~~spatially representative~~, as they may be affected by a lower signal-to-noise ratio and a higher  
18 influence of other local non-climate effects.

19

1  
2  
3 **2.63.4 Last millennium climate from a aretic-stacked NG  $\delta^{18}\text{O}$  records in relation**  
4 **to other proxy records and possible forcing factors**

5 The NG-stack covers the time between 753 AD and 1994 AD (Fig. 65). For a better  
6 visualisation of decadal to centennial scale variability a 30-year running mean is added. The  
7 running mean shows the warmest period around 1420 AD and the coldest in about 1680 AD.  
8 The isotopically warmest single year during the last 1000 years in northern Greenland was 1928  
9 AD, whereas 1835 AD was the coldest.

10 Distinct decadal- to centennial-scale warm and cold anomalies can be detected in the stacked  
11 (Fig. 65) as well as individual  $\delta^{18}\text{O}$  records (Fig. 2) and ~~are partly related~~ coincidence to well-  
12 known climate anomalies (~~MCA, LIA, ETCW, marked in Fig. 5), such as the Medieval Climate~~  
13 ~~Anomaly (MCA, 950–1250 AD, Mann et al., 2009), the Little Ice Age (LIA, 1400–1900,~~  
14 ~~Mann et al., 1998)(LIA, 1400–1700 AD, Mann et al., 1998; Mann et al., 2009) and Early~~  
15 ~~Twentieth Century Warming (ETCW 1920–1940 AD, Semenov and Latif, 2012).~~

16  
17 We find a pronounced warm period from 850 to 1100 AD, which has its maximum between  
18 900 and 1000 AD. This is about 100 years earlier than the described MCA in Mann et al. (2009).  
19 The warm period is followed by a quasi-periodical change of warm and cold phases observed  
20 approximately every ~~50–60~~ to ~~70–80~~ years until about 1600 AD. During this phase, the most  
21 distinct warm period is observed around 1420 AD.

22 A longer period of cold temperatures occurred during the 17<sup>th</sup> and early 19<sup>th</sup> century and was  
23 already attributed to the LIA by a prior NGT study that used only 4 cores (B16, B18, B21 and  
24 B29, Fischer et al., 1998c). A cold period in northern Greenland corresponding to the LIA is  
25 later than reconstructed for the entire Northern Hemisphere by Mann et al. (1998) (~~Mann et~~  
26 ~~al., 1998; Mann et al., 2009~~), with lowest values during 1620-1780 AD and in the first half of  
27 the 19<sup>th</sup> century. Interestingly, the warmest mean values of the last 1000 years at 1420 AD lie  
28 within the timeframe of LIA.

29 A ~~clear~~distinct, but compared to other periods not outstanding, warm event ~~corresponding to~~  
30 ~~the ETCW is~~ in the early 20<sup>th</sup> century corresponds to the ETCW. Since the 1870s AD, the values  
31 are above the 1000-year mean. At the end of the 20<sup>th</sup> century, the temperature stagnates at a  
32 high mean level. However, as the NGT cores were drilled between 1993 and 1995 AD, the

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1 warmest years of the recent decades (Wood et al., 2010) are not included in our record.

2 For the NG-stack as well as most of the individual NGT cores the isotopically warmest periods  
3 besides the 1420 AD event were in the 10<sup>th</sup> and 20<sup>th</sup> centuries, in particular between 1900 and  
4 1950 AD. These years are even warmer than the most recent years covered by the NGT cores  
5 (i.e. the 1980s).

6 → discussion

7 To set the results in an Arctic-wide context we compare our northern Greenland temperature  
8 record (NG-stack) to ice-core records from the Russian Arctic (Akademii Nauk – AN, Opel et  
9 al., 2013), Canada (Agassiz Ice Cap – Agassiz, Vinther et al., 2008), Svalbard  
10 (Lomonosovfonna - Lomo, Divine et al., 2011) and south Greenland (Dye3, Vinther et al.,  
11 2006b) as well as a multi-proxy reconstruction of annual Arctic SAT (Arctic2k, PAGES 2k  
12 Consortium, 2013, Fig. 96) that cover our time period.

13 Note that some of these time series (Agassiz, Arctic2k) are also stacked records with a wider  
14 regional representativeness, whereas others are single records (Dye3, AN, Lomo), which  
15 influences the strength of correlation due to different signal-to-noise ratios. For the discussion  
16 of the temperature record, we concentrate on the smoothed values (30-year running means).

17 The strongest correlations to our NG-stack are found for the Agassiz and Arctic2k records ( $r =$   
18  $0.58$  and  $0.66$ , respectively). For the latter, we have to consider that some of the NGT cores  
19 (B16, B18 and B21 on the old time scale) are used to generate this multi-proxy record. ~~The aim~~  
20 ~~of PAGES 2k was to generate an Arctic wide representative record.~~ In total, 59 records  
21 including 16 ice cores were used. NGT cores represent only 3 out of these 59 records. The  
22 correlation coefficient between the stacked anomalies of B16, B18 and B21 and the Arctic2k  
23 temperature is small ( $r = 0.24$ ) so we can assume that the NGT records do not dominate the  
24 reconstruction.

25 We conclude that a good correlation between the NG-stack and the Arctic2k record show that  
26 the temperature in northern Greenland follows in general the Arctic-wide mean temperature.

27 The Lomonosovfonna record is interpreted as a winter record and has only a weak correlation  
28 to the NG-stack ( $r = 0.22$ ). More summer snow in northern Greenland compared to  
29 Lomonosovfonna could be one possible explanation for the weak correlation between both  
30 records. While for the other drill sites we have comparable r-values for both substacks as for  
31 the NG-stack, the Lomo has a stronger correlation to stack “East” ( $r = 0.2$ ) than to stack  
32 “Divide” ( $r = -0.12$ ) which supports the argument of different moisture sources or seasonal  
33 distribution of snow fall in north-east of Greenland.

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1 ~~On a short term scale, there are differences in the well known climatic events (MCA, LIA and~~  
2 ~~ETWC; Fig. 9), which are reflected with different intensity in the  $\delta^{18}\text{O}$  values and show spatial~~  
3 ~~patterns.~~

4 The Lomonosovfonna, Akademii Nauk and Arctic2k records show significantly more enriched  
5  $\delta^{18}\text{O}$  values during the MCA. However, smaller events of abnormal warm temperatures during  
6 the MCA ~~are~~ are observed for Agassiz and Dye3. Our NG-stack shows warmer values earlier  
7 than the MCA time period given by ~~Mann et al. (2009)~~ Mann et al. (1998). We conclude that  
8 further north in the Arctic the warm events during MCA ~~are~~ may be less pronounced or earlier  
9 in timing.

10 The Lomonosovfonna and Arctic2k records show a dominant cold period during the LIA from  
11 1580 to 1870 AD. Also, our northern Greenland as well as the Agassiz and Akademii Nauk ice  
12 cores reveal distinct LIA cooling periods in contrast to the Dye3 ice core from south Greenland.  
13 Like in our NG-stack, the cooling appears in two phases and some decades later than described  
14 by Mann et al. (2009). For the NG-stack, the younger phase (1800-1850 AD) is of minor  
15 amplitude and shorter duration.

16 Between 1920 and 1940 AD, there was a major warming period in the Arctic, known as ETCW  
17 and observed in all ~~shown~~ records shown here. Chylek et al. (2006) determined from  
18 meteorological data that the 1920–30 warming was stronger than the 1995–2005 warming. For  
19 the NG-stack and Akademii Nauk record, the ETCW was warmer than the second half of the  
20 20<sup>th</sup> century, which distinguishes them from other shown records. The ETCW is assumed to be  
21 independent of external forcing but caused by internal climate variability, in particular sea ice-  
22 atmosphere feedbacks (Wood and Overland, 2010). This let us conclude that northern  
23 Greenland may also be a good place to study forcing independent, i.e. internal, climate changes.

24 However, natural external forcing (i.e. insolation, solar irradiance and volcanic eruptions) is  
25 assumed to influence the temperature that can be studied from northern Greenland's ice cores.

26 In general, higher solar activity causes higher temperatures (as during the MCA) whereas cold  
27 periods (e.g. LIA) are dominated by lower solar activity (Ammann et al., 2007). Based on some  
28 of the NGT records (B16, B18, B21 and B29), Fischer et al. (1998c) explained most of the long-  
29 term variation in northern Greenland by changes in solar activity.

30 Volcanism causes strong negative radiative forcing (Robock, 2000). It is assumed that volcanic  
31 eruptions inject large quantities of sulfur-rich gases into the stratosphere and global climate can  
32 be cooled by 0.2-0.3 °C for several years after the eruption (Zielinski, 2000). Results from

1 Crowley (2000) indicate that volcanism generally explains roughly 15–30% of the variability  
2 in global temperatures.

3 Miller et al. (2012) argued that century-scale cold summer anomalies of which the LIA  
4 represents the coldest one, occur because natural forcing is either weak or, in the case of  
5 volcanism, short-lived. PAGES 2k Consortium (2013) shows that periods with strong volcanic  
6 activity correspond to a reduced mean temperature. LIA may be therefore caused by a 50 year-  
7 long episode of volcanism and kept persistently cold because of ocean feedback and a summer  
8 insolation minimum.

9 ~~To check the impact of volcanic eruptions on the temperature of northern Greenland, we  
10 compared the  $\delta^{18}\text{O}$  values of the high-resolution data of the individual NGT cores as well as of  
11 the stacked record 5 years before and after major volcanic eruption (Table 2).~~

12 ~~Not in all cases are eruptions followed by a distinct cold period. For example the TAMBORA  
13 eruption in 1815/16 AD or HUYANAPUTINA in 1601 AD took place within a general cold period  
14 in northern Greenland (Fig. 2), and a possible additional cooling effect cannot be clearly  
15 attributed to the volcanic eruptions. For the Mt. St. Helens eruption in 1479 AD, we see an  
16 ongoing warming trend, whereas the 1259 AD eruption took place during an ongoing cooling.  
17 Thus the eruption cannot be the reason for the onset of the cold period. After the Katmai  
18 eruption in 1912 AD, we observe a cooling in some of the cores with higher accumulation rate  
19 (e.g. B29 and B26). The cores with the lowest accumulation rates (B17–B21) do not show any  
20 temperature response to the volcanic eruption.~~

21 ~~Thus, there is no general direct relationship between volcanic eruptions and cooling in northern  
22 Greenland; neither in the NG-stack nor in the single  $\delta^{18}\text{O}$  records. It was therefore also not  
23 possible to distinguish between equatorial and Icelandic volcanoes.~~

24 ~~The reconstructions of Box et al. (2009) showed that volcanic cooling is concentrated in western  
25 Greenland, which is consistent with the findings from instrumental records (Box, 2002; Robock  
26 and Mao, 1995), and is largest in winter as the dynamically active season. From our dataset, we  
27 conclude as Fischer et al. (1998e) that volcanic climate forcing is limited in northern Greenland.  
28 As Swingedouw et al. (2015) argue it also might be possible that the direct cooling response of  
29 volcanic eruptions is first to the ocean and only after years seen in the  $\delta^{18}\text{O}$  values from ice  
30 cores which complicates the study of cooling after volcanic eruptions from ice core data.~~

31 ~~Between about 1100 and 1600 AD we observe quasi-periodic (50–60–70–80 a) cold and warm  
32 anomalies in the NG-stack which is not present in the other shown Arctic records (Fig. 96). The  
33 main period determined using Fourier decomposition between 1100 and 1600 AD for 30-year  
34 running mean smoothed values is calculated with 76.31 a.~~

1 The Atlantic Multidecadal Oscillation, AMO, could be one possible influence causing these  
2 low-frequency oscillations. ~~Chylek et al. (2012) explain that the AMO is visible in  $\delta^{18}\text{O}$  values~~  
3 ~~from central Greenland by Chylek et al. (2012).~~ As the AMO index reconstruction (Gray et al.,  
4 2004) does not cover the time between 1100 and 1600 AD, we only can speculate about an  
5 influence in that time due to the similar periodicity. For the time period 1567-1990 AD, the  
6 correlation between the NG-stack and the AMO index is weak ( $r = 0.06$ ), which might be due  
7 to the uncertainties in historical AMO data. However, since 1800 AD we observe a higher  
8 correlation coefficient ( $r = 0.66$ ,  $p < 0.05$ ) implying a possible relation. ~~Chylek et al. (2012)~~  
9 ~~discussed~~

10 One of these warmer periods is about 1420 +/- 20 AD, an abnormal warm event which is  
11 observed in our northern Greenland record and has not been pointed out in other ice core studies  
12 before. The event is observable in all nine NGT cores covering this time (Fig. 2) as well as in  
13 NGRIP but not in the ~~temperature-isotope~~ records from southern Greenland as the Dye3 ice  
14 core (Fig. 96). One reason here might be the specific geographical position in the North.

15 Furthermore, we observe a difference between the Canadian and ~~Siberian-Russian~~ Arctic  
16 regarding the 1420-event. Unlike the ~~Siberian-Russian~~ Akademii Nauk ice core, the  $\delta^{18}\text{O}$  values  
17 of the Agassiz cores from Ellesmere Island also show a trend to more enriched values in that  
18 period but not as strong as in northern Greenland.

19 The fact that the 1420 event is not clearly noticeable in other surrounding Arctic ice cores  
20 emphasizes that this event may have occurred on a smaller regional scale. However, it seems  
21 to have been of dominant influence and is also reflected in a smaller warming for the Arctic2k  
22 record (Fig. 96).

23 The spatial distribution of the 1420 event in northern Greenland is mapped in figure 3b. The  
24 event is strongest in the upper north and shows a different pattern than the  $\delta^{18}\text{O}$  anomalies of  
25 the 1920/1930 warm phase, which is also attributed to internal variability and is strongest in the  
26 northeast of Greenland.

27 Figure 10 shows possible forcing factors ~~causing that might be related to~~ the 1420 AD event.  
28 According to the reconstructed total solar irradiance record of Steinhilber et al. (2009), there  
29 was no solar maximum observed for 1420 AD that could explain the warmer temperatures in  
30 northern Greenland. As we see no forcing anomaly, we interpret the 1420-event as ~~likely be~~  
31 caused by internal Arctic climate dynamics with a sea-ice-atmospheric feedback.

32 Box (2002) argued that climate variability in Greenland is linked to the North ~~Atlanticern~~  
33 Oscillation (NAO), volcanism and sea ice extent. NAO (Vinther et al., 2003) is calculated to be  
34 weakly reflected ( $r = -0.2$ ,  $p < 0.01$ ) in the NG-stack, similar ~~to the results of~~ White et al.



1 (1997) for summit ice cores, whereas none of the single NGT records is significantly correlated  
2 ( $p < 0.05$ ) to the NAO index. The NG-stack has an increased signal-to-noise level, which is why  
3 the correlation here might be clearer than from individual records. Also, the sub-stack of the  
4 records on the ice divide (~~group-stack H~~ "Divide") as well as those east (~~group-stack F~~ "East")  
5 are significantly correlated ( $r = -0.19$  and  $-0.17$ ,  $p < 0.05$ ) to the NAO index. The cores east of  
6 the main ice divide are expected to be out of the major cyclonic track. We conclude that NAO  
7 is not of major importance for northern Greenland  $\delta^{18}\text{O}$  values.

8 Around 1420 AD, an anti-correlation between sea-ice extent in the Arctic Ocean (Kinnard et  
9 al., 2011) and the  $\delta^{18}\text{O}$  values is observed (Fig. 407). ~~The sea-ice extent reconstruction of~~  
10 ~~Kinnard et al. (2011) is based on 69 proxy records of which 22 are  $\delta^{18}\text{O}$  records. Out of these~~  
11 ~~22  $\delta^{18}\text{O}$  records 5 (NGRIP, B16, B18, B21 and B26) are used also in our NG-stack. We do not~~  
12 ~~expect circular reasoning in the interpretation of the 1420 event because B16 and B26 do not~~  
13 ~~reach the age of 1420 AD and we do not see a strong anti-correlation during any other time~~  
14 ~~period.~~

15 The sea ice in the Arctic Ocean shows a recession ~~in only during this that time of~~ warm  
16 ~~temperatures period~~ in northern Greenland. A shrunken sea ice extent would cause higher  
17 temperatures on a regional scale and would increase the amount of water vapour from local  
18 sources. Therefore, compared to distant sources, more isotopically-enriched moisture (Sime et  
19 al., 2013) may contribute to precipitation in northern Greenland, in particular east of main ice  
20 divide.

21 However, we do not see any direct relationship between sea-ice extent and our NG-stack during  
22 the rest of time, ~~which does not exclude the relationship between sea-ice extent and  $\delta^{18}\text{O}$  in~~  
23 ~~northern Greenland.~~ The used sea ice ~~record reconstruction~~ is ~~an~~ Arctic-wide ~~one~~, which means  
24 that the climatic events of regional extent, ~~like an additional moisture source for northern~~  
25 ~~Greenland's  $\delta^{18}\text{O}$ ,~~ do not have to be always reflected, ~~in the sea ice extent record.~~ Nevertheless,  
26 also the recent NEEM  $\delta^{18}\text{O}$  record from northwest Greenland, shows a generally close  
27 relationship with the Labrador Sea / Baffin Bay sea ice extent (Masson-Delmotte et al., 2015;  
28 Steen-Larsen et al., 2011).

29 ~~The sea-ice extent reconstruction of Kinnard et al. (2011) is based on 69 proxy records of which~~  
30 ~~22 are  $\delta^{18}\text{O}$  records. Out of these 22  $\delta^{18}\text{O}$  records 5 (NGRIP, B16, B18, B21 and B26) are used~~  
31 ~~also in our NG stack. We do not expect circular reasoning in the interpretation of the 1420~~  
32 ~~event because B16 and B26 do not reach the age of 1420 AD and we do not see a strong anti-~~  
33 ~~correlation during any other time period.~~

34

## 1 **34** Conclusions

2  
3 With the full set of the NGT records, it was now for the first time possible to describe regional  
4 differences in the  $\delta^{18}\text{O}$  values in northern Greenland over the last 1000 years.

5 Because of the ice sheet topography we see a clear east-to-west difference in northern  
6 Greenland  $\delta^{18}\text{O}$  distribution. -12 % of the spatial  $\delta^{18}\text{O}$  variability is attributed to ice sheet  
7 topography. The east-to-west gradient is larger than the north-to-south gradient. We find a more  
8 pronounced persistence of warm or cold events east of the main ice divide and assume more  
9 stable climate conditions there. The eastern part is more influenced by local effects like changes  
10 in the Arctic Ocean, which has to be supported by the results of climate models. For the first,  
11 time a local warm event at 1420 +/- 20 AD was pointed out. We assume an atmosphere-sea ice  
12 feedback as one possible reason for this event.

13 Due to the shadowing effect of the main ice divide we find the lowest accumulation rates in the  
14 northeast, whereas the lowest mean  $\delta^{18}\text{O}$  values are found east of the main ice divide north of  
15 summit. The lowest  $\delta^{18}\text{O}$  mean values seem to be independent of accumulation rate.

16 We have presented a new 1000 year stacked  $\delta^{18}\text{O}$  record for northern Greenland covering 10 %  
17 of the area of Greenland. We found this NG-stack to be representative for the northern  
18 Greenland temperature.

19 Northern Greenland  $\delta^{18}\text{O}$  represents known climatic variations of the last millennium. We see  
20 a warm MCA and can derive distinct LIA cooling from our NG-stack.

21 The results of single site ice-core studies are likely weakened by the finding that there is -only  
22 22 % common of variability in the 13 NGT cores, the local  $\delta^{18}\text{O}$  signal is related to climate. 12  
23 % of the variability is attributed to ice sheet topography. The remaining 66 % are therefore due  
24 to other processes.

25 The solar activity and internal Arctic climate dynamics are likely the main factors influencing  
26 the temperature in northern Greenland. In contrast we could not find a general cooling effect of  
27 volcanic eruptions in our data.

28

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1 **Acknowledgements**

2  
3 Stefanie Weißbach was financed by the “Earth System Science Research School (ESSReS)”,  
4 an initiative of the Helmholtz Association of German Research Centres (HGF) at the Alfred  
5 Wegener Institute (AWI), Helmholtz Centre for Polar and Marine Research.

6 Anna Wegner acknowledges REKLIM for funding.

7 This study contributes to the Eurasian Arctic Ice 4k project funded by Deutsche  
8 Forschungsgemeinschaft (grant OP 217/2-1 awarded to Thomas Opel).

9 ~~Anna Wegner acknowledges REKLIM for funding.~~

10 Many thanks to the drill and lab team who have measured the  $\delta^{18}\text{O}$  (76.930 samples) with  
11 endurance over more than 20 years. We also thank Johannes Freitag and Katja Instenberg  
12 for high resolution (CT) density measurements, Martin Rückamp for compiling the maps,  
13 Martin Werner, Thomas Laepple and Johannes Freitag for helpful discussions that improved  
14 the manuscript and Kirstin Meyer for proofreading language check.

15 "Supplementary data are available at <http://dx.doi.org/10.1594/PANGAEA.849161>"

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35

Formatiert: Deutsch (Schweiz)

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1 Table 1. Overview of all NGT drill sites.

| Core Id | Core length (m) | Elevation (m a. sl.) | Geographic Position |                |
|---------|-----------------|----------------------|---------------------|----------------|
|         |                 |                      | Latitude (°N)       | Longitude (°W) |
| B16     | 102.4           | 3040                 | 73.94               | 37.63          |
| B17     | 100.8           | 2820                 | 75.25               | 37.63          |
| B18     | 150.2           | 2508                 | 76.62               | 36.40          |
| B19     | 150.4           | 2234                 | 78.00               | 36.40          |
| B20     | 150.4           | 2147                 | 78.83               | 36.50          |
| B21     | 100.6           | 2185                 | 80.00               | 41.14          |
| B22     | 120.6           | 2242                 | 79.34               | 45.91          |
| B23     | 150.8           | 2543                 | 78.00               | 44.00          |
| B26     | 119.7           | 2598                 | 77.25               | 49.22          |
| B27     | 175.0           | 2733                 | 76.66               | 46.82          |
| B28     | 70.7            | 2733                 | 76.66               | 46.82          |
| B29     | 110.5           | 2874                 | 76.00               | 43.50          |
| B30     | 160.8           | 2947                 | 75.00               | 42.00          |

2

Table 2. Depth of volcanic horizons used for dating. The given year is the time of aerosol deposition on the Greenlandic Ice Sheet. All depths are given in meter water equivalent. If a horizon could not be clearly identified a hyphen is shown in the table. A field is empty if the horizon is deeper than the length of the ice core. The maximum uncertainty difference is estimated from a comparison between cores dated by annual layer counting (Mieding, 2005; Schwager, 2000) and the dating used for this study. Given is also the VEI (Newhall and Self, 1982) and the total northern hemisphere stratospheric sulfate aerosol injection (Gao et al., 2008) for each used volcanic eruption.

\*)*(Sigl et al., 2013)*, \*\*)*(Friedmann et al., 1995)*

| Year [AD]                              | Event             | B16   | B17   | B18    | B19   | B20   | B21   | B22   | B23   | B26   | B27    | B28   | B29   | B30    | VEI | Sulfate |
|--|-------------------|-------|-------|--------|-------|-------|-------|-------|-------|-------|--------|-------|-------|--------|-----|---------|
| 1912                                   | Katmai*           | 11.60 | 9.31  | 8.48   | 7.38  | 7.86  | 8.62  | 11.56 | 9.49  | 14.27 | 13.69  | 14.44 | 11.41 | 13.12  | 6   | 11.0    |
| 1816                                   | Tambora*          | 24.49 | 20.27 | 18.91  | 16.77 | 17.27 | 19.46 | 26.17 | 21.54 | 31.50 | 31.13  | 31.91 | 25.97 | 29.91  | 7   | 58.7    |
| 1783                                   | Laki*             | 29.36 | 24.19 | 22.45  | 19.94 | 20.32 | 23.10 | 31.25 | 25.93 | 37.77 | 37.19  | 38.07 | 31.28 | 35.80  | 4   | 93.0    |
| 1739                                   | Tarumai*          | 35.52 | -     | 26.90  | 24.10 | 24.62 | -     | -     | -     | -     | -      | -     | -     | 43.07  | 5   | 0       |
| 1694                                   | Hekla**           | -     | 34.47 | 31.84  | 28.54 | 29.16 | 32.87 | 44.06 | -     | -     | -      | -     | 44.22 | 50.45  | 4   | 0       |
| 1666                                   | Unknown**         | 46.22 | -     | 34.75  | 31.20 | 32.10 | 35.93 | 48.13 | -     | -     | -      | -     | 48.50 | -      | -   | 0       |
| 1640                                   | Komagatake**      | 49.90 | -     | 37.48  | 33.69 | 34.80 | -     | -     | -     | -     | -      | -     | 52.36 | -      | 4   | 33.8    |
| 1601                                   | Huaynaputina*     | -     | 44.97 | 41.62  | -     | 38.70 | 42.95 | -     | 48.31 | 69.22 | 68.39  | -     | 58.25 | 65.94  | 4   | 46.1    |
| 1479                                   | Mt. St. Helenes** | -     | 58.84 | 54.42  | -     | 51.31 | 56.04 | 75.09 | -     | -     | 89.42  | -     | 76.81 | 86.60  | -   | 7.4     |
| 1259                                   | Samalas*          | -     | -     | 76.60  | 68.03 | 72.86 | -     | -     | 89.35 | -     | 126.10 | -     | -     | 122.10 | -   | 145.8   |
| 1179                                   | Katla*            | -     | -     | -      | -     | 80.04 | -     | -     | 98.60 | -     | -      | -     | -     | -      | -   | 0       |
| 934                                    | Eldgia*           | -     | -     | 109.20 | 99.20 | -     | -     | -     | -     | -     | -      | -     | -     | -      | -   | 0       |
| Max. age of core [AD]                  |                   | 1470  | 1363  | 874    | 753   | 775   | 1372  | 1372  | 1023  | 1505  | 1195   | 1763  | 1471  | 1242   | -   | -       |
| Max. <u>uncertainty difference</u> [a] |                   | 7     | -     | 3      | -     | 8     | 6     | -     | -     | 4     | -      | -     | 3     | -      | -   | -       |

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1 Table 3. Resulting mean accumulation rates (from the surface to the deepest volcanic horizon  
 2 and in brackets for their common time window (1505-1953 AD)) for each NGT drill site, the  
 3 lowest and highest rate within the whole core length, the time period from surface to the  
 4 deepest volcanic horizon and the age at the bottom of the ice core calculated by extrapolation  
 5 of the deepest calculated accumulation rate.

| Core    | Mean accumulation rate [kg m <sup>-2</sup> a <sup>-1</sup> ] | Accumulation rate range [kg m <sup>-2</sup> a <sup>-1</sup> ] | Time period [AD] | Age at bottom of core[AD] |
|---------|--|---|------------------|---------------------------|
| B16     | 141 [141]  | 134-148   | 1640-1993        | 1470                      |
| B17     | 114 [114]  | 113-119   | 1479-1993        | 1363                      |
| B18     | 103 [106]  | 100-110   | 934-1993         | 874                       |
| B19     | 94 [94]  | 90-99   | 934-1993         | 753                       |
| B20     | 98 [100]   | 90-105  | 1179-1994        | 775                       |
| B21     | 109 [109]  | 105-113   | 1479-1994        | 1372                      |
| B22     | 145 [145]  | 141-154   | 1479-1994        | 1372                      |
| B23     | 121 [122]  | 116-132   | 1179-1994        | 1023                      |
| B26     | 176 [176]  | 172-190   | 1601-1995        | 1505                      |
| B27/B28 | 180 [181]  | 165-187   | 1783-1995        | 1195                      |
| B29     | 149 [150]  | 137-161   | 1479-1995        | 1471                      |
| B30     | 166 [169]  | 158-178   | 1259-1995        | 1242                      |

6

1 Table 4. The 15-m fir temperature, Mean annual  $\delta^{18}\text{O}$  values for each ice core, the range of  
 2 the highest and lowest  $\delta^{18}\text{O}$  values and the year they occurred as well as the standard deviation  
 3 (SD) all given for their common time window (1953-1505 AD).

4 \*(*Vinther et al., 2006b*), *\*\**(*Schwager, 2000*), *\*\*\* interpolated from (Schwager, 2000)*

| Core    | <u>**15 m</u><br><u>Firn</u><br><u>temperature</u><br><u>[°C]</u> | Mean<br>$\delta^{18}\text{O}$<br>[‰] | $\delta^{18}\text{O}$ range [‰] | Years [AD]<br>of<br>lowest-<br>highest value | SD<br>of<br>$\delta^{18}\text{O}$<br>[‰] | Time period<br>[AD]<br>(whole core<br>length) |
|---------|---|--------------------------------------|---------------------------------|--|--|---|
| B16     | <u>-32.5***</u>   | -37.07                               | -40.64 to -33.11                | 1839-1937                                    | 0.99                                     | 1470-1993                                     |
| B17     | <u>-32.3***</u>   | -37.13                               | -40.06 to -33.89                | 1835-1879                                    | 1.08                                     | 1363-1993                                     |
| B18     | <u>-32.3***</u>   | -36.53                               | -41.52 to -31.75                | 1761-1889                                    | 1.44                                     | 874-1993                                      |
| B19     | <u>-30.9 (±0.5)</u>   | -35.49                               | -38.97 to -31.77                | 1575-1826                                    | 1.32                                     | 753-1953                                      |
| B20     | <u>-30.4***</u>   | -35.41                               | -39.34 to -30.69                | 1699-1929                                    | 1.42                                     | 775-1994                                      |
| B21     | <u>-30.1***</u>   | -34.53                               | -38.29 to -30.95                | 1814-1871                                    | 1.29                                     | 1372-1994                                     |
| B22     | <u>-29.8***</u>   | -34.54                               | -39.11 to -29.84                | 1921-1953                                    | 1.34                                     | 1372-1994                                     |
| B23     | <u>-29.3 (±0.5)</u>   | -35.98                               | -42.11 to -32.23                | 1918-1928                                    | 1.28                                     | 1023-1994                                     |
| B26     | <u>-30.3***</u>   | -33.86                               | -37.22 to -29.42                | 1597-1893                                    | 1.25                                     | 1505-1995                                     |
| B27/B28 | <u>-30.6 (±0.5)</u>   | -34.47                               | -38.26 to -30.58                | 1566-1892                                    | 1.25                                     | 1195-1995                                     |
| B29     | <u>-31.6 (±0.5)</u>   | -35.65                               | -39.22 to -31.59                | 1834-1928                                    | 1.18                                     | 1471-1995                                     |
| B30     | <u>-31.8 (±0.5)</u>   | -35.46                               | -38.53 to -31.52                | 1862-1928                                    | 1.09                                     | 1242-1988                                     |
| NGRIP*  |   | -35.42                               | -40.12 to -30.81                | 1836-1928                                    | 1.24                                     |   |

Formatierte Tabelle

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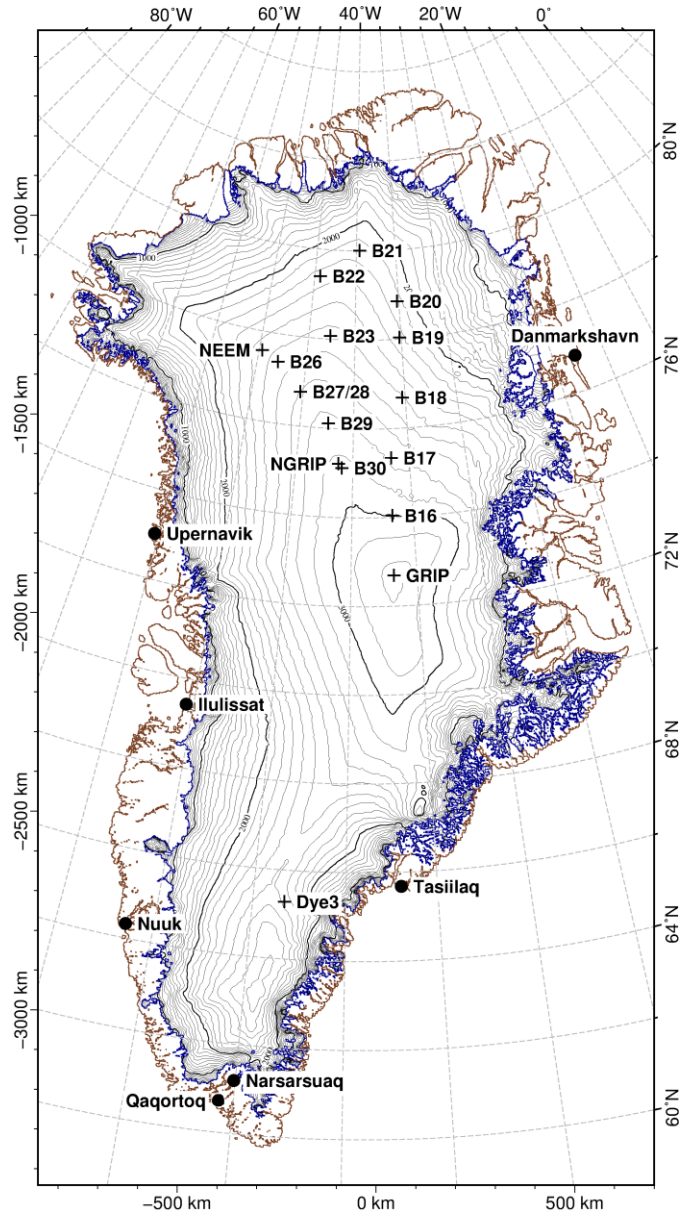
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1 Table 5. Correlation coefficients (r) of the stacked  $\delta^{18}\text{O}$ -record with annual and seasonal (DJF,  
 2 MAM, JJA and SON) extended Greenland temperature records <sup>\*)</sup>(Vinther et al., 2006a), North  
 3 west Iceland instrumental data <sup>\*\*)</sup>(Hanna et al., 2004; Jónsson, 1989), annual mean Greenland  
 4 ice sheet near-surface air temperatures from combined instrumental and model output <sup>\*\*\*)</sup> (Box  
 5 et al., 2009) and Arctic temperature reconstruction <sup>\*\*\*\*)</sup>(Wood et al., 2010). All correlations are  
 6 done with 5-year running means and are significant on 95 % level ( $p < 0.05$ ).

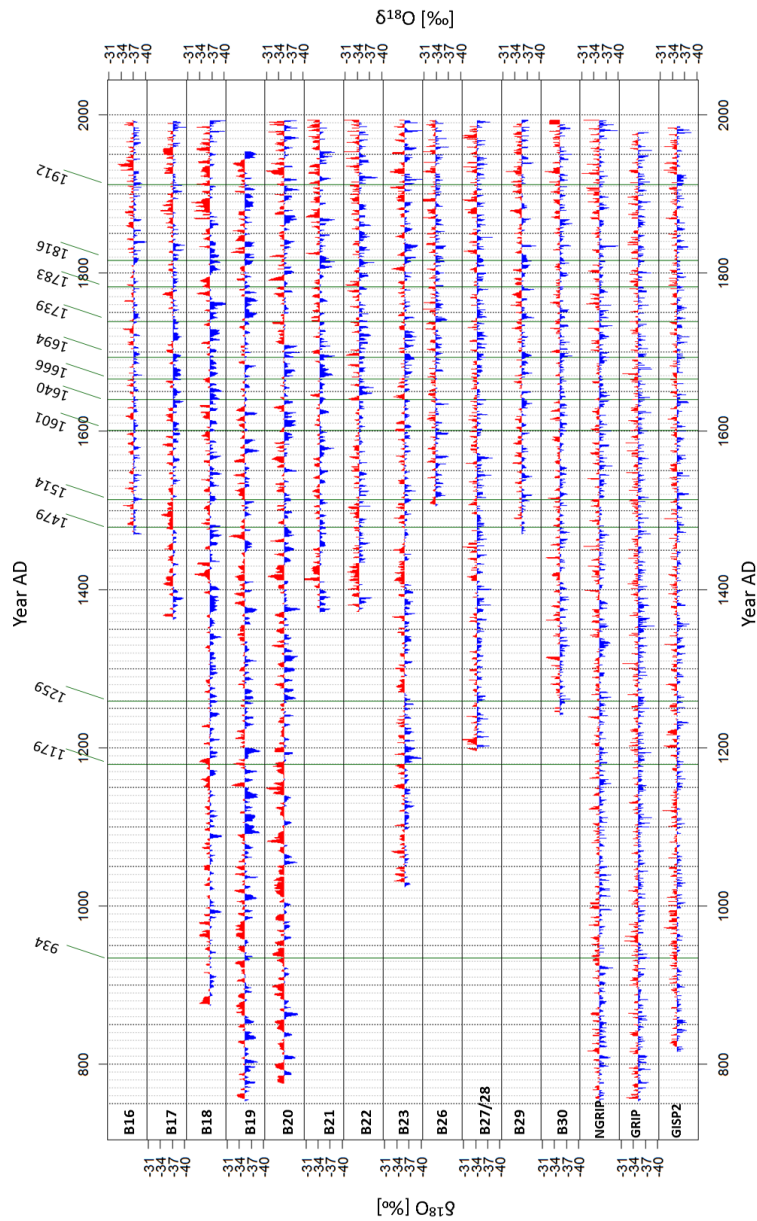
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|  | r<br>annual | r<br>seasonal | Years of<br>overlap |
|--|-------------|---------------|---------------------|
| *) Merged South<br>(Greenland)                       | 0.51        | DJF           | 0.47                |
|  |             | MAM           | 0.62                |
|  |             | JJA           | 0.51                |
|  |             | SON           | 0.5                 |
| *) Ilulissat<br>(Greenland)                          | 0.46        | DJF           | 0.50                |
|  |             | MAM           | 0.42                |
|  |             | JJA           | 0.36                |
|  |             | SON           | 0.45                |
| *) Nuuk<br>(Greenland)                               | 0.41        | DJF           | -                   |
|  |             | MAM           | 0.55                |
|  |             | JJA           | 0.47                |
|  |             | SON           | 0.47                |
| *) Qaqortoq<br>(Greenland)                           | 0.39        | DJF           | -                   |
|  |             | MAM           | 0.50                |
|  |             | JJA           | 0.50                |
|  |             | SON           | 0.36                |
| **) Stykkisholmur<br>(Iceland)                       | 0.41        | DJF           | -                   |
|  |             | MAM           | 0.36                |
|  |             | JJA           | 0.35                |
|  |             | SON           | 0.31                |
| ***) Mean Greenland<br>surface air temperature       | 0.50        |               | 1840-1994           |
| ****) Extended<br>instrumental temperature<br>record | 0.55        |               | 1802-1994           |

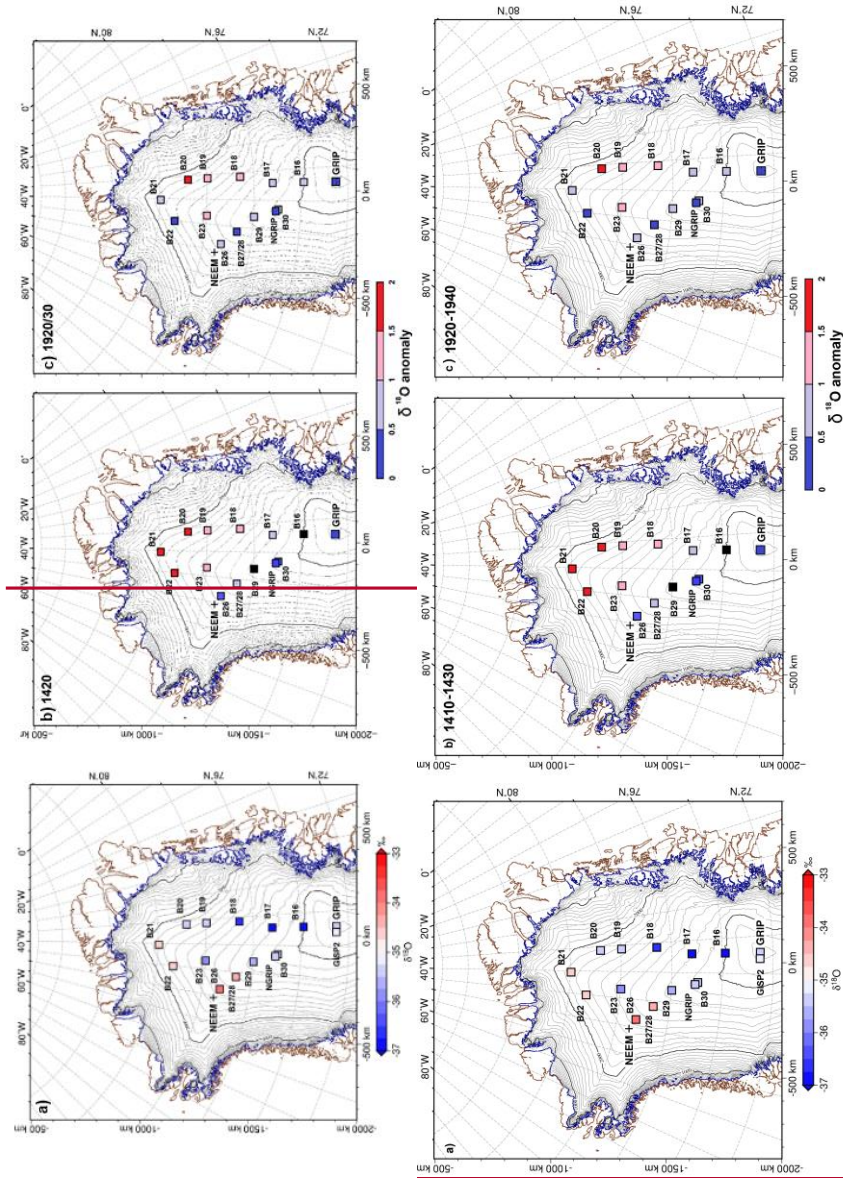
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1  
 2 Figure 1. Map of Greenland with NGT ice cores (B16-B23, B26-B30 crosses), deep drilling  
 3 sites (crosses) and towns (black dots). The ice surface topography is according to Bamber et al.  
 4 (2013), (mapping: Polar Stereographic (WGS84) , Standard Parallel 71, Latitude of Projection  
 5 Origin -39)



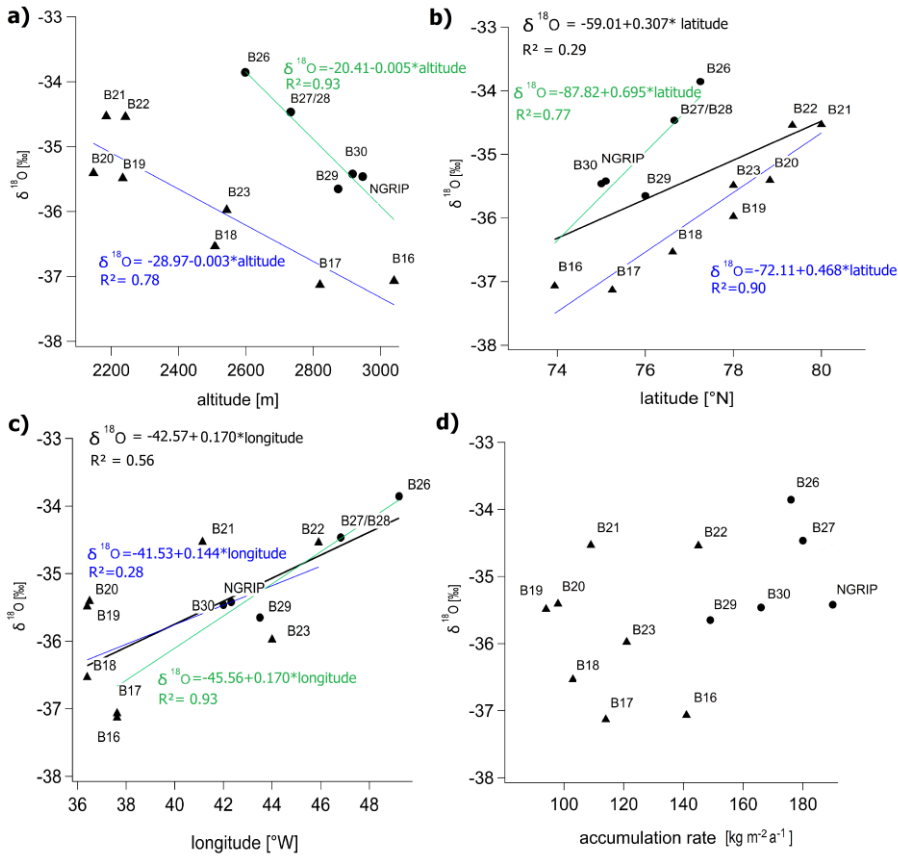
1  
 2 Figure 2. Annual  $\delta^{18}\text{O}$  records at the 12 NGT sites (this study) and NGRIP (Vinther et al.,  
 3 2006b), GRIP (Vinther et al., 2010) and GISP2 (Grootes and Stuiver, 1997). Blue are the values  
 4 below the mean over their common time window (1505 -1953 AD) and red are the higher ones.  
 5 Dark green vertical lines mark the volcanic eruptions (years given at top) used as time markers.



1  
 2 Figure 3. Spatial distribution of  $\delta^{18}\text{O}$  values in northern Greenland. a) The mean  $\delta^{18}\text{O}$  values of  
 3 the northern Greenland ice cores in their common time window (1505-1953 AD) is given with  
 4 color coded squares. Blue colors representing lighter values, red colors heavier values.  
 5 Mapped mean anomalies of  $\delta^{18}\text{O}$  compared to a) for two different periods: b) 1410-1430 AD  
 6 and c) 1920-1940 AD. If a record not cover the required time period the square is filled in black.

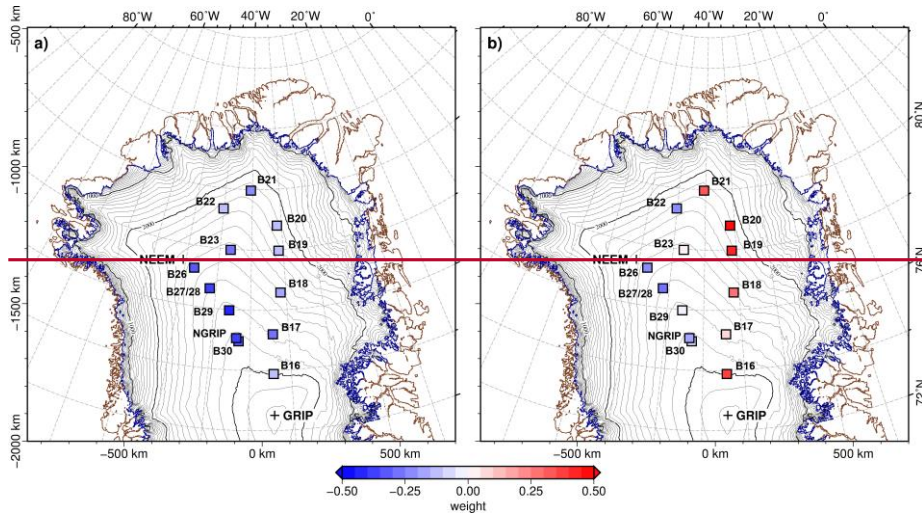


1

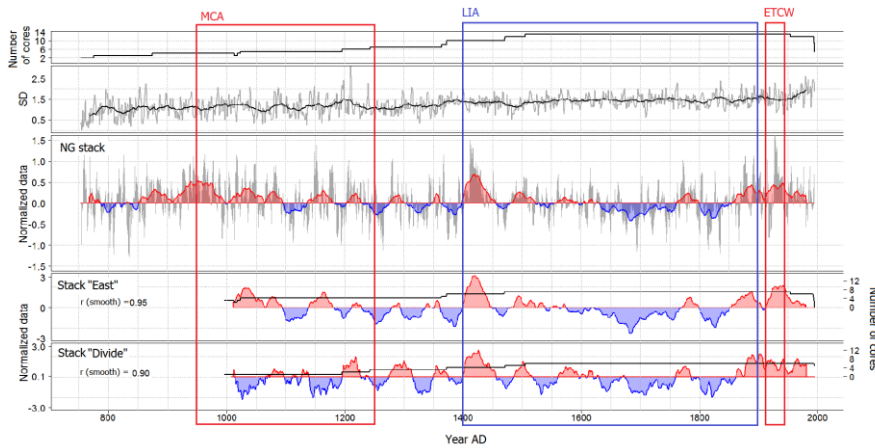


2

3 Figure 4. Mean  $\delta^{18}\text{O}$  (1505-1953 AD) as a function of a) altitude, b) latitude and c) longitude  
4 d) accumulation rate of northern Greenland ice core drill sites. The red line gives the linear  
5 regression functions. Cores with higher accumulation rates ( $< 145 \text{ kg m}^{-2} \text{a}^{-1}$ ) are given as black  
6 dots and lower rates as black triangles, which is similar to the differentiation between east of  
7 and on the main ice divide. For statistically significant correlations the lines give the linear  
8 regression functions (black: mean, green: higher accumulation rates, blue: lower accumulation  
9 rates).



1  
 2 **Figure 5. Map of loading for the first a) and second b) principal component on the annual**  
 3 **northern Greenland  $\delta^{18}\text{O}$  values between 1505 and 1953 AD.**



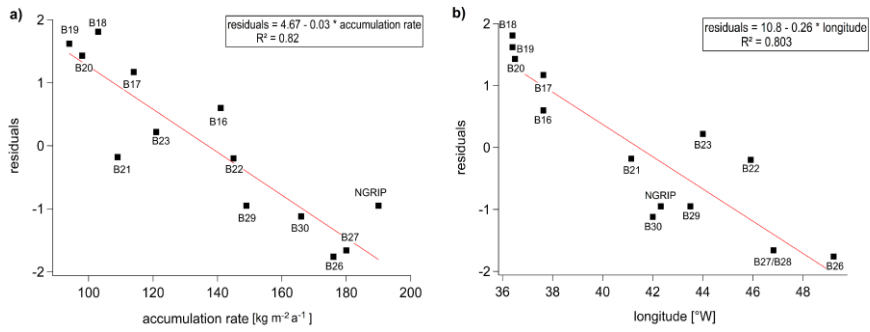
1  
 2 **Figure 65.** At top of the figure the number of cores used for the stack and the standard deviation  
 3 (SD, gray: annual values, black: 30-year running mean) of all times and are given the number  
 4 of cores used for the stack is given.  
 5 Middle: Annual stacked  $\delta^{18}\text{O}$  (grey) and smoothed record (30-year running mean). Values more  
 6 enriched compared to the mean (1953-1505 AD) are red, values less enriched are shown in  
 7 blue. Known climate anomalies are marked: Medieval Climate Anomaly (MCA, 950 - 1250  
 8 AD (Mann et al., 2009)), the Little Ice Age (LIA, 1400 - 1700-1900 AD - (Mann, 2009  
 9 #124; Mann, 1998 #207) (Mann et al., 1998)). Early Twentieth Century Warming (ETCW,  
 10 1920 - 1940 (Semenov and Latif, 2012; Wood and Overland, 2010)). At top of the figure the  
 11 standard deviation (SD, gray: annual values, black: 30-year running mean) of all times and the  
 12 number of cores used for the stack is given.  
 13 Bottom: 30-year running mean on z-levels (centred and normalized data) of stacked northern  
 14 Greenland  $\delta^{18}\text{O}$  records over the last 1000 years. Stack "East": B16, B17, B18, B19, B20, B21  
 15 and B23, stack "Divide": B22, B26, B27, B29, B30 and NGRIP. Values in red are more  
 16 enriched compared to the mean over their last 1000 years, and blue are less enriched. Given is  
 17 also the correlation coefficient of 30- year running means between the NG-stack and the sub-  
 18 stacks (1505-1993 AD). The coefficient for a similar correlation between the two substacks is  
 19 calculated with  $r = 0.71$ .

Formatiert: Schriftfarbe: Automatisch

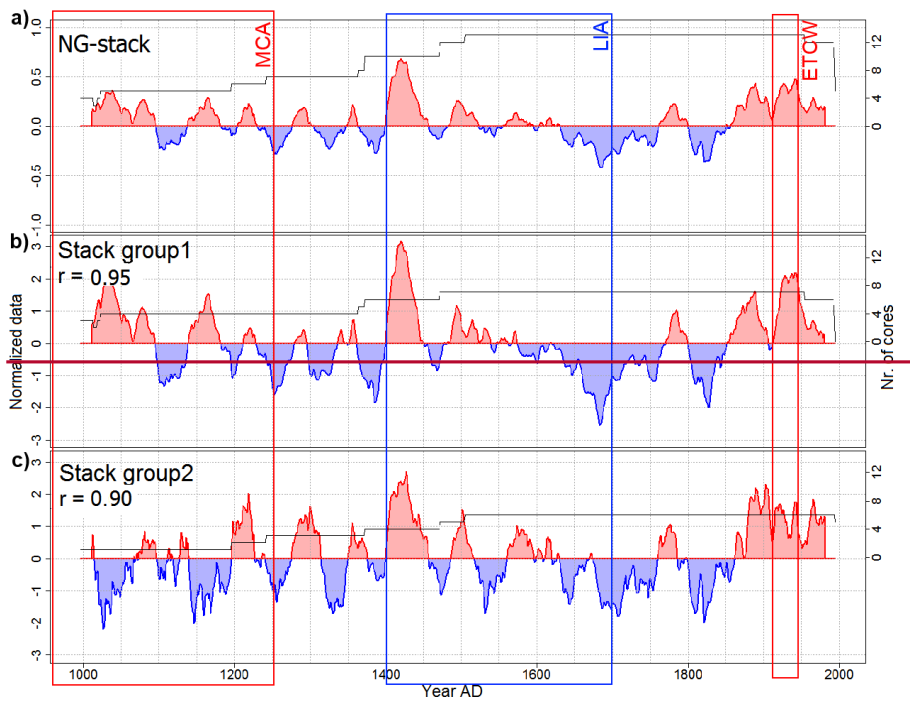
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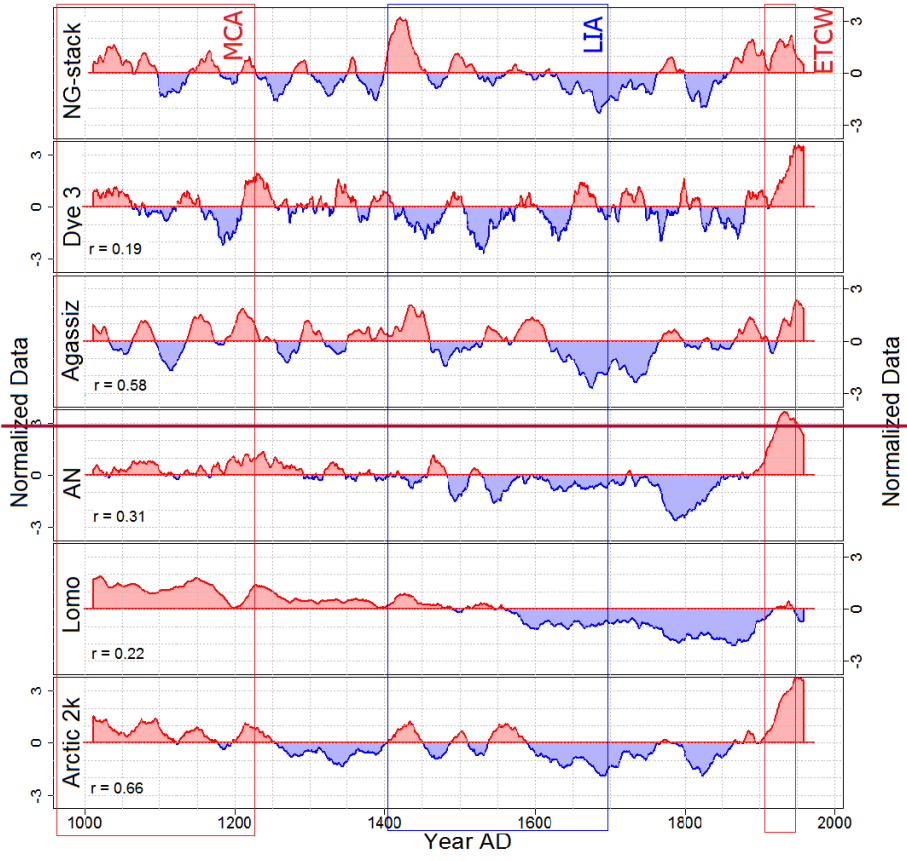
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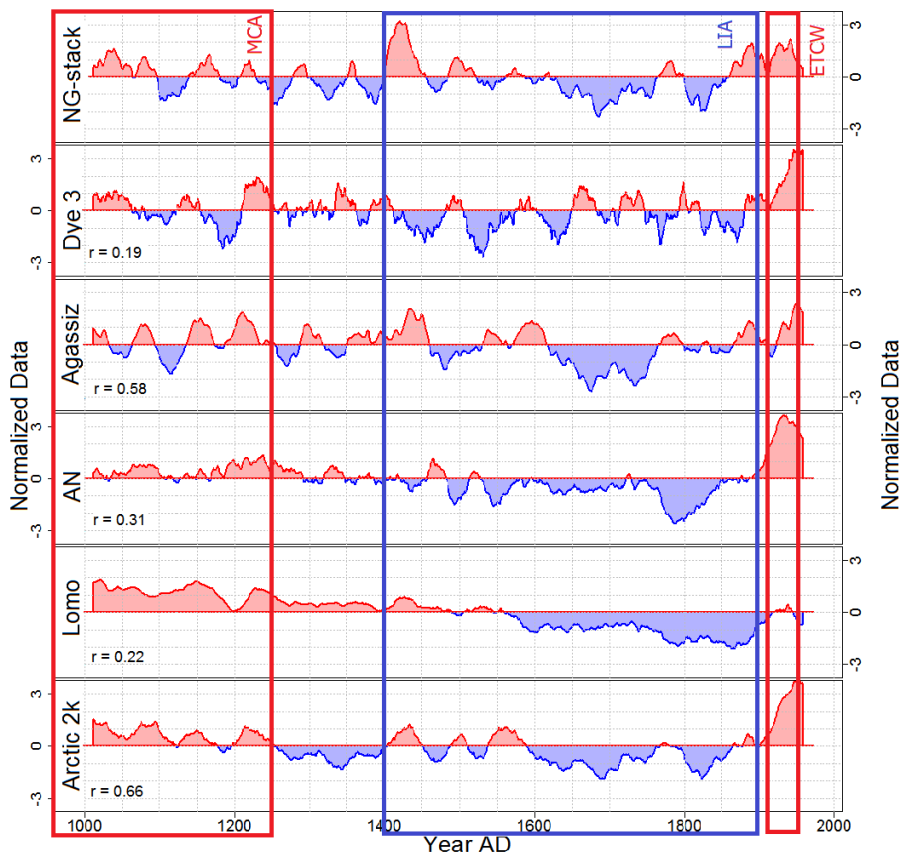


1  
 2 **Figure 7. Residuals of the observed  $\delta^{18}\text{O}$  mean values and the results of the Jonhsen model**  
 3 **(Jonhsen et al., 1989), taking into account multi parameter relationships over a) the**  
 4 **accumulation rate b) the longitude.**

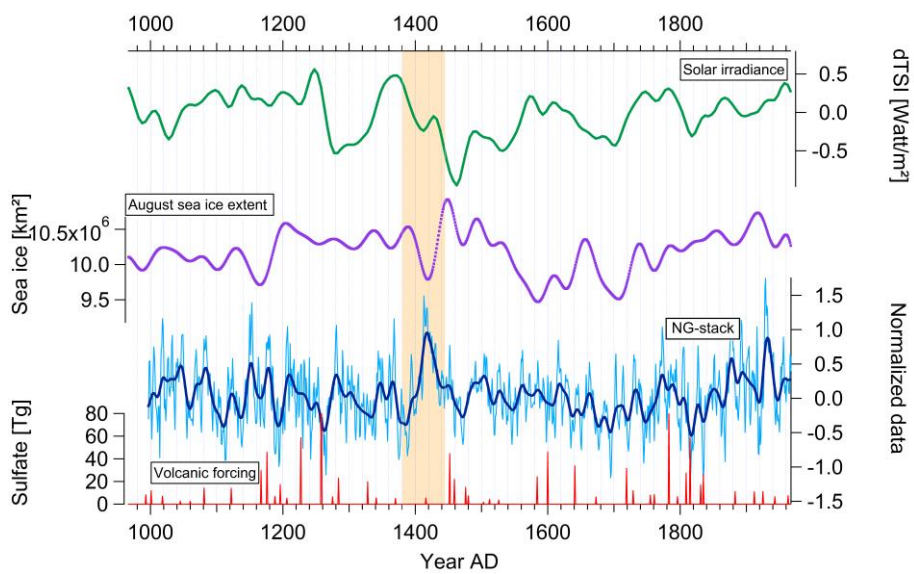


1  
 2 **Figure 8.** 30-year running mean on z-levels (centred and normalized data) of stacked northern  
 3 Greenland  $\delta^{18}\text{O}$  records over the last 1000 years. a) stack over all northern Greenland cores  
 4 used in the study (NG-stack) b) stack group I (B16, B17, B18, B19, B20, B21 and B23), c)  
 5 stack group II (B22, B26, B27, B29, B30 and NGRIP). Values in red are more enriched  
 6 compared to the mean over their last 1000 years, and blue are less enriched. Given is also the  
 7 correlation coefficient on 30-year running mean between the stack over all cores and the stack  
 8 of the core groups (1993-1505 AD). The coefficient for a similar correlation between the two  
 9 groups is calculated with  $r = 0.71$ .





1  
 2 Figure 96. 30-year running mean for  $\delta^{18}\text{O}$ -values from different Arctic regions: northern  
 3 Greenland (NG-stack, this study), southern Greenland (Dye3, Vinther et al., 2006b),  
 4 Canada (Agassiz Ice Cap, Agassiz, Vinther et al., 2008), ~~Siberia-Russian Arctic~~ (Akademii  
 5 Nauk, AN, Opel et al., 2013), Svalbard (Lomonosofvonna, Lomo, Divine et al., 2011) and a  
 6 reconstructed record (Arctic2k, Consortium Pages2k, 2013). All records are given on z-  
 7 level scales (centered and normalized data). Also the correlation coefficient for the  
 8 smoothed values to our stack is given.



1  
 2 Figure 407. The northern Greenland stack (NG-stack, blue: annual, dark blue: smoothed) is  
 3 shown with possible forcing factors: Green the reconstructed total solar irradiance (Steinhilber  
 4 et al., 2009), in purple the reconstructed August arctic sea- ice extent (Kinnard et al., 2011)  
 5 and in red at the bottom the stratospheric sulphate aerosol injection for the northern hemisphere  
 6 (Gao et al., 2008). All values are 40-year- low-pass filtered. The discussed 1420 AD event is  
 7 marked with beige colour.