Reply to the Interactive reviewers comments on “Stable water isotopes and accumulation rates in the Union Glacier region, West Antarctica over the last 35 years” by Kirstin Hoffmann et al.

Ref #1: S. Goursaud (Referee)

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Summary This study describes new stable water isotope and surface mass balance records from six ices cores in the Ellsworth region, at the crossing point between West Antarctic Ice Sheet, East Antarctic Ice Sheet, and the Peninsula. This region is poorly understood in terms of climate variability. Thus, the new datasets provide substantial inputs for extending our current knowledge of recent climate variability of Antarctica, and the manuscript fully fits within the framework of TC. However, I have a few major concerns. First, I suggest that the paper should be re-articulated at some points, to show more explicitly the results which are robust, the uncertainties and clarify the underlying hypotheses.

The methods used in this study, which are mainly based on statistics, should be justified, and the associated uncertainties or confidence levels should be reported. I thus recommend this study to be accepted after some revisions.

General comments: This coastal region is particular, as it is located in the mountains. A spatio-temporal variability in surface mass balance could be then expected, related to wind drift, but this aspect is not mentioned.

Answer: We agree that in high mountain areas post-depositional processes such as the relocation of snow due to wind drift are likely. In the old manuscript this subject is first touched when describing meteorological data (Chapter 3.1, p 7), the site-specific characteristics of firm core GUPA-1 (Chapter 3.3, p 7) and further when we compare the accumulation rates of single firm cores (Chapter 4.2.1, p 10). Chapter 4.2.1 (p 10) starts with an extensive comparison of the different firm cores and these are discussed in the framework of their site-specific characteristics, including their potential influence by wind drift (1st paragraph). We do not see the necessity to change the text. Rev#2 also requested a more detailed description of the differences between coring localities that has been added to Chapter 2.1 (p 4) in the new manuscript.

Introduction: This introduction is quite difficult to follow, and not enough explicit about the scientific questions which are addressed in the manuscript. I provide hereafter suggestions to make it more understandable (specific comments). There is limited information and citations of existing literature related to climate variability in the region of the Ellsworth Mountains, as well as for the state of the art for surface mass balance and stable water isotopes. I expect the surface mass balance and winds in the region are to be highly variable both in space and time. My recommendation is to further describe the state of the knowledge for these aspects (including knowledge gaps), referring to literature specific or relevant for this region, and to explicitly frame the question of potential deposition and post-deposition effects imprinted in firm core records, as evidenced in several other regions.

Answer: We are grateful for this comment. We completely revised the introduction chapter and, as suggested by Rev #1, introduced with three neighboring regions EAIS, WAIS and AP) as our study site is located in the intersection area between them. We also sharpened the argumentation towards the key scientific questions to be addressed in our manuscript. Unfortunately, there is very little published data specifically for the region around Union Glacier. The only existing data (Rivera et al., 2010 and Rivera et al., 2014) is cited in the manuscript in the introduction, in the meteorology chapter (Chapter 3.1) as well as used for the discussion (Chapter 4.2). Here also the information is given about available local and regional accumulation data (Chapter 4.3.1).
Methods - For the ice core chronology, please make sure anyone can reproduce it thanks to a more detailed description. I am not sure that this is possible from the information given in the paper. For instance, Figure 2 suggests that some peaks of MSA and nssSO4 were not counted, contrary to dD peaks. Why? What makes water stable isotopes more reliable in this site? Other studies of coastal locations such as Goursaud et al. (2018b) have shown that water stable isotopes are less reliable than chemical signals for dating firn cores in Adelie Land.

**Answer:** We changed the description of the ice-core chronology and now provide more details in Chapter 2.2 of the new manuscript (p 5). We hope that our clarification fit the requirements of Rev #1. Generally, we used the SCH-2 firn core chronology, which bases on annual layer counting (ALC) of stable water isotope and chemistry data, as anchor to which we compared and matched the other cores, from which only stable water isotope data are available. However, firn core PASO-1 was dated independently based on ALC of stable water isotopes and chemical parameters as well as the use of the volcanic peak of Mt. Pinatubo as tie point.

Regarding Figure 2: It is obvious that neither all MSA, nor SO4^{2-}, nor all stable water isotope peaks are considered for the chronology of SCH-2. In general, we consider H2O as most reliable parameter for dating as it is directly connected to the insolation cycles (thus to solar radiation). Most maxima and minima in H2O correspond to maxima/minima in the dD record (a temperature proxy), supporting the H2O-based dating. In contrast, MSA and SO4^{2-} are connected to marine-biogenic processes, which reflect the presence/absence of sea ice, which in most, but not all cases show a seasonal cycle. Hence, the dating of SCH-2 is primarily based upon H2O, with MSA and SO4^{2-} only used for corroboration and this revealed that, contrary to Goursaud (2018b), dD also seems to reflect seasonal cycles quite well.

It would be also relevant to have an objective assessment of the age scale uncertainty due to ambiguity in peak detection.

**Answer:** In order to get a first depth-age relationship, i.e. an idea of the maximum dating uncertainty, we did an independent annual layer counting based on all firn core minima and maxima in stable water isotopes (see Table 1 below this answer). Based on this approach only, the firn cores yield a maximum dating uncertainty range of ±1 year (DOTT-1) and ±6 years (BAL-1). However, this was only an experiment, which has been carried out before using seasonally varying chemical parameters for constructing the final age scale. As already described above the chemistry-based age scale of SCH-2, which we consider as most reliable, has been used as reference and the other firn cores were matched to this age scale. For PASO-1 an independent dating has been carried out, which includes a nssS peak attributed to Mt. Pinatubo. We found that for most firn cores the final age scale, i.e. the total number of years, does not correspond to the isotope-based ALC range. Furthermore, there is no systematic offset between the final age scale and the isotope-based ALC range (see Table 1). We estimated the error associated to stable water isotope and glaciochemistry ALC, firn core inter-matching as well as the volcanic peak tie point and included the following sentence in Chapter 3.2:

“The estimated error associated to ALC is ±1 year for cores dated with glacio–chemistry (SCH-2 and PASO-1) and ±2 years for cores dated with stable water isotopes only (GUPA-1, DOTT-1, SCH-1 and BAL-1).”
Table 1: Results of annual layer counting (ALC) as well as final dating results for the six firn cores from Union Glacier. For each core the minimum and maximum number of years was determined by counting only clearly pronounced peaks and by counting all visually identifiable peaks in the respective stable water isotope profiles (δ¹⁸O/δD vs. depth). Determination of the final number of years and the corresponding period covered by each core bases on the seasonality of stable water isotopes and chemical parameters and subsequent inter-matching of stable water isotope profiles taking SCH–2 as reference.

<table>
<thead>
<tr>
<th>Firn Core</th>
<th>Winter Minima (δ¹⁸O/δD)</th>
<th>Winter Maxima (δ¹⁸O/δD)</th>
<th>ALC uncertainty (years)</th>
<th>Period</th>
<th>Total number of years (summer maxima)</th>
<th>Offset with respect to ALC dating (Min /Max summer maxima)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GUPA–1</td>
<td>Min 18</td>
<td>Min 18</td>
<td>±3.5</td>
<td>1989–2014</td>
<td>26</td>
<td>+8/+1</td>
</tr>
<tr>
<td></td>
<td>Max 25</td>
<td>Max 25</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DOTT–1</td>
<td>Min 18</td>
<td>Min 18</td>
<td>±1</td>
<td>1999–2014</td>
<td>16</td>
<td>-3/-5</td>
</tr>
<tr>
<td></td>
<td>Max 20</td>
<td>Max 21</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SCH–1</td>
<td>Min 35</td>
<td>Min 35</td>
<td>±2</td>
<td>1986–2014</td>
<td>29</td>
<td>-6/-10</td>
</tr>
<tr>
<td></td>
<td>Max 39</td>
<td>Max 39</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SCH–2</td>
<td>Min 40</td>
<td>Min 40</td>
<td>±5</td>
<td>1977–2015</td>
<td>39</td>
<td>-1/-11</td>
</tr>
<tr>
<td></td>
<td>Max 50</td>
<td>Max 50</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BAL–1</td>
<td>Min 28</td>
<td>Min 28</td>
<td>±6.5/±6</td>
<td>1980–2015</td>
<td>36</td>
<td>+8/-4</td>
</tr>
<tr>
<td></td>
<td>Max 41</td>
<td>Max 40</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PASO–1</td>
<td>Min 37</td>
<td>Min 36</td>
<td>±4</td>
<td>1973–2015</td>
<td>43</td>
<td>+7/-1</td>
</tr>
<tr>
<td></td>
<td>Max 45</td>
<td>Max 44</td>
<td></td>
<td></td>
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</tbody>
</table>

Why did you use a Mann-Kendall test? From what I know, it was used to detect inflections (Turner et al., Nature, 2016). -

Answer: Answer see below (p 9).

When reporting the outcomes of linear correlation analyses, can you please systematically provide the correlation coefficient?

Answer: The correlation coefficients are consistently given in Table 3, and have been inserted in the text wherever necessary.

Also, no need to give the exact p-value. It is sufficient to precise if it is <0.05 or <0.001.

Answer: This has been done consistently throughout the text where appropriate

I do not fully understand the relevance of a composite signal based on individual, non-correlated signals. Can you please justify the robustness, or point the limit of such an approach? How confident are you that this reflects a common climate signal, rather than noise (and thus influenced by the number of underlying records)? Could you maybe consider principal component rather than mean to extract a signal which would explain the maximum variance, thus potentially more representative of a regional signal? - I do not think that you should make two composites based on standardised and non-standardized data. You should first try to explain why the individual signals are not correlated to decide then to consider standardised
or no standardised data. If it turns out that the spatial variability results from deposition and post-deposition effects, it will be more consistent to use standardised data. Otherwise, non-standardised data should be used. Note that in Stenni et al. (2017), we used standardised data. If your initial idea differs, please specify as it is not straightforward.

**Answer:** This is a fundamental and important point for every glaciological investigation and it became more common in recent years to test for depositional and post-depositional effects in order to assess the signal-to-noise ratio at a given site.

As also requested by Rev #2 and #3, we assessed the signal-to-noise ratios of the stable water isotope and accumulation data (compare answer to Rev #2 and #3). We estimate the signal-to-noise ratio of stable water isotopes in the UG region (of between 0.6 and 0.86) as quite high, i.e. higher than signal-to-noise ratios at WAIS, and even better than for Dronning Maud Land cores on interannual timescales (Münch and Laepple, 2018). A new chapter discussing signal-to-noise ratios at the study site has been added to the manuscript (Chapter 4.1, p 8).

In line with comments from Rev#2 and #3, we have decided to consistently use standardized data in order to give each firn core the same statistical value. This information has been added to the text. However, as $\delta^{18}O$ shows a statistically significant positive trend in the non-standardized data, which is not visible in the standardized data anymore, we kept this information to demonstrate the effect of standardization on $\delta^{18}O$ trends. As this is not relevant for $d$ excess and accumulation trends, we omitted the information about non-standardized data from the manuscript in this respect. Further arguments are given below in the more specific comments.


Results - Results of not significant linear relationships (slope and p-value) should not be given.

**Answer:** The manuscript has been changed accordingly.

A discussion of potential noise should be added.

**Answer:** We discuss potential noises in a newly added chapter: 4.1 Potential noises influencing UG firn core records (see answer above).

For deposition, why do not you compare your reconstructed BMS with stack data and the climate model you cite in the discussion (Part 4.2.1, p11 l1)?

**Answer:** We do not understand this comment as the sentence Rev #1 refers to already is a comparison of the average accumulation rate derived from our firn cores for the the UG region with accumulation rates from model simulations and stake measurements carried out for the same and/or close-by site(s). The individual time series (stake measurements) from Rivera et al. (2014) are unfortunately not freely available. Van den Broeke (2006) provide modeled accumulation rates for a period from 1980 to 2004 only, and no data for individual years is freely available that could be compared to our dataset.

For the effects of isotopic diffusion, you could apply a simple diffusion model (Johnsen et al., 2000;Jones et al., 2017), or at a least evaluate if there is a loss of seasonal dO18 amplitude along the core and report the corresponding results.

**Answer:** We are aware that diffusion can significantly change the seasonal $\delta^{18}O$ signal in firn and ice cores, but due to the comparably high accumulation in the UG region ranging between ~0.18 m w.eq.a$^{-1}$ (GUPA-1 and PASO-1) and ~0.29 m w.eq.a$^{-1}$ (SCH-2) diffusion likely plays only a minor role at this site. However, as suggested by Rev #1 we have calculated the diffusion lengths for the six firn cores as described by Münch and

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Laepple (2018) and Laepple et al. (2018). The meteorological data from the two AWS (air temperature and air pressure), measured surface densities and derived accumulation rates are used as input data. Accordingly, the diffusion length for the maximum depth of the firn cores (excluding GUPA-1) was determined to range between 7.2 cm (PASO-1) and 8.7 cm (DOTT-1) and is, thus much lower than the mean annual layer thickness of between 34.6 cm (PASO-1) and 59.7 cm (DOTT-1). We therefore assume diffusion to be of minor importance for inducing noise to the stable water isotope records of the UG cores. This information has been added to the manuscript (Chapters 2.4 and 4.1).


Discussion - I suggest to begin by discussing potential noises (see above), before discussing the potential common climatic signal. - I recommend to dedicate a paragraph to the assessment of the dO18-temperature relationship in this region and the comparison with other Antarctic regions. Also, I do not understand why you suggest to reconstruct regional temperature based on your dO18 composite record whereas \( r^2 = 0.21 \). Why explains the 80% variance left?

**Answer:** We gratefully acknowledge the commentary of Rev #1. We introduced a new chapter at the beginning of the discussion part (Chapter 4.1: Potential noises influencing UG firn core records). In line with the other reviewers comments we incorporated the signal-to-noise calculations in this new discussion chapter. We then continue with the temporal and spatial variability of the stable water isotope data and its relationship to meteorological data. In fact, we did (and do) not want to suggest that all isotopic changes are related to climate, but for assessing this, we first need to correlate near-surface air temperature (T) and δ-values. The correlation coefficient between T and δ\(^{18}\)O is rather low, correct, but statistically significant. Nonetheless, we reduced the emphasis on the interpretation of temperature variability in the whole manuscript.

I note a contradiction between p9 l15 and your conclusion, p11 l32

**Answer:** As we do not emphasize the temperature interpretation from the stable water isotope data anymore, this contradiction does not further exist.

The discussion of negative slopes from the reconstructed SMB appears surprising given the fact that slopes are in fact very close to 0.

**Answer:** See answer to specific comments below (p 17).

Specific comments

Introduction

P2 112: Can you please add a transition word so we understand that you move to Peninsula, eg “In AP. . .”.

**Answer:** Sentence changed to: “For the AP, time series of near-surface air temperature from weather stations (Vaughan et al., 2003; Turner et al., 2005a) as well as from stable water isotope records from ice cores (Thomas et al., 2009; Abram et al. 2011; Stenni et al., 2017) provide evidence of a significant warming over the last 100 years reaching more than 3°C since the 1950s.”

P2 115: The sentence is difficult to read, please reword it to: “Factors affecting mechanisms forcing”

**Answer:** Sentence reworded to “Factors affecting mechanisms that force ...”
P2 l23: The references “Thompson and Wallace 2000; Thompson and Solomon, 2002; Gillet et al., 2006” are repeated in line 25. Please remove the second call to these references.

**Answer:** Citations removed.

P2 l28: I checked Turner et al., Intern. J of Climatology, 2013, surprised by your assertion that the positive SAM values from the 50s are partly attributed to “local confined sea-ice loss”. However, I found only a suggestion that the decrease in sea-ice extension (SIE) in AP could be linked to SAM (and not the opposite). Besides, Turner et al, Nature, 2016 shows that the changes in circulation lead to a decrease in the sea ice concentration in AP (see Fig 3). Only for the two last decades, for which a shift in circulation occurred (shifting warming in AP to cooling), a positive retroaction has been noted between the increase in SIE and changes in circulation. I suggest a careful introduction to the links between regional sea ice changes and circulation changes.

**Answer:** As our interpretation with SAM in the discussion part is very short, we decided not to mention the connection between SAM and sea ice in the introduction, and omitted the part of the sentence about the “local confined sea-ice loss”.

P2 l34: ENSO is a mode that has a specific pseudo-periodic behaviour, I thus suppose you meant “mode” instead of “cycle”.

**Answer:** “cycle” changed to “mode”.

P2 l34: Please add a comma after “scales”.

**Answer:** Comma added.

P2 l15 – P3 l3: You refer to near-surface temperature positive trends of the last decades in WAIS (1st paragraph) and AP (2nd paragraph) since the 1950s, and discuss the state-of-the-art of understanding potential causes. If you want to present your drilling site as a crossing area between WAIS, EAIS and AP, you should also write a third paragraph browsing a short state-of-the-art of recent climate variability of EAIS, citing for instance Stenni et al. (2017) (last 2k temperature reconstruction of Antarctica), and emphasizing the challenge to detect any trend. Note that even a weak cooling trend is not seen in some coastal areas such as the Adelie Land (Goursaud et al., 2017 and references herein).

**Answer:** We acknowledge this commentary and added a third paragraph about EAIS in the Introduction. We also wrote a summary paragraph about the challenges to detect trends in climate variables for Antarctica.

P3 l4: Your transition in unclear. You describe changes in trends in AP temperature associated with a cooling for the first part of the 21st century, the WAIS warming amplitude being part of the natural multi-decadal variability of last 2000 years (308 in the Thomas’ study, and 2000 in the Steig’s one), but also the weak cooling in the EAIS.

I think that you rather give the limits of the comprehension of the very last decades climate variability at the end of the last three paragraphs, i.e. tackle with the WAIS warming in your paragraph from P2 l29. But please when giving this information, stress that it is the rapidity of this warming which is unprecedented. Then, introducing the need for extended observations and monitoring in Antarctica, just give a short sentence to resume the limits of our comprehension of the recent climatic variability, whatever the considered Antarctic region.
**Answer:** As mentioned above we completely restructured the introduction considering all suggestions made by Rev #1. We stressed that the rapidity of the warming for both, the AP and the WAIS, is unprecedented and not the warming itself. We wrote a summary paragraph about the limits of the comprehension of the last decade’s climate variability in all three regions (see above). We have the impression that the manuscript gained in clearness due to the proposed restructuring of the introduction. It also became slightly longer, which contrasts with Rev #2, who proposed to condense the introduction.

P3 l11: There is a lack of data not only for the interior of Antarctica, but also for coastal areas, for instance in the Indian Ocean coastal region and in Adelie Land. You can refer to Jones et al. (2016) for the temperature, and the updated water stable isotope Antarctic database (Goursaud et al., 2018b).

**Answer:** We decided to change the text to “for most of Antarctica” instead of referring the the Antarctic interior only.

P3 l3: From “For the region”, please add a new paragraph, where you focus on this crossing point between the three main regions of Antarctica. In this paragraph, please be more explicit on the questions that you address in this study. I also recommend to report the fundamental literature related to the climate of Ellsworth region.

**Answer:** The state of the art of the selected region, i.e. the UG region, at the intersection between WAIS, EAIS and AP is given in the text of the introduction chapter. There is no additional proxy data or meteorological data for the wider study region available and that is why we think that our dataset is unique. The knowledge about the greater region, i.e. the Weddel Sea sector has been added to the respective paragraphs in the introduction. The introduction chapter finalizes with the key research questions that we wish to address in the manuscript.

P4 l1: change “WAIS in the south” to “southern WAIS”.

**Answer:** Sentence changed to “Do the UG region and surrounding areas experience the same strong and rapid air temperature and accumulation increases as observed for the neighbouring AP and WAIS and, if yes, to what extent?”

2 Data and Methodology

2.1 P4 l9: I cannot find neither in the paragraph nor in the Table 1 the ray in which the drilling sites are located. Could you please add it here? I would be also very interested in knowing here which sites are in crests or peaks, as surface mass balance should differ between these sites (Agosta et al., 2018), as well as the isotopic signature, at least at the second order.

**Answer:** This is in line with Rev #2, hence we added the information about the site-specific characteristics to the text (Chapter 2.1, p 4).

p4 l15: Please add a comma after“(2012)”.

**Answer:** Comma added.

P4 l19, P4 l25: Please add a space between numbers and units throughout the manuscript.

**Answer:** Spaces added.
P24 l4: How can you quantify that the precision is better than a specific threshold. Please give a precise uncertainty.

**Answer:** The precision was determined by calculating the mean standard deviation of all standards used in the measurements of the firn cores. These are the precisions given in the manuscript. “better than” has been deleted.

P5 l9: I understand that you compute a local meteoric water line based on ice core data, and especially only 6 points, which can be affected by deposition and post-deposition effects.

**Answer:** Yes. As stated in the manuscript, there are no precipitation samples from the study site available and thus no data on the stable water isotope composition of recent precipitation exists. Hence, we used the stable water isotope data (seasonal means) of the six firn cores for computing a LMWL (2348 data points), see Figure 5.

2.2 P5 l13: which ratio did you use to compute nssSO4? Did you use summer or winter ratio (Jourdain and Legrand, 2002)?

**Answer:** Values of nssS have been calculated from ssNa-concentrations and S/Na-ratios in seawater, respectively, using the following equation with relative abundances from Bowen (1979):

\[
nssS = S - ssNa \times (S/Na)_{seawater}
\]

Values of ssNa were calculated according to Röthlisberger et al. (2002) using relative abundances from Bowen (1979). This information has been added to the new manuscript. Seasonal differences have not been taken into account as our manuscript does not deal with nssS chemistry, but uses this information for dating only.


P5 l15: Please provide references for the seasonality of the aerosol signals preferentially for your region. For instance, in Adelie Land, there is no seasonal cycle in ssNa, so please check. You can also cite recent studies which apply such an annual layer counting to date firm ice cores and discuss the uncertainties (Vega et al., 2016; Caiazzo et al., 2016).

**Answer:** In line with the comment above, we use the seasonally changing parameters H2O2, nssS and stable water isotopes for dating only. Accordingly, the dating sequence is: annual layer counting using H2O2 (as directly connected to insolation, i.e. to the atmosphere) or nssS (as directly related to marine biogenic activity and eventually sporadic volcanic inputs) from chemical analysis, and stable water isotopes (as temperature proxy). The other chemical parameters mentioned in the manuscript – MSA, Cl/Na, SO4²⁻, nssS/ssNa - are used for confirmation only and not directly for the dating, i.e. the annual layer counting itself. The dating chapter in the manuscript has been re-written including additional references, in order to make the dating procedure more clear. However, as our study presents first firm core data for the UG region, including data on chemical parameters, no references for the seasonality of aerosol signals in the UG region are available.
P5 118: How did you estimate your uncertainty? I would have liked to see on the figures 1 and 2 what constitutes this age scale uncertainty (e.g. peaks that you did not count).

**Answer:** As already explained above we estimate that the error associated to ALC is ±1 year for cores dated with glacio-chemistry (SCH-2 and PASO-1) and ±2 years for the cores that were dated with stable water isotopes only and matched to the chemistry-based age scale of SCH-2 (GUPA-1, DOTT-1, SCH-1 and BAL-1). This information has been included to the text (Chapter 3.2). In Figures 2 and 3 maxima in the individual firn-core stable water isotope and chemistry records that have been included in the ALC fall on dashed lines (i.e. due to the $H_2O_2$ [SCH-2] or nss$^5$ [PASO-1] ALC assumed to be of higher significance; further details see below). This information has been added to the Figure captions of Figures 2 and 3.

P5 117: I do not fully understand the rationale behind the method used to match GUPA, DOTT, SCH-1 and BAL-1 dating to SCH-2: are the isotope records highly correlated, justifying such a method? (what is the implicit hypothesis and can you test it)?

**Answer:** We do not fully understand this commentary. We have two well-dated firn cores (independently dated through chemistry and stable water isotopes, SCH-2 and PASO-1). We use wiggle matching to match the other firn cores dated by ALC of stable water isotopes only to these better chronologies (see answer to previous comments above). For this purpose we used prominent minima and maxima in stable water isotopes (as visualized in Fig. 7 of the manuscript). Furthermore, for ALC we counted a minimum and maximum number of stable water isotopes peaks in all firn cores which brackets the age range for each firn core (see Table 1 above). SCH-1 and SCH-2 are situated nearby in the same valley at a altitudinal distance of ca. 250 m and are highly correlated in $\delta D$ and $\delta^{18}O$ (see statistical assessment between individual cores for isotopes and accumulation rates in Tables S6 and S7 in the supplements). Similar correlations are observed between SCH-2 with GUPA-1 and DOTT-1 despite their greater distance and different site-specific characteristics. GUPA-1 is being dealt with caution due to its proximity to the landing strip and has been excluded for statistical evaluations in the discussion. Hence the only critical core in this respect is the BAL-1, (fimn core in the neighbouring valley at a same altitude than SCH-2) which shows a very smooth isotope record in the lower part. We have nonetheless confidence in this core down to 1991 (see Fig. 7) as prominent minima and maxima are both visible in SCH-2 and BAL-1.

P5 124: Why did you use non-standardized data for composites? Please take into consideration the general comments.

**Answer:** This is in line with comments of Rev #2 and #3. We have decided to consistently use standardized data throughout the study in order to give each firn core the same statistical weight. This information has been added to the text. However, as $\delta^{18}O$ shows a statistically significant positive trend in the non-standardized data, which is not visible in the standardized data anymore, we kept this information to demonstrate the effect of standardization on $\delta^{18}O$ trends. As this is not relevant for $d$ excess and accumulation trends, we omitted the information about non-standardized data from the manuscript.

Why did you use the Mann-Kendall tests? It is usually used to detect inflections. Is it the case here? Please justify.

**Answer:** For the study site no inflections are present in the time series. Turner et al. (2016) use a sequential Mann-Kendall test, whereas we use a Mann-Kendall Tau and Sen slope estimator trend test. As in our study, the latter was also used by Turner et al. (2016) to estimate the statistical significance of linear trends. The Mann–Kendall Tau and Sen slope estimator trend test is commonly employed to detect linear and non-linear trends in time series of environmental, climate or hydrological data with its power and significance being independent of the actual distribution of the input data (Hamed, 2008). This means, that the input data, in our
case stable water isotope and accumulation data of firn cores, does not necessarily need to be normally
distributed and the test is not very sensitive to abrupt breaks caused by inhomogeneities in the analysed time
series. Hence, we believe that the Mann-Kendall trend test is the appropriate test to use as it is more
conservative than simple linear regression.

Hamed, K.H.: Trend detection in hydrologic data: The Mann-Kendall trend test under the scaling hypothesis,

2.3 P6 l4: please add a line break after “isotopes and accumulation.” to split observations from climatic modes.

Answer: Line break added.

Results

3.1 P6 l24: what initial point (coordinates and height) did you indicate for back trajectory simulations? Which
drilling site does it correspond to?

Answer: For the recalculation of backward trajectories – now 5 day- instead of 3 day-trajectories – we used
the coordinates of the drill site of firn core SCH-1, that is located at the ice divide between the glaciers
Schneider and Schanz (see Fig. 1b in the manuscript) as starting point. This location was selected, as it is less
influenced by post-depositional processes as well as shows little snow-drift and snow-redistribution, and is
therefore among all available firn-core drill sites the most representative for snow-fall events in the UG region.
The information is included in the revised version of the manuscript.

P6 l29 and P7 l1: change “was” to “is”.

Answer: “was” changed to “is”.

P7 l1: you choose in the manuscript the convention m we a-l for accumulation, so please change “m/s” to “m
s-1”. Also please change “was” to “is”.

Answer: “m/s” changed to ms⁻¹. “was” changed to “is”.

3.2 P7 l8: “the longest record”

Answer: “l” added (compare RC3).

P7 l11: What kind of extrapolation did you apply?

Answer: A linear extrapolation was applied using the linear depth–age–relationship between the previous two
clearly identifiable peaks (years 1987 and 1988). The explanation has been added in the manuscript.

P7 l11: please replace “furthermore” by another word as repeated from previous sentence. Could you give the
uncertainties associated with your dating for each firn core at the end of this paragraph? It is actually results
and not methods.

Answer: “Furthermore” deleted without replacement because it is unnecessary.
The revised sentence “The estimated error associated to ALC is ±1 year for cores dated with glacio-chemistry (SCH-2 and PASO-1) and ± 2 years for cores dated with stable water isotopes only (GUPA-1, DOTT-1, SCH-1 and BAL-1),” was moved from chapter 2.3 to chapter 3.2.

3.3 p7 l16: As you give the DO18 mean range, I do not think it is necessary to also give dD. I would also rather go for mean and standard deviation, which give more information about the variability.

**Answer:** Mean range for δD deleted and standard deviations for δ18O added in the text.

P7 l21: These values are not so low. If you refer to Figure 6 in Goursaud et al. (2018a), that shows the spatial variability of d, you will notice that d can reach minimum values of 0 to 4 per mille in Ross sea, and Amery sector, but also close in the Ellsworth sector!

**Answer:** We argue here that the range of mean d excess values is small among the firm cores as the difference between the firm core with the lowest and the highest mean d excess value is only 2.1 ‰. We do not state that the d excess values in general are low as we also find single d excess values in the cores that are < 0‰ (see minimum d excess values for each core in Table 1).

P7 l25: Please change into the brackets to “range values from . . . to...”.

**Answer:** “range” changed to “values range from ... to ...” in the brackets.

I am not convinced by the method used to estimate the LMWL obtained based on ice core data.

**Answer:** We explained in Chapter 2.1 of the old manuscript that unfortunately no fresh precipitation samples are available for the Union Glacier region. The study site is not manned year-round and therefore no continuous monitoring is possible. Hence, the only chance to derive co-isotopic relationships is with our firm-core data. We do that for individual cores (shifted to Supplement S3a-f) and for the composite (compare Figure 5) which yield similar co-isotopic slopes of between 7.94 and 8.24 (composite slope 8.02). For one other coastal site (near Neumayer station), firm cores of similar age yielded similar slopes as the local precipitation samples (Fernandoy et al., 2010). We believe that these co-isotopic relationships are, at first approximation, very similar to the LMWL at a given site. We therefore referred to the composite co-isotope relationship as LMWL (see Figure caption for Figure 5) knowing that LMWLs are originally based on monthly precipitation data. For clarification we added the information on individual firm cores’ co-isotopic relationships to the supplements (S3a-f).


P7 l27 to 30: there is a low spatial variability of your mean reconstructed SMB, and thus you could just give the mean and standard deviation of the SMB averages, instead of describing the core with the highest and lowest SMB. Details are then given in Table 1.

Then, your next message is substantial as you show that particular high (low) values are not concomitant between the firm cores.

**Answer:** The description of cores with highest and lowest mean accumulation rates was replaced by a description of mean values and standard deviations. The sentences “Highest mean accumulation rates (≥ 0.28 m w.eq.a⁻¹) were found for DOTT-1 and SCH-2, despite the site of SCH-2 being located further inland and at about 750 m higher altitude compared to DOTT-1 (Table 1 and Fig. 1b). Lowest mean accumulation occurs at the GUPA-1 and PASO-1 sites (~0.18 m w.eq.a⁻¹).” were replaced by “Mean accumulation rates vary
between ~0.18 m w.eq.a⁻¹ (GUPA-1 and PASO-1) and ~0.29 m w.eq.a⁻¹ (SCH-2) with the lowest standard deviations found at the DOTT-1 and PASO-1 sites (~0.05 m w.eq.a⁻¹) and the highest ones exhibited by cores SCH-2 and BAL-1 (~0.08 m w.eq.a⁻¹; Table 1)."

Discussion 4.1.1 p8 l15 and p8 l8: I do not see the point to report minimum and maximum values. What is your message from such information?

Answer: We omitted the reported minimum and maximum values and shifted this information to the Figure captions of Fig 7.

You could first discuss the differences in the mean δ18O values from one ice core to another noted in the results, and consistent as your write with continental effect. You could then discuss the lack of similarities in inter-annual variabilities (remaining results?), and confirming here by testing the correlation between the different δ18O over the overlapping time period 1998-2013. Here, you could write that 2002 is a maximum value in all firn core data.

Answer: We started this discussion chapter with the comparison of the stable water isotope composition of the individual firn cores (excluding GUPA-1) as suggested. We based the cross-correlations on the maximum overlapping period between two individual cores (as given in Table S6). We also computed the cross-correlations for the common overlapping period from 1999-2013, which yielded similar results (see Table S7). This information has been added to the manuscript. The information about a common maximum in 2002 has been placed where suggested.

There is some ambiguity on the structure of the manuscript, where some key results are reported in the discussion, and not in the section on results.

Answer: Section “At SCH–1, SCH-2 and BAL–1 accumulation decreased at a rate of ~0.002 m w.eq.a⁻¹ (p-value = 0.032), ~0.004 m w.eq.a⁻¹ (p-value < 0.0001) and ~0.003 m w.eq.a⁻¹ (p-value = 0.006), respectively. The decrease is highest at the DOTT–1 site, but not statistically significant (s = ~0.005 m w.eq.a⁻¹; p-value = 0.458). In contrast, accumulation exhibits a slight, albeit statistically significant increase at the PASO–1 site (s = ~0.001 m w.eq.a⁻¹; p-value = 0).” moved from chapter 4.2.1 to chapter 3.3 and reduced to “At SCH–1, SCH-2 and BAL–1 accumulation decreased at a rate of ~0.002 m w.eq.a⁻¹, ~0.004 m w.eq.a⁻¹ and ~0.003 m w.eq.a⁻¹ (p-values < 0.05), respectively. In contrast, accumulation exhibits a slight, albeit statistically significant increase at the PASO-1 site (s = ~0.001 m w.eq.a⁻¹, p-value < 0.05).”

Section “From time–series analysis of δ18O annual means (S5) statistically significant positive trends have been found for SCH–2 (s = +0.085 ‰ a⁻¹, p-value < 0.0001) and PASO–1 (s = +0.016 ‰ a⁻¹, p-value = 0.002), whereas for DOTT–1 (s = –0.110 ‰ a⁻¹, p-value = 0.015) and SCH–1 (s = –0.052 ‰ a⁻¹, p-value < 0.0001) the δ18O trend is negative. The BAL–1 δ18O record exhibits no trend.” moved from chapter 4.1.1 to chapter 3.3 and changed to “At SCH–1, SCH-2 and BAL–1 accumulation decreased at a rate of ~0.002 m w.eq.a⁻¹, ~0.004 m w.eq.a⁻¹ and ~0.003 m w.eq.a⁻¹ (p-values < 0.05), respectively. In contrast, accumulation exhibits a slight, albeit statistically significant increase at the PASO-1 site (s = ~0.001 m w.eq.a⁻¹, p-value < 0.05).”

P8 l114 to l116: relationships which are not significant, are useless. Please remove it. The two positive trends are results and not discussed here, so it should go to the “results” part.

Answer: Section “Time–series analysis of δ18O annual means (S3) reveals positive trends for SCH–1 (s = +0.039 ‰ a⁻¹) and BAL–1 (s = +0.054 ‰ a⁻¹), whereas for DOTT–1 (s = –0.071 ‰ a⁻¹), SCH–2 (s = –0.011 ‰ a⁻¹) and PASO–1 (s = –0.009 ‰ a⁻¹) the δ18O trend is negative. However, only the positive trends for SCH–1 and BAL–1 are statistically significant (α = 0.05, p-value < α; p-value (SCH–1) = 0.028; p-value (BAL–1) < 0.0001).” moved from chapter 4.1.1 to chapter 3.3 and reduced to “Time–series analysis of δ18O annual
means (S3) reveals statistically significant trends only for cores SCH-1 \((s = +0.039 \%{\text{a}^-1}, p\text{-value} < 0.05)\) and BAL-1 \((s = +0.054 \%{\text{a}^-1}, p\text{-value} < 0.05)\).”

P8 l17: I do not find that dO18 firn cores data are well correlated. Some are not correlated at all, eg PASO-1 with DOTT-1 etc., and the highest \(r\) is 0.658, ie \(r^2\) of 0.433, so I really would not go for a regional signal by a simple average of the time series. In the assessment of potential trends, the discussion should be explicit that only two of your firn cores present such trends (P8 l21).

**Answer:** see above. We believe that correlations are not too bad given all the uncertainties between the individual core sites (potential differences in local precipitation seasonality, redistribution due to wind drift etc.). We know that the data is neither spatially nor temporally equally distributed. However, we would not like to base our interpretation on a single firn core (where we always would have to deal with the spatial representability of this single core). We discuss the differences between individual cores. For instance, five out of six individual cores yield similar accumulation trends (except PASO-1). Moreover, all six cores show no clear trend in the \(\delta\)-values (either very low positive or negative), which allows for a general assumption, which would not be possible with one single core only. We interpret the individual cores first and then find similar patterns in the stack. We believe that this substantiates our approach to derive a stack to be more representative for the region.

P8 l22: Why did you prefer Sen slope rather than linear simulations?

**Answer:** The Sen slope estimator allows to determine the magnitude of the trend as the median of the slopes of all lines through pairs of two-dimensional sample points. It is more robust than the least-squares estimator due to its lesser sensitivity to outliers (Theil, 1950; Sen, 1968). Hence, we preferred to take the Sen slope estimator because it is the more conservative approach.


P8 l23: You cannot conclude an increase in near-surface temperature from a positive \(\delta^{18}O\) trend (which is I think not robust, see what I wrote before), whereas you did not test the multi-year dO18-T relationship in your region.

P8 l23 to l32: You discuss here the inter-annual variability in temperature. It should be in another paragraph dedicated to it, and using the results of dO18-temperature relationship you find in your data, and that should be cited in the results.

**Answer:** We restructured the related paragraphs and excluded any inference towards temperature change at UG based on firn-core stable water isotope data. Instead we put the UG firn-core stable water isotope data (not changing much) in the context of large-scale climate (also not changing much in the past 30 years except for WAIS).

P8 l33 – P9 l6: Is it Sen slopes of from linear regressions? If linear, please give the correlation coefficients for each simulated linear relationship. I am very surprised for such different trends. Either the relationships are very weak or trends can be neglected, or other effects than change in moisture origin might act here to explain the differences, as your drilling sites are relatively close to each other. Once more, I do not find it robust at all to make a mean for time series showing opposite trends, and where only two firn cores are correlated (DOTT-1 and SCH1).
**Answer:** Yes, Sen slopes have been used consistently throughout the manuscript. We agree that the time series do not show consistent trends in d excess as these relationships are weak. We reduced the discussion but left the information on the d excess (both individual and stack) for completeness. Even though the drilling sites are within 50 km horizontal distance (not too close actually), they are separated by orographic barriers, which might explain the dissimilarities in d excess/moistures sources. This information has been added to the text (Chapter 4.2.1, p 10).

4.1/2 This paragraph should come before discussing a potential temperature reconstruction.

**Answer:** We restructured both chapters and start with the spatial and temporal variability of stable water isotopes (Chapter 4.2.1 in the new manuscript), which are then related to near-surface air temperature changes (both instrumental and ERA-Interim data; Chapter 4.2.2 in the new manuscript). We conclude that the isotope-temperature relationship is weak and give reasons for this. A part of the δ¹⁸O variability is explained by near-surface air temperature though.

P9 112: You could compare near-surface temperature from the wx7 and Arigony AWS with ERA-interim. If the correlation is strong enough, you could test the linear relationship between dO18 and the near-surface temperature over longer period than for observations, thus using ERA-interim temperature. You could also test the relationship with each of your firn core. Have you considered that local processes could affect the signal, and could be more important at some locations?

**Answer:** This is in line with a comment of Rev #2 and Rev #3 and has been addressed in detail in the replies to the review of Rev #2. Please see below.

P9 115-16: You cannot use dO18 to reconstruct the temperature: the linear relationship is much too weak (l10), and this sentence is not consistent with l11: “However, a proper inference of near-surface temperature from dO18 values of precipitation in the UG region is not yet possible”.

**Answer:** We are grateful for this remark, which helped improving our argumentation further. As introduced above, we believe that the correlations are not too bad for six firn cores retrieved from distinctly different sampling locations each with individual site-specific characteristics. Moreover, we tested the signal-to-noise ratios for the single stable water isotope records (see discussion above), which revealed quite high values. Therefore, we believe that the generation of an isotope stack makes sense and a signal of regional significance can be extracted and then be correlated with the sea-ice extent.

4.1.3 This part is very interesting and show the potential of the isotopic signal to provide information about the Weddell Sea ice extent. It would be valuable to describe these results with due care, as they are based on composite analyses from individual series that are weakly correlated, challenging the confidence in a strong common climate signal. What is the likelihood of obtaining a link with sea ice extent using pure noise with a given frequency range?

**Answer:** We appreciate that Rev #1 recognizes the value of the sea ice extent – isotope connection. As introduced above, we believe that the correlations are not too bad for six firn cores retrieved from distinctly different sampling locations each with individual site-specific characteristics. Moreover, we tested the signal-to-noise ratios for the single stable water isotope records (see discussion above), which revealed quite high values. Therefore, we believe that the generation of an isotope stack makes sense and a signal of regional significance can be extracted and then be correlated with the sea-ice extent.

p10 15: why do you suggest this correlation to be an artefact? It is very weak (r = 0.315, ie r²= 0.0992!).

**Answer:** True. We omitted the word “artefact” in this context.
4.2.1 p10 l22: you do not need to give the precise value of p-values. Just write $p < 0.001$ or $p < 0.05$. Change throughout the manuscript.

**Answer:** p-values changed throughout the manuscript.

P10 l24: Remove the insignificant relationship for firn core DOTT-1.

**Answer:** Removed the sentence “The decrease is highest at the DOTT-1 site, but not statistically significant ($s = -0.005 \text{ m w.eq.a}^{-1}$; p-value = 0.458).”.

P10 l22-26: Deposition effects related to wind should be mentioned at the beginning of your study, as it can significantly modify your signal.

**Answer:** Done. We now refer to the effects related to wind already in the results, e.g. we added the following sentence to Chapter 3.1 (p 7): “... and imply the possibility of substantial redistribution of snow due to wind drift.”

P11 l2: Precise how far are the stake measurements from the firn cores, and the grid resolution of the model. What are the covered periods?

**Answer:** The required information has been added to the manuscript.

P11 l3: Can you also precise the location of Patriot Hills and the shortest distance between the closest ITASE ice core and your firn cores.

**Answer:** The required information has been added to the manuscript.

P11 l6: Could you compare the inter-annual from your firn cores with the stake measurements and model outputs? We have shown in our paper under review, the added value of such time series 1) to make the dating more robust, and 2) extract a regional signal.

**Answer:** The data from the stake measurement and the background data from the model runs from van den Broeke et al. (2006) are unfortunately not publicly available.

4.2.2 P11 l22: you suggest that ERA-interim fails to capture the effects of orography. You can show it by giving the surface height of the grid covering the drilling sites, while these ones differs from each other.

**Answer:** We are very thankful for this comment. As suggested we have extracted the elevation of the nearest ERA-Interim grid point for each firn core and now provide this information in Table 1. The elevations are [m asl.]:

DOTT-1: 641.5
GUPA-1: 911.3
SCH-1 and SCH-2: 1061.2
PAS-1 and BAL-1: 1208.4

The differences between the actual altitudes of the firn core drill sites and the elevations of the respective ERA-Interim grid points are quite significant (about 100 to 700 m) and therefore might provide evidence for the ERA-Interim model not capturing the local orography of the Ellsworth Mountains. This information has been added to the manuscript (Chapter 4.2.2).
You suggest also at the very end that your data could be affected by post-deposition effects. But couldn’t you test it, for instance by looking at the evolution of the seasonal amplitude along the cores (see again Goursaud et al., 2018b), or applying a proper diffusion model as done in Jones et al., J of Geoph. Research., 2017.

Answer: This comment has been answered above.

Conclusions

P12 l10: Remove the slope for non-standardized data.

Answer: Slope for non-standardized data removed.

Can you make the data available, either in supplementary material, on any public access depositary?

Answer: We added a link to public repository Pangaea, where the data will be uploaded after acceptance of the manuscript.

Figures and tables

Figure 1b: Names of the drilling sites are hardly readable (except GUPA-1 and DOTT-1).

Answer: The colouring and the font size of the names of the drilling sites have been changed to make them more readable.

Figure 2: What does “smooth 2p” correspond to? It is not specified in the legend or caption

Answer: Information added to figure captions. It is a 2 point running average.

Specify that depth is in water equivalent in unit (as well as for the following figures).

Answer: The depth is given in meters below surface not in water equivalent.

Figure 3: Why did you use nssSO4/ssNa? What does it correspond to? This is not explained in the paper.

Answer: We used the ratio nssS/ssNa for detecting signals of volcanic eruptions in order to use them as tie points for the dating of PASO-1. nssS can be either of marine biogenic or of volcanic origin, of which the former exhibits a seasonal cycle (phytoplankton). ssNa has only one seasonally changing source (sea salt). Hence, the ratio of nssS/ssNa gives clearer evidence of exceptionally high peaks of nssS that might point towards volcanic eruptions that superimpose the seasonal signal of marine biogenic activity. Furthermore, the questions of Rev #1 are in line with a comment of Rev #2 and have been also answered there.

How can you justify that you did not count peaks ~ 1.2 and ~5.2 m w.e.?

Answer: The small peak at 1.2 m is not found in the chemical parameters and has therefore not been counted as annual peak (location between two dashed lines; see answer to previous comment above). The large peak at 5.2 m has been counted (indicated by the dashed line). However, in general the maxima of the chemical parameters and the respective maximum of δ¹⁸O and δD, respectively, do not necessarily coincide due to the different seasonality of the proxies. This information has been added to the figure captions of Figures 2 and 3.
Figure 4: Monthly mean from Arigony AWS is hardly readable.

**Answer:** The legend of the figure has been enlarged and the colouring has been changed to make the Arigony AWS data more readable.

Figure 5: I suggest to move these figures to supplementary material.

**Answer:** We decided to leave the composite co-isotopic plot in the manuscript as it displays the Local Meteoric Water Line of the UG region. The co-isotopic plots of the individual firn cores were moved to the supplements as suggested (S3a-f).

Figure 6: for all figures displaying annual-scale data, can you draw it with cityscape vectors?

**Answer:** The figure is in line with the style of accumulation time series presented by Burgener et al. 2013 and to our understanding a question of personal preferences or gusto. We decided to leave the figure as it is.

Once more, slope is almost equal 0. Thus, the discussion of negative trends is not a robust finding.

**Answer:** The accumulation rates as deduced from Figure 6 are given in m w.eq. per year. This implies that a very low number for the Sen slope (e.g. -0.004 for SCH-2) corresponds to 4 mm w.eq. less accumulation per year and is thus in the same range as slopes given by Burgener et al. (2013) for central West Antarctica. Hence, we believe that the observed trends in accumulation rates at the different firn-core drill sites should still be reported in the manuscript.


Figure 7: Please remove the composite based on non-standardized data or standardised data, and use cityscape vectors.

**Answer:** We removed the composite records for non-standardized data for accumulation and d excess, but kept the one for δ18O as we think, that it is worth mentioning that it reveals a statistically significant positive trend. This has also been stated in the manuscript. Concerning the use of cityscape vectors see answer above (Figure 6).

Table 2: Periods for reconstruction are given in Table 1. Please move this table to supplementary material.

**Answer:** The total periods covered by each firn core are different than the periods given for accumulation rates as the latter are annual means and therefore refer to periods with only full years. However, Table 2 has been omitted and the respective information has been included into Table 1.
References


Interactive comment on “Stable water isotopes and accumulation rates in the Union Glacier region, West Antarctica over the last 35 years” by Kirstin Hoffmann et al.

M. Frezzotti (Referee)

Received and published: 19 November 2018

This manuscript provides a new stable records over the last 35 years of water isotope and snow accumulation from 6 firn cores of the Ellsworth Mountains area and ice rise on Filchner-Ronne Ice Shelf. The result of isotope and accumulation records are compared with re-analysis and large-scale modes of climate variability such as the Southern Annular Mode (SAM) and the El Niño–Southern Oscillation (ENSO) and sea ice extent.

The water isotope and snow accumulation records are very valuable because are representative of an area with very limited records. While I believe that this manuscript will make an important contribution for the characterisation of climatic history of this area, major comments should be addressed before its publication.

The title referred to Union Glacier is misleading, Ellsworth Mountains probably is more appropriate.

Answer: We included “Ellsworth Mountains” to the title.

The firn cores where collected in a complex area of about 400 km² at the boundary between WAIS plateau (PASO-1), Mountain glacier (BAL-1, SCH-1/2), outlet glacier/blue ice area (GUPA-1) and Ice rise on Filchner-Ronne Ice Shelf (DOTT-1). The Authors must be describing the site cores from morphological and climatological of point view and taking well in account their location/characteristic during the interpretation of the data, not only elevation and distance from the open sea determine the snow fall intensity and relative isotope compositions.

Answer: The description of the coring localities has been modified and several aspects (site-specific characteristics) have been included (Chapter 2.1 of the new manuscript). There is, however, no information on differences in local climatology between the sites available.

The storms that provide snow precipitation could be “similar” for all 6 cores, but the orographic effect on precipitation and the post depositional effect could be very different, as the records shown. Significant wind drift occurs at AWS with mean wind speed of 6.9 m-1, this agrees with the extensive presence of blue ice along Union Glacier, in particular for GUPA-1. At this site probably the anthropogenic effect is limited respect to wind scouring. The transportation by suspension (drift snow) starts at velocities greater than 5 m s-1 (within 2 m), and blowing snow (snow transportation higher than 2 m) starts at velocities of 7 m s-1.

Answer: We agree that wind drift is a major factor for redistribution of snow in the whole area, with a mean daily wind speed of ca. 7 m/s (max. 30 m/s), and we are convinced that there are differences between the sites. There are blue ice areas in the UG region, but these have not been sampled (e.g. GUPA-1 is a core in firm without contribution of any blue ice). We are grateful for the hint, but do not see any reason to revise our manuscript in this respect.
The authors compare the data without a clear analysis of the ratio between signal vs noise and their representativeness at local/regional scale (see ex RUPPER et al., 2015, Eisen et al., 2008)

**Answer:** This comment is in line with remarks by Rev #1 and #3. Please find answers in our responses to their reviews on how we addressed the signal-to-noise ratio problem.

The Authors must be provide firstly evidence of a correlation with the ERA re-analysis with meteo station and/or core records before looking at large scale modes such as SAM or ENSO.

**Answer:** This comment is in line with remarks by Rev #1 and #3. We combined ERA-Interim re-analysis and meteorological data. See answer to comment on Section 4.1.2 below.

The assumption of relationship between snow accumulation/isotope temperature with sea ice extent must be demonstrate in general.

**Answer:** The general interplay between snow accumulation, air temperatures and sea ice extent is obvious. The closer the open water, the more moisture may be generated and transported towards the continent and, thus, increase accumulation rates. Higher air temperatures will be responsible for more open water and warm air should transport more moisture than cold air. However, these simplistic considerations may turn out to be much more complex in specific settings, and may be obliterated by manifold processes such as wind drift, wind directions, moisture content of air masses etc. This general information has been added to the discussion in the new manuscript (Chapter 4.3.2).

*How the stable water isotopes fit into this system of moisture transport, precipitation, and redistribution is the topic of our study. According to a comment by Rev #1, we changed our conclusions regarding the inference of air temperature changes from stable water isotopes and, hence this part of the question has already been answered in the reply to the review of Rev #1.*

The $d$-excess is correlated to the moisture source region (sea ice) and distillation effect along the trajectory, instead the oxygen and deuterium rate are strictly correlated to snow precipitation temperature, their seasonality and frequency.

**Answer:** We agree, but do not see the need for changes in the manuscript in this respect.

The Authors compares the result mainly with the coastal part of WAIS (Amundsen and Bellingshausen Sea) and AP, with very small attention to the closer Filchner-Ronne Ice Shelf (Berkner island ex.), WAIS inner site (Kaspari, et al., Burgener et al.) and DML (Coats Land) with analogous moisture source area Weddell Sea.

**Answer:** Thanks for this comment. In general, there is very little data for these regions avaialble. We have incorporated this information in the discussion (in particular Chapters 4.2.1 and 4.3.1 of the new manuscript), where we compare our data to available evidence from these regions, including the WAIS (Kaspari et al., Burgener et al.), the Ronne-Filchner Ice Shelf (Graf et al.), Berkner Island (Mulvaney et al.), Coats Land and DML (Philippe et al., Medley et al.). In line with comments of Rev #1, we changed our introduction and compared the UG region with WAIS, AP and EAS. The reference to Burgener et al. has been added to the introduction and the discussion (Chapter 4.3.1).

The area is not a “coastal area”, open sea is around 1000 km far from Weddell Sea

**Answer:** This is true. The only time we used the term “coastal” is for core DOTT-1 to indicate that it is the firm core closest to the sea. We changed this to “closest to the sea” in the text.

Detail: Introduction too long, without a clear finalization of the paper.
Answer: This contradicts comments by Rev #1 who requested a more detailed introduction regarding the position of the study site at the intersection between EAIS, WAIS and AP (which needs more information on the main differences between these three Antarctic sectors). However, as both reviewers recommended a clearer defined scientific target, we restructured the introduction, which closes now with a section on the main scientific objectives of our study.

2.3 dating.

NO clear evidence of Pinatubo nssS signal in SCH-2 and PASO-1, value similar to other annual peaks (SCH-2) or much lower (PASO-1).

Answer: In the manuscript we only state that we have found a signal of Mt. Pinatubo in PASO-1. For the dating of SCH-2 Mt. Pinatubo could not be used as a tie point because we did not find it in the SO2- record. Identification of Mt. Pinatubo in the PASO-1 record took place via the comparison of the nssS- and nssS/ssNa-records (Fig. 3). nssS is primarily of marine biogenic origin (phytoplankton) exhibiting a clear seasonality with maxima occurring in late summer/early fall and minima occurring in winter. However, during volcanic eruptions nssS is excessively emitted into the atmosphere superimposing the seasonal cycle since atmospheric nssS-concentrations potentially stay at high levels throughout the year. Hence, regarding PASO-1 the coincidence of an above-average peak in the nssS/ssNa-record with a lacking winter minimum in the nssS-record at 9.5–9.7 m depth provide evidence for the presence of a signal of the Mt. Pinatubo eruption in the core. ALC of the respective nssS- and nssS/ssNa-peaks starting at 9.7 m depth (1991) towards the top of the core (2015) supports this hypothesis. Similar changes in wintertime nssS were observed in the well-dated PIG2010, DIV2010, and THW2010 cores from West Antarctica (Pasteris et al., 2014).

For clarification, the following information has been added to the manuscript:

“For the dating of PASO-1 the signal of the Mt. Pinatubo eruption (1991) could be found via the coincidence of an above-average peak in the nssS/ssNa (sea salt Na)–record with a lacking winter minimum in the nssS–record at 9.5–9.7 m depth (Fig. 3). Similar changes in wintertime nssS were observed in the well-dated ice cores PIG2010, DIV2010 and THW2010 from West Antarctica (Pasteris et al., 2014). Hence, the signal of the Mt. Pinatubo eruption was used as additional tie point for the age model construction of PASO-1.”


How has been composed and which is the grade of confidence of the time series at annual scale if the error associated to ALC vary from 1 yr (2 cores) to 2 years (4 cores) and without taking in account the ratio of signal/noise due to sastrugi? See Noise vs signal, 1985 snow accumulation at SCH-2 vs PASO-1 pag 7

Answer: We are certain that wind drift and redistribution of snow play an important role in the UG region. Generally, the only parameters helpful for assessing wind drift are the wind speed (i.e. > 5 m/s) and wind direction from the AWS. Unfortunately, there is AWS data only for one firm-core drill site available (GUPA-1) covering the period 2010-2018, only. Hence, there is no way to retrieve reliable information from the different firm-core drill sites, e.g. on wind taking up snow at PASO-1 and redistribution of snow by the predominantly south-westerly winds towards the lower altitudinal core sites in 1985 (SCH-2). Such processes are possible, but not supported by any data and would lead us to speculations which we tried to avoid.

Our error estimate of ±1 (chemistry-dated plus isotope-based ALC) to ±2 years (isotope-based ALC only) might have an impact on correlations and their statistical significance (as it was obvious from comparison with an earlier age model), but not on the overall trends. The signal-to-noise discussion has also been requested by Rev #1 and #3 and has been inserted to a newly included discussion chapter (Chapter 4.1).
Which is the cross correlation between the different cores for isotope and accumulation?

**Answer:** Cross-correlations are given in the supplements S6 (maximum overlapping period between two individual firn cores) and S7 (common overlapping period, 1999-2013).

2.4 Which is the difference between the two AWS station? show both data in figure 4

**Answer:** Actually we display the data of both AWS in Figure 4 including the overlapping period, but the differences between the two are simply not visible as the records are nearly identical. No change needed here.

Which threshold of snow precipitation is used from ERA Interim for HYSLPIT? Why the analysis is performed only 4 years from 2010 to 2014?

**Answer:** The $d$ excess records (individual firn cores and UG $d$ excess-stack) show no significant trends or changes at least during the last four decades. This means that most likely the moisture sources and transport pathways for the UG region have not been subject to significant shifts during that period, which would require or justify HYSLPIT backward trajectory calculations further back in time. Thus, we believe that the HYSLPIT calculations have the highest reliability for the period where we have meteorological data overlapping with firn-core data (2010-2015). Moreover, we use this data to characterize the site rather than interpreting temporal differences. We used a minimum threshold corresponding to 1% of the annual accumulation (i.e. ~2.5 mm $d^{-1}$) for the calculations, a quantity which is percentually equivalent to the one used by Thomas & Bracegirdle (2009). This information has also been added to the manuscript.


3.3 SCH-2/1 and BAL-1 are within 10 km and show similar accumulation, the comments about higher and lower accumulation should be addressed for these sites also at annual scale or better a pluriannual (e.g. 3 years), to see the ratio signal/noise.

**Answer:** We have calculated the signal-to-noise ratios based on $\delta^{18}O$ time series for all six cores (0.66) and for five cores excluding GUPA-1 (0.60). When referring to the overlapping period (1999-2013) these are 0.72 for all six cores and 0.78 for five cores excluding GUPA-1. In line with the comments of the other reviewers we included this information to the text. We estimate the signal-to-noise ratio in the UG region as quite high (i.e. comparable to signal-to-noise ratios at WAIS). The signal-to-noise ratio is similar when referring to the three neighbouring cores only (BAL-1, SCH-1 and SCH-2) and yields 0.60 for the entire cores and 0.86 for the overlapping period (1999-2013), even though BAL-1 shows relatively low correlation with all other cores (excluding SCH-1; r=0.44).

We have also calculated the signal-to-noise ratios based on accumulation time series for all six cores (0.23) and for five cores excluding GUPA-1 (0.29). Compared to the signal-to-noise ratios for stable water isotopes they are very low, probably reflecting the strong influence of the site-specific characteristics on accumulation rates (e.g. the different exposure to wind drift). When referring to the overlapping period (1999-2013) the signal-to-noise ratios do not improve: They are 0.10 for all six cores and 0.32 for five cores excluding GUPA-1. However, the signal-to-noise ratio is significantly higher when only referring to the three neighbouring cores BAL-1, SCH-1 and SCH-2 or even just to SCH-1 and SCH-2, which were retrieved from the same valley, and yields 0.79 and 1.67, respectively when referring to the entire core records. This might be due to the proximity of their drill sites (within 10 km distance) and the similarity between the site-specific characteristics of the three cores, i.e. the location in northwest-southeast oriented, U-shaped glacial valleys, leading to similar accumulation patterns. However, when referring to the overlapping period the signal-to-noise ratio stays at a low value of 0.24 for the three cores, but is still high for SCH-1 and SCH-2 (1.2). In line with the comments of the other reviewers we included all information on signal-to-noise calculations to the text (Chapter 4.1).
SCH-2 is isotopic “less depleted” than SCH1 with 250 m of difference in elevation and BAL-1 at the same elevation, PASO1 presents a similar isotope mean with Bal1 with 400 m of difference in elevation. GUPA-1 is “more depleted” than SCH-1/SCH2 with a difference in elevation of 500-800 m. Before any consideration in discussion about the isotope and accumulation some comments must be addressed on these difference and their significant, also in comparison with the other core sites in different geographical position and much far.

**Answer:** We agree with Rev #2 that the isotope-altitude relationship is not straightforward. When plotting for all six firn cores mean δ¹⁸O versus altitude plots, we achieve a rather low coefficient of determination of $R^2 = 0.38$ (p-value = 0.191; Fig. 1 below). However, when excluding GUPA-1, which shows very low δ¹⁸O for the height of its coring position, the δ¹⁸O-altitude-relationship becomes statistically significant and the coefficient of determination increases substantially and yields: height = $-142 \times \delta^{18}O – 3477$, $R^2 = 0.81$, p-value = 0.036. This corroborates our decision to exclude GUPA-1 from statistical analysis. When referring to the overlapping period (1999-2013), that actually makes the cores more comparable among each other, similar results are obtained (Fig. 2 below). We included the information for the overlapping period to the manuscript.

**Figure 1:** Relation between mean stable water oxygen composition and altitude for the UG firn cores considering all six cores (blue) and excluding GUPA-1 (orange), respectively. The equation, the coefficient of determination ($R^2$) and the p-value are given for both linear regressions.
Figure 2: Relation between mean annual stable water oxygen composition and altitude for the UG firn cores considering all six cores (blue) and excluding GUPA-1 (orange), respectively, referring to the overlapping period (1999-2013). The equation, the coefficient of determination (R²) and the p-value are given for both linear regressions.

4.1.2 Line17-21, Is ERA-Interim or the staked records that are not able to capture the Climate of Ellsworth Mountain? ERA-interim should be firstly compared with AWS data and than with firn records. Isotope and snow accumulation represent the snow fall events plus the noise due to post-deposition process, the absence of correlation with ERA-Interim must be better analysed also in comparison with AWS.

Answer: This is in line with comments of Rev #1 and #3. We did this exercise and compared the available meteorological data from the two AWS (near-surface air temperature) with the ERA-Interim data for the period February 2010 - November 2015 (overlapping period between AWS record and firn cores). We used ERA-Interim near-surface air temperatures extracted for the GUPA-1 drill site as this is the firn core site closest to the two AWS. Monthly mean air temperatures from both datasets are highly and statistically significantly correlated (R² = 0.99, p-value = 0; Fig. 3 below) and show the same variability. This information has been added to the text (Chapter 4.2.2 in the new manuscript).

As the two AWS are placed at a lower altitude (at approx. 700 m asl., near GUPA-1) compared to the nearest grid point of the ERA-Interim model (911 m asl.; see Table 1 in the manuscript and answer to Rev #1 above), the ERA-Interim data must display lower overall monthly mean air temperatures (due to the lapse rate; see Fig. 3: on average about 5°C lower). With respect to the firn core records that do capture a local climate signal obliterated by post-depositional processes the same issue arises. The mean height of all six firn cores is 1289 m and thus almost 600 m higher than the location of the AWS whose near-surface air temperature we correlate with the UG δ¹⁸O-stack (see Chapter 4.2.2 in the new manuscript). Furthermore, the differences between the actual altitudes of the firn-core drill sites and the elevations of the respective nearest ERA-Interim grid points are large, ranging from about 100 m (DOTT-1) up to 700 m (PASO-1) (see Table 1 in the new manuscript). Hence, this might be responsible for the absence of a correlation between UG stable water
isotopes and ERA–Interim based near–surface air temperatures as the ERA–Interim model does not capture the local orography of the study region well. This information has been also added to the text (Chapter 4.2.2).

4.2.1

PASO-1 presents an accumulation from 37 to 27% less than SCH1/2 and BAL1.

No sense the average value of 0.25 weq a-l and their comparison with other measurements at hundred km far.

**Answer:** We agree that the accumulation is different at the different firn core sites, which is obvious as increasing distance from the ocean and increasing altitude induces a decrease in the level of moisture in the air. We first present accumulation rates for all firn core sites (Chapter 3.3 in the new manuscript). Since these vary from 0.18 to 0.29 m w.eq. a⁻¹, we found these values similar enough to draw conclusions on a larger region, i.e. to calculate an average accumulation rate for the UG region. Therefore, we kept this information in the text.

Line 7-9 These data must be compared with the closer site of inner WAIS, Filchner- Ronne Ice Shelf and DML (Coats Land) instead of AP and Coastal Ellsworth Land with difference moisture source.

**Answer:** As already answered above, there is generally very little data for these regions available. We compared our data to the nearest data on accumulation rates available to us (Chapter 4.3.1), including UG itself (Rivera et al.), Patriot Hills (Casassa et al.) and the closest ITASE ice-core site (Kaspari et al.). In the new manuscript we also included data on the Ronne-Filchner Ice Shelf (Graf et al.) and Dronning Maud Land (e.g. Schlosser et al., Medley et al.).
Interactive comment on “Stable water isotopes and accumulation rates in the Union Glacier region, West Antarctica over the last 35 years” by Kirstin Hoffmann et al.

Anonymous Referee #3

Received and published: 2 December 2018

This manuscript presents a new dataset of stable water isotopes and accumulation rates from firn cores in the Ellsworth mountains at the northern edge of the West Antarctic Ice Sheet for the period 1980 – 2014. As measurements at the intersection between the Antarctic peninsula, the West Antarctic Ice Sheet and the East Antarctic Ice Sheet are particularly sparse, this new dataset is an important contribution toward a better understanding of climate variability in this region. I see the value of the manuscript therefore primarily in the publication of this dataset, while the accompanying meteorological analysis is limited. This is acceptable, as the dataset itself deserves a publication, but I recommend minor revisions before final publication.

Answer: We thank Rev #3 for acknowledging the value of the manuscript.

General comments

The drilling and measuring process is nicely explained, but I miss details on the trajectory analysis. Where did you start the trajectories from (lat/lon/lev), and how many per precipitation event (I hope more than one)? Also three days might not be enough, and the origin of the trajectories does not always reflect where the moisture comes from, because some trajectories could be very dry and not contribute to precipitation at all. I suggest using the moisture source diagnostic from Sodemann et al. (2008), which is also based on backward trajectories, but specifically identifies moisture uptake regions.

Answer: The backward trajectory analyses starts from the position of firn core SCH-1, which is located at the Schneider-Schanz glaciers divide. The coordinates are given in Table 1 of the manuscript. This information has now been added to the new version of the paper. Regarding the number of days considered, we computed 5-day trajectories for this new version and checked if these are in line with the 3-day trajectories. Both calculations show similar results, but 5-day trajectories provide a better picture of the moisture transport and therefore we will show only these in the new version of the paper. To select precipitation events we use a slightly modified procedure as proposed by Thomas and Bracegirdle (2009). Differently to them we considered 2.5 mm d⁻¹ instead of 10 mm d⁻¹, in our case representing 1% of the total annual accumulation, which will discard events lower than the actual isotope resolution of the SCH-1 core analysis. We appreciate the hint to use more sophisticated trajectory models which include moisture uptake diagnostics. As this is not the main focus of this first manuscript about UG firn cores, we would like to stick to our approach which sufficiently allows for identification of potential moisture source regions. As the variation in d excess is rather small, we do not expect major shifts in moisture source and uptake regions, which would favor a more sophisticated diagnostics.

Referring to the lack of correlation between the firn core data set and local ERA-Interim data, you speculate that either the model is unable to capture the orography of the Ellsworth mountains or this is evidence of post-depositional processes at the firn core sites. You could get a better idea which of the two is the case by correlating local ERA-Interim data with the two weather stations near the firn core sites.


Answer: This is in line with comments of Rev #1 and #2 and has been answered in the replies to the review of Rev #2. Please see above.
Looking at Table 3 and the discussion, there are barely any significant correlations between the isotope signal / accumulation rates and the other variables, meaning that there must be other factors influencing their variability. It would be nice to have some discussion on what these factors could be.

**Answer:** We are grateful for this comment as this helps sharpening our interpretation and drawing substantial conclusions. As requested by Rev #1 and #2, we assessed the signal-to-noise ratios of our stable water isotope and accumulation data (compare answer to Rev #1 and #2). We estimate the signal-to-noise ratios for stable water isotopes in the UG region (of between 0.6 and 0.86) as quite high, i.e. higher than signal-to-noise ratios at WAIS, and much better than for Dronning Maud Land cores on interannual timescales (Münch and Laepple, 2018). The signal-to-noise ratios calculated for the accumulation records (ranging between 0.10 and 1.7) most likely reflect the strong influence of the site-specific characteristics on accumulation rates (e.g. the different exposure to wind drift), as they are very low when considering all cores but significantly increase when referring to cores from close-by and similar drill sites (BAL-1, SCH-1 and SCH-2). This has already been explained above.

The UG firn cores are characterized by local differences (plateau vs. valley position, altitude, slope, ...). Hence, we tried to generate a regionally representative picture by combining the firn cores to a stacked record (minimum 3 cores/year). Nonetheless, the correlations with well known large-scale climate drivers such as SAM, ENSO, SIE are low. Therefore, we state in the revised version of the manuscript that either our stack is not regionally representative or not visibly linked with these drivers.


Specific comments

Page 5, line 23: Please explain the terms standardized and non-standardized, and why you use both (why not only standardized).

**Answer:** In line with comments of Rev#1 and #2, we have decided to consistently use standardized data throughout the text in order to give each firn core the same statistical weight. This information has been added to the text. However, as δ¹⁸O shows a statistically significant positive trend in the non-standardized data, which is not visible in the standardized data anymore, we kept this information to demonstrate the effect of standardization on δ¹⁸O trends. As this is not relevant for d excess and accumulation trends, we omitted the information about non-standardized data from the manuscript.

Standardization has been done using the following equation (not included in the new manuscript):

\[ z = \frac{x - \mu}{\sigma} \]

where \( x \) is the raw value, \( z \) the standardized value, \( \mu \) the mean value and \( \sigma \) the standard deviation of the respective firn core record.

Page 5, line 28: Introduce abbreviation AWS

**Answer:** Abbreviation introduced.

Page 7, line 8: “t” missing in “the”.

**Answer:** Missing “t” added.

Page 7, line 23: Could you explain what you mean by that? Meteoric as opposed to what?
**Answer:** We omitted the term meteoric in the sentence. We wanted to say that the original (oceanic) moisture source signal is preserved.

Page 9, line 29: Fig. 9b instead of 9c.

**Answer:** 9c changed to 9b.

Page 9, line 32: “a significant correlation” instead of “a correlation”.

**Answer:** “a correlation” changed to “a significant correlation”.

Page 11, line 20: Fig. 9c instead of 9b.

**Answer:** Fig. 9b changed to Fig. 9c.

Page 11, line 21: “Similar results have been found” instead of “Similar has been found”.

**Answer:** “Similar has been found” changed to “Similar results have been found”.

Page 12, line 14: Delete “are”.

**Answer:** “are” deleted.

Fig. 5: For completeness, please explain what the red dashed line and the dots show.

**Answer:** The red dashed line gives the correlation and the dots the individual measured samples. This information has been added to the figure captions.

Fig. 6 and 7: Since the timeseries all have the same units, it might be possible to show them all in one plot (with one y axis) using different colors for the different sites. In this way it would be easier to compare them.

**Answer:** Especially Fig. 6 is quite busy already. This is the reason why we do not display all individual cores in one plot as the differences would not be visible anymore. As we decided to do so for Fig. 6, we would – for consistency reasons - also leave Fig. 7 unchanged.

Fig. 10: Please add numbers to the colorbar. Why the irregular spacing?

**Answer:** We have replaced the old Figure 10 by two new ones (Figure 10 and 11). In these two figures, the problem with the colorbar and the spacing has been solved differently.

Table 1: Why only δ¹⁸O for the period covered by all cores?

**Answer:** We have used only δ¹⁸O for the period covered by all cores because we used only this proxy for determining the altitudinal gradient from low-altitude, coastal to high-altitude firm cores.

References

Stable water isotopes and accumulation rates in the Union Glacier region, **Ellsworth Mountains**, West Antarctica over the last 35 years

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Abstract

West Antarctica is well known as a region that may be highly susceptible to atmospheric and oceanic warming. However, due to the lack of long-term and in situ meteorological observations little is known about the magnitude of the warming and the meteorological conditions in the region at the intersection between the Antarctic Peninsula (AP), the West Antarctic Ice Sheet (WAIS) and the East Antarctic Ice Sheet (EAIS). Here we present new stable water isotope data (δ18O, δD, d excess) and accumulation rates from firn cores in the Union Glacier (UG) region, located in the Ellsworth Mountains at the northern edge of the WAIS. The firn core stable oxygen isotope and the d excess composition reveals no statistically significant trend for the period 1980-2014 suggesting that regional changes in near-surface air temperature and moisture source variability have been small during the last 35 years. As for stable oxygen isotopes no statistically significant trend has been found for the d excess suggesting overall little change in the main moisture sources and the origin of precipitating air masses for the UG region at least since 1980. Backward trajectory modelling revealed the Weddell Sea sector and Coats Land and DML-Dronning Maud Land sectors to be the likely main moisture source regions for the study site throughout the year. We found that mean annual δ-values in the UG region are correlated with sea ice concentrations (SIC) in the northern Weddell Sea, but not strongly influenced by large-scale modes of climate variability such as the Southern Annular Mode (SAM) and the El Niño-Southern Oscillation (ENSO). Only mean annual d excess values show a weak, positive correlation with the SAM.

On average annual snow accumulation in the UG region amounts to about 0.25±0.02 m w.eq. a−1 between in 1980-2014, and 0.30±0.03 m w.eq. a−1 before in 1980-2014. Mean annual snow accumulation has slightly decreased during this period. It is since 1980 neither related to sea ice conditions in the dominant moisture source regions nor correlated with (≤ 0.001 m w.eq. a−1, p-value = 0.006). However, snow accumulation at UG is neither correlated with sea ice nor with SAM and ENSO.

We conclude that neither the rapid warming nor the large increases in snow accumulation observed on the AP and in West Antarctica during the last decades have extended inland to the Ellsworth Mountains. Hence, the UG region, although located
at the northern edge of the WAIS and relatively close to the AP, exhibits rather stable climate characteristics similar to those observed in East Antarctica.

confirming that the large increases in snow accumulation observed on the AP and in other coastal regions of Antarctica have not extended inland to the Ellsworth Mountains. We conclude that the UG region — located in the transition zone between the AP, the WAIS and the EAIS — is exhibiting rather East than West Antarctic climate characteristics.

1. Introduction

Antarctic temperature change has been a major research focus in the past decades. Despite the scarcity and short duration of the observations, it shows a contrasting regional pattern between the Antarctic Peninsula (AP), the West Antarctic Ice Sheet (WAIS) and the East Antarctic Ice Sheet (EAIS; Stenni et al., 2017).

Both AP and WAIS have experienced significant atmospheric and oceanic changes during recent decades. The WAIS is considered as one of the fastest warming regions on Earth based on the analysis of meteorological records (Steig et al., 2009; Bromwich et al., 2013) and ice cores (Steig et al., 2013; Stenni et al., 2017). Bromwich et al. (2013) reported for central West Antarctica an increase in annual air temperature by more than 2°C since the end of the 1950s. The rapid warming in West Antarctica at the end of the last century is anomalous, but seems to be not unprecedented in the past 300 years (Thomas et al., 2013) and even in the past two millennia (Steig et al., 2013), respectively. The significant increase in near-surface air temperatures is accompanied by regionally different trends in accumulation rates. Thomas et al. (2015) reported a dramatic increase in snow accumulation in coastal Ellsworth Land during the 20th century that is unprecedented in the past 300 years.

In contrast, Burgener et al. (2013) found a statistically significant negative trend in snow accumulation across the central WAIS during the last four decades. This opposite pattern has been recently confirmed by a study of Medley and Thomas (2019) demonstrating that snow accumulation increased over the eastern but decreased over the western WAIS throughout the past 100 years.

For the AP, time series of near-surface air temperature from weather stations (Vaughan et al., 2003; Turner et al., 2005a) as well as from stable water isotope records from ice cores (Thomas et al., 2009; Abram et al., 2011; Stenni et al., 2017) provide evidence of a significant warming over the last 100 years reaching more than 3°C since the 1950s. Concomitantly, precipitation and accumulation rates have significantly increased during the 20th century at a rate that is exceptional in the past 200-300 years (Turner et al., 2005b; Thomas et al., 2008; Thomas et al., 2017; Medley and Thomas, 2019). The rapidity of the 20th century warming of the AP is unusual, but not unprecedented in the context of late-Holocene natural climate variability (i.e. 2000 years BP; Mulvaney et al., 2012). Furthermore, Turner et al. (2016) revealed that air temperatures on the AP have decreased since the late 1990s, contrasting the warming of previous decades.

Contrary to the AP and the WAIS, the EAIS has experienced rather a cooling or constant climate conditions in recent decades (Turner et al., 2005a; Nicolas and Bromwich, 2014; Smith and Polyani, 2017; Goursaud et al., 2017). However, Steig et al. (2009) reported slight, but statistically significant warming in East Antarctica at a rate of +0.10±0.07°C per decade for the period 1957-2006 similar to the continent-wide trend. A positive and significant trend in near-surface air temperature has also been found for Dronning Maud Land (DML) for the last 100 years (Stenni et al., 2017) and in particular for the period 1998-2016 (+1.15±0.71°C per decade; Medley et al., 2018). Snowfall and accumulation rates on the EAIS are usually considered to show no significant changes (Monaghan et al., 2006) or clear overall trends due to counterbalancing of increases and decreases in different regions (van den Broeke et al., 2006; Schlosser et al., 2014; Altnau et al., 2015; Phillipe et al., 2016). However, more recent studies provide a different picture: based on an ice core from western DML, Medley et al. (2018) derived a significant increase in snowfall since the 1950s, which is unprecedented in the past two millennia. Furthermore, Medley and
Thomas (2019) show that snow accumulation over the EAIS has steadily increased during the 20th century despite a decrease since 1979. Hence there is still no conclusive evidence about general trends in near-surface air temperature and accumulation rates in Antarctica. In summary, the detection and assessment of trends in climate variables, such as air temperature and precipitation (accumulation), for the three Antarctic regions - AP, WAIS and EAIS - is challenging, due to the shortness of available instrumental records and the incompatibility between climate model simulations and in-situ observations (Jones et al., 2016; Steini et al., 2017). In addition, determined trends are often regionally and/or seasonally contradicting on interannual to decadal or multannual timescales, and are at the same order of magnitude as the associated uncertainties.

Factors affecting mechanisms that force the anomalously strong and rapid warming of the AP and the WAIS with their associated precipitation changes as well as the contrasting constant air temperatures on the EAIS have been widely discussed. For the AP the significant warming and increase in snow accumulation has been linked to the shift of the Southern Annular Mode (SAM) towards its positive phase during the second half of the 20th century (Thompson and Solomon, 2002; Turner et al., 2005b; Gillett et al., 2006; Marshall, 2006; Marshall et al., 2007; Thomas et al., 2008), while the recently observed decrease in air temperature has been attributed to an increased cyclonic activity in the northern Weddell Sea (Turner et al., 2016). The SAM is the principal zonally-symmetric mode of atmospheric variability in extra-tropical regions of the Southern Hemisphere (Limpasuvan and Hartmann, 1999; Thompson and Wallace, 2000; Turner, 2004). The positive phase of the SAM is characterized by decreased geopotential height over the polar cap, but increased geopotential height over the mid-latitudes. This leads to a strengthening and poleward shift of the mid-latitude westerlies over the Southern Ocean and hence to increased cyclonic activity and advection of warm and moist air towards Antarctic coastal regions (Thompson and Wallace, 2000; Thompson and Solomon, 2002; Turner, 2004; Gillett et al., 2006). Consequently, a positive (negative) SAM is associated with a warming (cooling) on the AP and anomalously low (high) temperatures over eastern Antarctica and the Antarctic plateau (EAIS). Hence the slight cooling of the EAIS during recent decades is connected to a more positive SAM (Turner et al., 2005a; Steini et al., 2017). The recent shift of the SAM towards its positive phase has been attributed to the increase of anthropogenic greenhouse gas concentrations in the atmosphere and to stratospheric ozone depletion (Thompson et al., 2013; Gillett et al., 2008).

The rapid warming of the WAIS and the contemporaneous precipitation trends have been suggested to be driven by sea surface temperature (SST) anomalies in the central and western (sub)tropical Pacific (e.g. Schneider et al., 2012; Ding et al., 2011; Steige et al., 2013; Bromwich et al., 2013). They further seem to be linked to the recent deepening of the Amundsen Sea Low (ASL) influencing meridional air mass and heat transport towards West Antarctica (Genthon et al., 2003; Bromwich et al., 2013; Hoskin et al., 2013; Raphael et al., 2015; Burgeener et al., 2013; Thomas et al., 2015). Changes in the absolute depth of the ASL are strongly related to the phase of the El Niño Southern Oscillation (ENSO) and the SAM (Raphael et al., 2015). ENSO is the largest climatic mode on Earth on decadal and sub-decadal timescales, originating in the tropical Pacific. ENSO directly influences the weather and oceanic conditions across tropical, mid- and high-latitude areas on both hemispheres (Karoly, 1989; Díaz and Markgraf, 1992; Díaz and Markgraf, 2000; Turner, 2004; L’Heureux and Thompson, 2006). The surface air temperature variability of both East and West Antarctica has been linked to the variability of ENSO, although not showing any consistent trend on interannual timescales (Rahaman et al., 2019).

Current trends in Antarctic climate and their drivers are still not completely understood, especially on regional scales. Consequently, there is a strong need for extended observations and monitoring in all regions of Antarctica. Therefore, data on meteorological parameters such as air temperature, precipitation (accumulation rates), moisture sources and transport pathways of precipitating air masses are vital to assess past and recent changes of Antarctic climate. Direct observations of these parameters are lacking for most of Antarctica and, thus proxy data derived from firm and ice cores, e.g. stable water isotopes, provide important information on past and recent climate variability on local to regional scales (Thomas and Bracegirdle, 2015). For the region at the intersection of AP, WAIS and EAIS data is sparse, and little or no long-term meteorological data
are available for this part of the Antarctic continent (Stenni et al., 2017; Thomas et al., 2017). The region is located at the transition to the Ronne-Filchner Ice Shelf, for which a recent modelling study suggests a high susceptibility to destabilization and disintegration under a warming climate (Hellmer et al., 2012; Hellmer et al., 2017), as already observed for ice shelves around the AP and the WAIS (e.g. Pritchard and Vaughan, 2007; Cook and Vaughan, 2010; Scambos et al., 2014; Rignot et al., 2014; Joughin and Alley, 2011).

This study aims at improving our understanding of climate variability in the region at the intersection of AP, WAIS and EAIS based on firn-core stable water isotope data from Union Glacier (UG), located in the Ellsworth Mountains at the northern edge of the WAIS (79°46’S, 83°24’W, 770 m above sea level [asl]; Fig. 1a). The UG region has not been intensively investigated, yet. Rivera et al. (2010, 2014) mapped the surface and subglacial topography and determined ice dynamical and basic glaciological characteristics of UG. Meteorological and stake measurements yielded a mean daily air temperature of -20.6°C (2008-2012) and a mean snow accumulation of 0.12 m w.eq.a⁻¹ (2008-2009). However, the available data records are very short and do not allow conclusions on long-term trends.

In this study we use high-resolution density and stable water isotope data of six firn cores drilled at various locations in the UG region for reconstructing accumulation rates and inferring connections to recent changes in meteorological parameters such as air temperature on local to regional scales. We further investigate how these variables are related to temporal changes of moisture source regions, sea ice extent and concentration (SIE and SIC) and atmospheric modes such as SAM and ENSO. Backward trajectory analyses are applied to determine potential source regions and transport pathways of precipitating air masses reaching the UG region. We aim to characterize the UG region with isotope geochemical methods to be able to place it in the regionally diverse pattern of Antarctic climate variability. The main focus of this study lies on the following question: Do the UG region and surrounding areas experience the same strong and rapid air temperature and accumulation increases as observed for the neighbouring AP and WAIS and, if yes, to what extent, or does the UG region follow the rather constant air temperature and accumulation conditions as observed for most of the EAIS?

The Antarctic Peninsula (AP) and the West Antarctic Ice Sheet (WAIS) have gained scientific interest as both regions have been experiencing significant atmospheric and oceanic changes during recent decades. The WAIS is considered as one of the fastest warming regions on Earth based on the analysis of meteorological records (Steig et al., 2009; Bromwich et al., 2011) and ice cores (Steig et al., 2013). Time series of near-surface air temperature from weather stations (Turner et al., 2005; Vaughan et al., 2003) as well as stable water isotope records from ice cores (Thomas et al., 2009; Abram et al., 2011) provide evidence that the AP has warmed by more than 3°C since the 1950s.

The mechanisms and factors forcing the anomalously strong and rapid warming of the AP and the WAIS have been widely discussed. For the AP the warming process has been linked to the shift of the Southern Annular Mode (SAM) towards its positive phase during the second half of the 20th century (e.g. Thompson and Solomon, 2002; Gillett et al., 2006; Marshall, 2006; Marshall et al., 2007). The SAM is the principal zonally symmetric mode of atmospheric variability in extra-tropical regions of the Southern Hemisphere (Limpasuvan and Hartmann, 1999; Thompson and Wallace, 2000; Turner, 2003). The positive phase of the SAM is characterized by decreased geopotential height over the polar cap, but increased geopotential height over the mid-latitudes. This leads to a strengthening and poleward shift of the mid-latitude westerlies over the Southern Ocean and hence to increased cyclonic activity and warm air advection towards Antarctic coastal regions (Thompson and Wallace, 2000; Thompson and Solomon, 2002; Turner, 2004; Gillett et al., 2006). Consequently, a positive (negative) SAM is associated with a warming (cooling) on the AP and anomalously low (high) temperatures over eastern Antarctica and the Antarctic plateau (Thompson and Wallace, 2000; Thompson and Solomon, 2002; Gillett et al., 2006).

The recent shift of the SAM towards its positive phase has been attributed to the increase of anthropogenic greenhouse gas concentrations in the atmosphere and to stratospheric ozone depletion (Thompson et al., 2011; Gillett et al., 2006), but also to locally confined sea-ice loss (Turner et al., 2013).
The exceptional rapid warming of the WAIS has been suggested to be driven by sea surface temperature (SST) anomalies in the central and western tropics (e.g. Schneider et al., 2012; Ding et al., 2011; Steig et al., 2013; Bromwich et al., 2013). It further seems to be linked to the recent deepening of the Amundsen Sea Low (ASL), influencing meridional air mass and heat transport towards West Antarctica (Bromwich et al., 2013; Horning et al., 2013; Raphael et al., 2015). Changes in the absolute depth of the ASL are strongly related to the phase of the El Niño–Southern Oscillation (ENSO) and the SAM (Raphael et al., 2015). ENSO is the largest climatic cycle on Earth on decadal and sub-decadal time scales originating in the tropical Pacific. ENSO directly influences the weather and oceanic conditions across tropical, mid- and high-latitude areas on both hemispheres (Karey, 1989; Dixa and Markgraf, 1992; Dixa and Markgraf, 2000; Turner, 2004; LHeureux and Thompson, 2006).

However, current trends in Antarctic climate and their drivers are still not completely understood, especially on regional scales. Turner et al. (2016) revealed that temperatures on the AP have decreased since the late 1990s, presumably due to increased cyclonic activity in the northern Weddell Sea. Thomas et al. (2013) showed that the warming in West Antarctica at the end of the 20th century was not unprecedented in the past 300 years. Rapidity of AP warming, which is unprecedented. In addition, the East Antarctic Ice Sheet (EAIS) has rather experienced a slight cooling during recent decades, in line with the occurrence of a more positive SAM (Turner et al., 2005; Steini et al., 2017). However, Steig et al. (2008) reported significant warming in East Antarctica at 0 10°0.07°C/decade for the period between 1957 and 2006 similar to the continent-wide trend. Hence, there is still no conclusive evidence about a general Antarctic warming.

Hence, there is a strong need for extended observations and monitoring in all regions of Antarctica. Therefore, data on meteorological parameters such as air temperature, precipitation (accumulation rates), moisture sources, and transport pathways of precipitating air masses are vital to assess past and recent changes of Antarctic climate. Direct observations of these parameters are lacking, particularly in the interior of these most of Antarctic continent, and thus proxy data derived from firm and ice cores, e.g. stable water isotopes, provide important information on past and recent climate variability on local to regional scales (Thomas and Bracegirdle, 2015). For the region at the intersection between the AP, the WAIS and the East Antarctic Ice Sheet (EAS), data is generally sparse, and little or no long-term meteorological data are available from this part of the Antarctic continent (Steini et al., 2017; Thomas et al., 2017). The region is located at the transition to the Ronne-Filchner Ice Shelf, for which a recent modelling study suggests its susceptibility to destabilization and disintegration under a warming climate (Hellmer et al., 2012; Hellmer et al., 2017), as already observed for ice shelves around the AP and the WAIS (e.g. Fricker and Vaughan, 2007; Cook and Vaughan, 2010; Scambos et al., 2014; Rignot et al., 2014; Jouglard and Alley, 2011).

This study aims to improve our understanding of climate change at the intersection area between the AP, the WAIS and the EAS based on firm- and pure stable water isotope data from the Union Glacier (UG) region, located in the Ellsworth Mountains at the northern edge of the WAIS (70°56’S, 83°21’W; 770 m above sea level [asl]; Fig. 1a). Union Glacier (70°56’S, 83°21’W; 770 m above sea level [asl]; UG) is one of the major outlet glaciers within the Ellsworth Mountains and flows into the Ronne-Filchner Ice Shelf in the Weddell Sea sector of Antarctica. It is composed of several glacier tributaries – the main ones being Union and Schütz Glaciers – covering an estimated total area of 2564 km². UG has a total length of 36 km, a maximum ice thickness of 1540 m and a maximum depth of the firm–ice boundary layer of 120 m (Rivera et al., 2014). The subglacial topography of the glacier valley is smooth with U-shaped flanks and the bedrock is located below sea level (+858 m; Rivera et al., 2014).

In this study, we use high-resolution data on the density and stable water isotope composition of firm cores drilled at various locations in the UG region for reconstructing accumulation rates and inferring recent changes in meteorological parameters such as air temperature on local to regional scales. We further investigate how these variables are related to temporal changes...
of moisture source regions, sea ice extent and concentration (SIE and SIC) and atmospheric modes such as SAM and ENSO. Backward trajectory analyses are applied to determine potential source regions and transport pathways of precipitating air masses reaching the UG. We aim to conclude concluding on whether and to what extent the UG region and surrounding areas are experiencing the same strong and rapid warming as observed for the neighbouring AP in the north and the WAIS in the south, respectively.

2. Data and Methodology

2.1 Fieldwork, sample processing and analysis

Two glaciological field campaigns were conducted in the UG region in austral summers 2014 and 2015. Union Glacier is one of the major outlet glaciers within the Ellsworth Mountains and flows into the Ronne–Filchner Ice Shelf in the Weddell Sea sector of Antarctica (Fig. 1). It is composed of several glacier tributaries – the main one being Union and Schanz Glaciers – covering an estimated total area of 2561 km². UG has a total length of 86 km, a maximum ice thickness of 1540 m and a maximum depth of the snow–ice boundary layer of 120 m (Rivera et al., 2014). The subglacial topography of the glacier valley is smooth with U-shaped flanks. The bedrock is located below sea level (~358 m; Rivera et al., 2014).

Here we examine six firn cores (GUPA–1, DOTT–1, SCH–1, SCH–2, BAL–1, PASO–1) retrieved using a portable solar-powered and electrically operated ice-core drill (Backpack Drill; icedrill.ch AG), at different locations ranging between 760 m a.s.l. (GUPA–1 and DOTT–1) and 1900 m a.s.l. (PASO–1) in altitude. GUPA–1 has been core-drilled near the ice-landing strip on UG and DOTT–1 originates from an ice rise towards the Ronne–Filchner Ice Shelf. SCH–1 was retrieved from the ice divide between the glaciers Schneider and Schanz, SCH–2 and BAL–1 were both taken in U-shaped glacial valleys (Glacier Schneider and Glacier Balish). PASO–1 (Fig. 1b) originates from a plateau west of the Gifford Peaks (Fig. 1b). Details on the drill locations and basic core characteristics are given in Table 1.

For cores BAL–1 and PASO–1 high-resolution (< 1 mm) density profiles were obtained using X-ray microfocus computer tomography (ICE–CT; Freitag et al., 2013) at the ice-core processing facilities of the AWI Bremerhaven. The cores were sampled at 0.025 m and analysed for stable water isotopes using a cavity ring-down spectrometer (L2130–i, Picarro Inc.) coupled to an auto–sampler (PAL HT–x; CTC Analytics AG) at the Stable Isotope Laboratory of AWI Potsdam. Stable water isotope raw data was corrected for linear drift and memory effects following the procedures suggested by van Geldern & Barth (2012), using six repeated injections per sample from which the first three were discarded. The drift- and memory-corrected isotopic compositions were then calibrated with a linear regression analysis using four different in-house standards that have been calibrated to the international VSMOW2 (Vienna Standard Mean Ocean Water)/SLAP2 (Standard Light Antarctic Precipitation) scales. Stable water isotope ratios are reported in permil (‰) versus VSMOW2. Precision of the measurements is ±0.08 ‰ for δ18O and ±0.5 ‰ for δD.

For cores GUPA–1, DOTT–1, SCH–1 and SCH–2 density profiles were constructed by section-wise determining the core volume and weight. Accordingly, average resolution of density profiles is 0.25 cm for GUPA–1, 0.40 cm for DOTT–1, 0.27 cm for SCH–1 and 0.78 cm for SCH–2. Cores GUPA–1, DOTT–1 and SCH–1 were then sampled at 0.05 cm resolution for stable water isotope analysis carried out at the Stable Isotope Laboratory of UNAB in Viña del Mar, Chile. For the measurements an off–axis integrated cavity output spectrometer (TLWIA 4SEP; Los Gatos Research) was used with a precision of being better than 0.1 ‰ for δ18O and 0.8 ‰ for δD (Fernando et al., 2016). Each sample was measured twice in different days, using ten repeated injections from which the first four were discarded. Stable water isotope raw data was corrected for linear drift and memory effects and then normalized to the VSMOW2/SLAP2 scales using the software LIMS (Laboratory Information Management System; Coplen & Wassenaar, 2015). For data normalization three different in-house standards and one USGS standard (USGS49) calibrated to the international VSMOW2/SLAP2 scale were used.
Core SCH-2 was analysed at the British Antarctic Survey (BAS). Stable water isotopes were determined at 0.05 cm resolution using a Picarro L2130-i analyser with measurement precision of 0.08‰ for δ¹⁸O and 0.5‰ for δD. Major ions (Cl⁻, NO₃⁻, SO₄²⁻, Na⁺, K⁺, Mg²⁺, Ca²⁺) were measured at 0.05 cm resolution using a Dionex reagent-free ion chromatography system (ICS-2000). Furthermore, longitudinal subsections of the core (32 mm x 32 mm in size) were melted continuously on a chemically inert, ultra-clean melt head to measure electrical conductivity, dust and H₂O₂ at high resolution (~1 mm; Continuous Flow Analysis (CFA); McConnell et al., 2002). In addition, core PASO-1 was analysed for liquid conductivity, H₂O, NO₃⁻, NH₄⁺, Black Carbon and various chemical elements at the Trace Chemistry Laboratory of the Desert Research Institute (DRI) according to methods described in Röthlisberger et al. (2000), McConnell et al. (2002) and McConnell et al. (2007). Chemical elements of which Na⁺ and S are used for core chronology were measured using two Thermo Finnigan Element ICP-MS instruments. Subsequently, values of sSS (sea-salt Na) and nssS (non-sea-salt S) which are used for the core chronology of PASO-1 were calculated from Na⁺ and S-concentrations according to Röthlisberger et al. (2002) and Sigl et al. (2013), respectively, applying relative abundances from Bowen (1979, Eq. S1). Based on the corrected and calibrated δ¹⁸O and δD values were used to calculate the δ excess was calculated (δ excess = δD – 8*δ¹⁸O; Dansgaard, 1964) and, to derive a co-isotopic relationship (δD = m*δ¹⁸O + n) was derived for each core. Since there is no recent precipitation stable water isotope data of recent precipitation available for the UG region, a Local Meteoric Water Line (LMWL) was inferred from the co-isotopic relationships of all cores. Based on findings by Fernandoy et al. (2010) we believe that this composite co-isotopic relationship is a first approximation – can be referred to as LMWL at UG.

### 2.4.2 Dating of Firn cores and time series construction

Recent studies have used the seasonality of stable water isotopes and chemical parameters to reliably date firn cores from East Antarctica (e.g. Vega et al., 2016; Caiazzo et al., 2016). Stable water isotope profiles (δ¹⁸O and δD) of the six firn cores are displayed with respect to depth in Figure S2. Data gaps in GUPA-1, DOTT-1 and SCH-1 are due to leaking sample bags (GUPA-1: 2 samples; DOTT-1: 3 samples; SCH-1: 2 samples). Accordingly, firn cores for which glacio-chemical data is available, i.e. SCH-2 and PASO-1, SCH-2 and PASO-1 were dated using annual layer counting (ALC) of stable water isotopes and chemical parameters focusing on Methanesulphonate acid (MSA), SO₄²⁻, the Cl/Na⁺ ratio and on H₂O₂ for SCH-2 (Fig. 2) and nssS (non-sea-salt S) and the nssS/Na⁺ (non-sea-salt Na)/Na⁺ ratio for PASO-1 (Fig. 3). H₂O₂ and nssS as proxy parameters exhibit both clear seasonal alternations between highest and lowest values, since the former parameter is directly linked to the annual insolation cycle (Lee et al., 2000; Stewart et al., 2004) and the latter one to marine biogenic activity (phytoplankton; Kaufmann et al., 2010). In addition, for age model construction of SCH-2 methanesulphonate acid (MSA), SO₄²⁻ and the Cl/Na⁺ ratio were used for corroborating the years identified by ALC of H₂O₂ and stable water isotopes (Vega et al., 2018). For the dating of PASO-1 the signal of the Mt. Pinatubo eruption (1991) could be clearly identified through the coincidence of an above-average peak in the nssS/Na⁺ record with a lacking winter minimum in the nssS-record at 9.5 ± 1.2 m depth (Fig. 3). Similar changes in wintertime nssS were observed in the well-dated ice cores PIG2010, DIV2010 and THW2010 from West Antarctica (Pasteris et al., 2014). Hence, especially in the nssS record and hence the signal attributed to the Mt. Pinatubo eruption was used as additional tie point for the age model construction of PASO-1 (Fig. 2). For cores GUPA-1, DOTT-1, SCH-1 and BAL-1 we applied ALC of stable water isotopes and then matched the preliminary age-depth relationships to the SCH-2 age scale. We dated core SCH-2 using ALC of stable water isotopes and matching to the SCH-2 age scale. The estimated error associated to ALC in all years for cores dated with glacio-chemistry and ALC is ± 2 years. Snow accumulation rates at the firn core sites were determined and converted to meters of water equivalent per year (m w.eq. a⁻¹) based on measured densities (Fig. S3).
Composite stable water isotope and accumulation rates were constructed for the entire UG region by combining time series of annually averaged stable water isotopes and accumulation rates of the individual firn cores. In order to assign each firm core the same weight and to not overrepresent a certain firm core drill site, annual averaged data were standardized (Eq. S4). Linear trends were calculated and tested for their statistical significance using the non-parametric Mann–Kendall test and Sen slope (s) estimator trend test (Mann, 1945; Kendall, 1975; Sen, 1968) with correction for autocorrelation according to Yue & Wang (2004). Signal-to-noise ratios for stable water isotope and accumulation rate time series of UG firm cores were estimated according to Fisher et al. (1985; Eq. S5).

2.4.2 Meteorological database and backward trajectory analysis

Meteorological data from an automatic weather station (AWS) located at the UG ice runway (79° 42’ 46” S, 82° 34’ 16” W, 705 m asl, Fig. 1b) covers the 4-year period from 1st February 2010 to 8th February 2014. The AWS (station: Wx7) records near-surface air temperature (2 m), wind speed, wind direction, relative humidity and air pressure every ten minutes. Additionally, hourly-resolved data of the same meteorological parameters are available from a second AWS (station: Arigony) operated on Union Glacier (79°46’ S, 82°54’ W, 693 m asl, Fig. 1b) covering the period from 14th December 2013 to 29th March 2018. Since differences between the Wx7 and the Arigony records are small for all meteorological parameters throughout the overlapping period (14th December 2013 to 8th February 2014; e.g. mean difference in air temperature/pressure: 0.74°C/5.76 hPa), the two datasets were combined in order to expand the meteorological record. The meteorological data from the two AWS (air temperature and air pressure) along with measured surface densities (Fig. S3) and derived accumulation rates (Fig. 6 and Table 1) were used to model depth-dependent diffusion lengths for each firn core across the entire length following the approach described by Münch and Laepple (2018) and Laepple et al. (2018), respectively. Local near-surface air temperatures at the firm-core drill sites were estimated from the AWS measurements by rescaling using the altitude of the respective site and a lapse rate of 1°C/100 m. Local surface air pressures were estimated from the barometric height formula.

Based on the meteorological data from the two AWS (in particular air temperature and air pressure), measured surface densities and derived accumulation rates, diffusion lengths were calculated for each firm core across its entire length. We also used fields of near-surface air temperature (2 m), precipitation, evaporation and geopotential heights (850 mbar) from the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Reanalysis (ERA-I; Interim, 1979-2019; background, spatial resolution: 79 km) to Dee et al., 2011; available at: https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim) for comparison with UG composite records of stable water isotopes and accumulation rates. ERA-Interim reanalysis data were aggregated to daily, monthly or annual values.

Annually-averaged stable water isotopes and accumulation rates were also related to time series of climate modes such as SAM and ENSO as well as to SIE and SIC in order to identify potential dominant drivers of potential climate variability in the UG region. For the comparison with UG stable water isotopes and accumulation rates, monthly SIE for different Antarctic sectors (Weddell Sea: 60° W – 20° E; Indian Ocean: 20° E – 90° E; Western Pacific: 90° E – 160° E; Ross Sea: 160° E – 130° W; Bellingshausen–Amundsen Sea: 130° W – 60° W) was obtained from the National Aeronautics and Space Administration (NASA; Cavalieri et al., 1999, 2012; available at: https://nsidc.org/data/nsidc-0079). Note that these data are only available for the period 1979-2012. Satellite-derived SIC data was acquired from the National Snow and Ice Data Center (NSIDC). The data set NSIDC 4079 Bootstrap SIC from Nimbus 7 SMMR and DMSP SSM/I/SSMIS, Version 3 with a spatial resolution of 25 km x 25 km was used (available at: https://nsidc.org/data/nsidc-0079; Comiso, 2017). Furthermore, we used the Marshall SAM Index (Marshall, 2003) as indicator for the prevailing SAV phase (available at: https://legacy.bas.ac.uk/met/gjma/sam.html) and the Multivariate ENSO Index (MEI; Wolter and Timlin, 8000).
as indicator for the occurrence and strength of El Niño and La Niña events (available at: https://www.esrl.noaa.gov/psd/enso/monitor/table.html).

Mean monthly SST for different Antarctic sectors (Weddell Sea: 60°W, 1993, 2017; Indian Ocean: 70°E, 2015; Western Pacific: 140°E; Ross Sea: 160°E, 2013; Bellingshausen, Antarctic Sea: 130°W, 2008) were obtained from the National Snow and Ice Data Center (NSIDC). These data are NSIDC 0078-1 Bootstrap SFC from Nimbus 7 C1DMR and DMSP SSM/I SSMIE. Version 2 with a spatial resolution of 25 km was used (available at: https://nsidc.org/data/nsidc-0078; Comiso, 2017). Spatial and cross-correlation analyses between UG composite time series of stable water isotopes and accumulation rates and time series of ERA-Interim reanalysis data, SIE, SIC, the Marshall SAM Index and the MEI, respectively, were carried out calculating Pearson correlation coefficients (r) and p-values at the 95% confidence level (i.e. α = 0.05). For calculating spatial correlations all time series were detrended. Spatial and cross-correlation analyses with UG time series were carried out calculating Pearson correlation coefficients (r) and p-values at the 95% confidence level (i.e. α = 0.05).

We performed backward trajectory analysis using the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Hess, 1998; Stein et al., 2015; available at: https://ready.arl.noaa.gov/index.php) in order to determine potential moisture source regions and transport pathways of precipitating air masses for the UG region. The drill site of firm core SCH-1 was taken as initial point for the calculation of 3-day backward trajectories. This location was selected as it is less influenced by post-depositional processes as well as wind-induced redistribution and removal of snow, and thus is among all available firm-core drill sites the most representative for snow fall events in the UG region. Input data for the 3-day backward trajectories model was taken from the Global Data Assimilation System (GDAS-1; freely available from the NOAA website: https://www.ready.noaa.gov/archives.php) ERA-Interim time series of daily precipitation extracted from the nearest grid point at 1001 m a.s.l. for the period 2010–2015 from the nearest grid point for the period 2010–2015 (resolution: 0.75°x0.75°; available at: http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc) served as input to extrac precipitation events on a daily scale. We used a minimum threshold corresponding to 1% of the annual accumulation (i.e. 2.5 mm w.e. below). A value in terms of percentage is 1% potential equivalent to the one using a similar procedure as applied by Thomas & Bracquemond (2009). Input data for the calculation of 3-day backward trajectories The location of the AWS Arigny (see above) corresponds to the drill site of firm core SCH-1. ERA-Interim was used as initial point. Based on input data from the Global Data Assimilation System (GDAS-1; available at: https://www.ready.noaa.gov/archives.php) ERA-Interim, 121 backward trajectories were calculated corresponding to 214 daily single precipitation events occurring in the period 2010–2014. They were then sub-divided into their respective seasons (DJF, MAM, JJA and SON). Furthermore, individual backward trajectories were time combined into four different clusters, which group similar precipitation events with statistically similar transport pathways according to their spatial variance (Stein et al., 2015).

3. Results

3.1 Meteorological data

The mean daily air temperature for the composite record of near-surface air temperature (Fig. 4) was -21.3°C with an absolute minimum of -46.8°C recorded on 17 July 2017 and an absolute maximum of +3.3°C measured on 21 February 2013.

Daily air temperatures are highest during December and January with mean values of -9.2°C and -9.1°C, respectively, and lowest from April to September with mean values below -25°C. The coldest month of the whole composite record period (2010–2018) is July with a mean air temperature of -28.8°C. Daily wind speeds have a mean value of 6.9 m/s, with a predominant direction from SW (220°). The maximum wind speed recorded was 29.7 m/s. Generally, the wind...
speeds are higher than 1.2 m/day in > 75% of all data. These observations are in line with those made by Rivera et al. (2014) for the period 2008–2012 and imply the possibility of substantial redistribution of snow due to wind drift.

### 3.2 Firn core age model

The results of firn core dating are given in Table 1. The estimated dating uncertainty is ±1 year for cores dated with stable water isotopes and glacio-chemistry (SCH-2 and PASO-1) and ±2 years for cores dated with stable water isotopes only and subsequent matching to the SCH-2 age scale (GUPA-1, DOTT-1, SCH-1 and BAL-1). Stable water isotope profiles ($^{18}$O and $^{2}$H) of the six firn cores are displayed with respect to depth in Fig. S2. Data gaps in GUPA-1, DOTT-1 and SCH-1 are due to leaking sample bags (GUPA-1, 2 samples; DOTT-1, 1 sample; SCH-1, 2 samples). The number of years identified in each core by ALC and the respective period covered is summarized in Table 2: Core DOTT-2 (16 years, 1999–2014) exhibits the shortest and PASO-1 (43 years, 1973–2015) the longest record. Note that for age model construction of GUPA-1 two years (1990, 2001) and of BAL-1 three years (1983, 1984, 1993) were excluded from linear interpolation and are not clearly visible in the stable water isotope record due to smoothing of the stable water isotope record in the respective core sections. Furthermore, for SCH-1 the first year (1986) was identified by linear extrapolation at the lower end of the core using the depth–age relationship between the previous two clearly identifiable peaks (years 1987 and 1988). For all cores the last year (either 2014 or 2015) was excluded from further analysis as it is incomplete. The estimated error associated to ALC is ±1 year for cores dated with glacio-chemistry and ±2 years for cores dated with stable water isotopes only.

### 3.3 Firn core stable water isotopes and accumulation rates

The mean stable oxygen isotope composition of the six firn cores ranges from $-36.6 \%$ (PASO-1) to $-29.9 \%$ (DOTT-1) with standard deviations varying between 2.3 % (PASO-1) and 3.9 % (DOTT-1). For $^{18}$O and $^{2}$H, $^{18}$O and $^{2}$H (Table 1). Absolute minimum $^{18}$O values are found in GUPA-1, absolute maximum $^{18}$O values in DOTT-1. Note that the results for GUPA-1 have to be handled with caution as this core was drilled next to the UG field camp and ice–landing strip. Therefore, snow relocation effects due to wind drift and/or human activities (e.g. runway maintenance) might have biased its stable water isotope composition. This is also indicated by less pronounced seasonal alternations in the GUPA-1 stable water isotope record (Fig. S2). Despite different drill locations and altitudes, the range in mean d excess values of the six cores is small (from 4.9 % [SCH-2] to 7.0 % [PASO-1]). The slope of the $\delta^{18}$O–isotopic relationship (Table 1 and Fig. 5a) is very close to that of the Global Meteoric Water Line (GMWL; Craig, 1961) for all individual firn cores ranging between 7.94 (GUPA-1) and 8.24 (PASO-1). Hence, the atmospheric origin of the firn is evident in the stable water isotope signal is preserved during moisture transport and snow deposition at the study site (Clark and Fritz, 1997). For all cores $\delta^{18}$O and $\delta^{2}$H values are highly correlated ($R^2 > 0.98$) with the largest variation in d excess observed for SCH-2 (values range from $-5.6 \%$ and $17.2 \%$). The LMWL of the UG study region was determined as $SD = 8.02 \delta^{18}$O + 6.57 ($R^2 = 0.99$, Fig. 5a).

Time-series analysis of $\delta^{18}$O annual means (Fig. S7) reveals statistically significant trends ($p$-value < 0.05) only for cores SCH-1 ($s = -0.039 \%$ a$^{-1}$) and BAL-1 ($s = -0.054 \%$ a$^{-1}$). Statistically significant positive trends of d excess annual means (Fig. S8) have been found for SCH-2 ($s = -0.085 \%$ a$^{-1}$) and PASO-1 ($s = -0.016 \%$ a$^{-1}$), whereas for DOTT-1 ($s = -0.110 \%$ a$^{-1}$) and SCH-1 ($s = -0.052 \%$ a$^{-1}$) the d excess trend is negative. The BAL-1 d excess record exhibits no trend.

Mean accumulation rates vary between 0.18 m w.eq.$^{-1}$ (GUPA-1 and PASO-1) and 0.29 m w.eq.$^{-1}$ (SCH-2) with the lowest standard deviations found at the DOTT-1 and PASO-1 sites (~0.05 m w.eq.$^{-1}$) and the highest ones exhibited by cores SCH-2 and BAL-1 (~0.08 m w.eq.$^{-1}$, Table 1). Highest mean accumulation rates (~0.23 m w.eq.$^{-1}$) were found for DOTT-1 and SCH-2 despite the site of SCH-2 being located further inland and at about 750 m higher altitude compared to DOTT-1 (Table 1 and Fig. 1b). Lowest mean accumulation occurs at the GUPA-1 and PASO-1 sites (~0.18 m w.eq.$^{-1}$). In general,
Annual minimum accumulation ranges between 0.1 and 0.2 m w.eq.a⁻¹ and annual maximum accumulation reaches values of ≥ 0.3 m w.eq.a⁻¹ with the absolute maximum found at the SCH-2 site in 1985 (0.47 m w.eq.a⁻¹). However, in the same year accumulation reaches an absolute minimum of 0.08 m w.eq.a⁻¹ at the PASO-1 site (Fig. 6). At SCH-1, SCH-2 and BAL-1 accumulation decreased at a rate of -0.002 m w.eq.a⁻¹, -0.004 m w.eq.a⁻¹ and -0.003 m w.eq.a⁻¹ (p-values < 0.05), respectively. In contrast, accumulation exhibits a slight, albeit statistically significant increase at the PASO-1 site (s = +0.001 m w.eq.a⁻¹, p-value < 0.05).

4. Discussion

4.1 Potential noises influencing UG firn core records

In order to properly assess the environmental signals in stable water isotope and accumulation data of the UG firn cores, several aspects that could potentially induce noise need be taken into account: the intermittency of precipitation, the redistribution of snow by wind drift as well as diffusion in firm.

The analysis of diffusion lengths for the maximum depth of the UG firn cores revealed values of between 0.072 m (PASO-1) and 0.087 m (DOTT-1), which are much lower than the mean annual layer thickness of between 0.35 cm (PASO-1) and 0.60 m (DOTT-1; Table S11). Therefore, we assume diffusion to be of minor importance for inducing noise to the stable water isotope records of the UG firn cores.

In contrast, wind drift and redistribution of snow certainly play an important role in the UG region, which is supported by data on wind speed (on average 7 ms⁻¹) and wind direction (predominantly from SW) from the two AWS. The location of the individual firn cores at different altitudes as well as in different topographic positions (near the ice-landing strip, valley vs. plateau) causes site-specifically different susceptibility towards wind drift and thus to the reallocation of snow. However, as there is AWS data from only one location, i.e. the GUPA-1 drill site, for the period February 2010 - March 2018 available, we have no reliable meteorological information for the other firn core drill sites in order to assess the local effects of wind drift in detail Rivera et al. (2014) report that in the UG region katabatic winds can cause strong snow drift due to acceleration by the slope of the glacial valleys feeding UG. Studies of drifting snow in Antarctica using satellite remote sensing (Palm et al., 2011) and regional climate modelling (Lenaerts et al., 2012; Lenaerts and van den Broeke, 2012) provide evidence for a drifting snow frequency (defined as the fraction of days with drifting snow) of about 15.30% in the UG region. Also, studies from close-by areas such as Patriot Hills (Casassa et al., 1998) and the Ronne-Filchner Ice Shelf (Graf et al., 1988) as well as from DML (Schlosser and Oerter, 2002; Kazczenska et al., 2004) revealed that wind drift and random sastrugi formation are the main reasons for large spatial and temporal variations in accumulation rates. However, linkages between the different firn core drill sites at UG are speculative, e.g. the potential uptake of snow at the PASO-1 drill site (absolute minimum accumulation) and its redistribution towards the lower-altitudinal core sites (SCH-2; absolute maximum accumulation) by the predominantly south-westerly winds in 1985. The calculation of signal-to-noise ratios for stable water isotopes and accumulation rates can help to further assess the extent to which the UG firn cores are influenced by noise-inducing processes such as wind drift and diffusion.

In the following, firn core GUPA-1 is excluded from statistical evaluation due to the likely biasing and smoothing of its stable water isotope and accumulation records as a consequence of its position near the UG ice-landing strip. Based on the two-by-two signal-to-noise ratios between the individual cores (Tables S9 and S10), we have calculated the signal-to-noise ratio of δ¹⁸O for the UG firn cores to 0.60 for the entire record period (1973-2014), and to 0.78 when referring to the overlapping period (1999-2013). The signal-to-noise ratios are similar when considering only the three neighbouring cores BAL-1, SCH-1 and SCH-2 situated within 10 km distance in similar valley positions. They yield 0.60 for the entire period and 0.86 for 1999-2013. The signal-to-noise ratios of δ¹⁸O in the UG region of between 0.6 and 0.86 are quite high, i.e. they are similar to or slightly higher than signal-to-noise ratios of δ¹⁸O on the WAIS for interannual timescales (±0.5-0.7), and much higher than those in DML (≤ 0.2) for multiannual to decadal timescales (Münch and Laepple, 2018).
Calculation of the signal-to-noise ratio for accumulation rate time series of UG firm cores revealed a value of 0.29 for the entire record period and a value of 0.32 for the overlapping period. Compared to the signal-to-noise ratios of δ¹⁸O, these values are much lower, probably reflecting the strong influence of the site-specific characteristics on accumulation rates, e.g. the different exposure to wind drift and the subsequent relocation of snow. The signal-to-noise ratio increases significantly when referring to the close-by cores BAL-1, SCH-1 and SCH-2 or to SCH-1 and SCH-2 only (Tables S9 and S10), and yields 0.79 and 1.67, respectively, when referring to the entire record period. This might be due to the proximity of the drill sites (within 10 km distance) and the similarity of the site-specific characteristics of the three cores, i.e. the location in northwest-southeast oriented U-shaped glacial valleys, leading to similar accumulation patterns. When referring to the overlapping period only, the signal-to-noise ratio stays at a low value of 0.24 for the three cores, but remains high for SCH-1 and SCH-2 (1.2, Tables S9 and S10). In summary, the signal-to-noise ratios of accumulation rates at UG are consistent with those determined by Schlosser et al. (2014) and Altnau et al. (2015) for firm cores from Fimbul Ice Shelf, DML, and much higher than those found in low-accumulation areas of the Amundsenisen mountain range, DML, (Graf et al., 2002; Altnau et al., 2015). Generally, the higher the accumulation rates at a specific site are, the higher are the signal-to-noise ratios for stable water isotopes and accumulation rates (Hoshina et al., 2014; Münch et al., 2016). Hence, the UG region with higher accumulation rates as compared to low-accumulation sites on the EAIS (e.g. Oerter et al., 2000) exhibits relatively high signal-to-noise ratios for both stable water isotopes and accumulation rates despite the likely influence by post-depositional processes, in particular the redistribution of snow due to wind drift. Hence, we conclude that the UG firm core records allow to deduce temporal changes in stable water isotopes and accumulation rates on a regional scale.

4.1.3 Spatial and temporal variability of firm core stable water isotope composition and relation to near-surface air temperatures, sea ice and climate modes

4.1.3.14 Spatial and temporal variability of stable water isotopes

Prominent maximum in δ¹⁸O time series of UG firm cores are found in 1991, 1997, 2002, 2006 and 2013 (Fig. 7). The above average warm summer in 2002 is the only maximum found in all cores. Prominent minima occur, although not visible in all cores, in the years 1995, 2001, 2004, 2010 and 2014. In the following, firm core GUPA-1 is excluded from statistical evaluation due to the likely biasing and smoothing of its stable water isotope record as a consequence of its site specifications. From the inter-comparison of mean, minimum and maximum values of δ¹⁸O annual means for the overlapping period (1999–2013; Table 1 and Fig. S7), generally a depletion of the stable water isotope composition with increasing height (“altitudinal effect”) and distance from the sea (“continentality effect”) has been detected as expected for a Rayleigh distillation process (Clark and Fritz, 1997). Core PASO-1 situated at greatest altitude and greatest distance from the sea shows lowest lightest mean δ¹⁸O values (-36.43‰), whereas the low-altitude firm core DOTT-1, which is situated closest to the sea, displays a distinctly heaviest mean stable water isotope composition (29.7‰). However, core SCH-2 exhibits less depleted mean δ¹⁸O values (-34.1‰) than SCH-1 (-34.7‰) although located at about 250 m higher altitude. This inverted pattern, that is also visible in the mean, minimum and maximum δ-values derived from all samples of the respective core (Table 1), might originate from snow reallocation processes within the glacial valley due to katabatic winds. Nonetheless, the existence of an “altitudinal effect” is confirmed by the δ¹⁸O-altitude-relationship calculated from δ¹⁸O annual means for the overlapping period (excluding GUPA-1) yielding altitude = -152.7*δ¹⁸O + 3803.4 with R² = 0.85 and p-value = 0.026 (Fig. S12).

The individual firm cores are generally well correlated with each other for δ¹⁸O and δD, for both the maximum overlapping period between two individual cores and the overlapping period (1999–2013, S4 and S10). All cores display a common δ¹⁸O maximum in summer 2002 (Fig. 7). The correlation coefficients are highest for nearby firm cores such as SCH-1 and SCH-2 reaching up to r = 0.66 (p-value = 0.199-2013; r = 0.58, p-value = 0.025) for δ¹⁸O and r = 0.71 (p-value = 0, 1999-
construct a composite Hence, an overall mean δD record (UG δD stack) has been constructed based on from both for non-standardized and standardized annually averaged data spanning the period that comprises at least three core records per year (1980–2014, excluding GUPA-1; Fig. 8). From the UG δD stack. This allows to draw a more regional picture of the isotopic characteristics of precipitation at UG can be drawn without overrepresenting a certain firm core drill site. As a result from this, we found only a negligible positive trend in δD which is statistically not significant (β = ±0.03, p-value = 0.517). Thus, we infer that at UG regional changes in δD values must have been negligible during the last 35 years. This is in line with findings from ice cores retrieved from the nearby Ronne-Filchner Ice Shelf and the Weddell Sea sector, respectively, that show no statistically significant trends in their stable water isotope time series (e.g. Foundation Ice Stream [Graf et al., 1999; Berkner Island [Mölve et al., 2002; Stenni et al., 2017]). This allows to draw a more regional picture of the isotopic characteristics of precipitation at UG. However, it is worth mentioning that stacking from the non-standardized UG firm core δD stack without previous standardization (excluding GUPA-1) stack yields a statistically significant positive trend of $s = +0.058 \text{‰} \text{yr}^{-1}$ (p-value < 0.0001; Fig. 8). This trend most likely results from the dominance of SCHR-1 and BAL-1 as these are the only cores showing statistically significant (positive) trends (S27). It has been found suggesting that the UG region might have experienced a slight warming at least since 1980. When using standardized data, there is only a negligible positive δD trend is still preserved which is, however, is not statistically not significant anymore (β = ±0.03, p-value = 0.517). From this we infer that the regional increase changes in δD values must have been negligible during the last 35 years.

In order to detect possible changes in the origin of precipitating air masses reaching the UG region the δd excess time series of individual firm cores have been inter-compared (Fig. S8). Furthermore, in line with δD δD and δD, the second order parameter δD excess does not show clear trends or similar contemporaneous changes among the firm cores suggesting little change in the main moisture sources and the origin of air masses precipitating over the UG region at least during the last four decades, since at least 1980. This is corroborated by the absence of a statistically significant trend in the composite δd excess record (UG δd excess stack) that has been calculated for the period 1980–2014 (excluding GUPA-1; Fig. 8) despite although therefor individual firm cores show no cross-correlations in the δd excess (Tables S9 and S10). The composite δd excess record (UG δd excess stack) has been calculated (non-standardized and standardized) and analyzed for the period 1980–2014 (Fig. S1). Neither the non-standardized nor the standardized records exhibit a statistically significant trend. Disimilarities between δd excess trends of individual firm cores might be partly explained by the presence of orographic barriers that separate different drill sites from each other and thus might lead to dissemblarities in moisture sources, even though the drill sites are located within only 50 km horizontal distance.

4.2.2 Relation of stable water isotopes to near-surface air temperature records meteorological data records. Linear regression between stacked seasonal means of non-standardized firm core δ18O and seasonal means of AWS derived near-surface air temperature for the overlapping period February 2010 - November 2015 (Fig. S12) revealed a statistically significant positive δ18O-T relationship (δ18O = 0.175° - 31.6, R² = 0.21, p-value = 0.03). Linear regression between non-standardized seasonal means of AWS derived UG near-surface air temperature and δ18O for the period 2010-2015 (S86) revealed a statistically significant positive δ18O-T relationship (δ18O = 0.175° - 31.6, R² = 0.21, p-value = 0.03). In order to test the δ18O-T relationship for the entire period covered by the UG δ18O stack (1980-2014), monthly means of ERA interim FRA-Interim near-surface air temperatures extracted for the GUPA-1 site, that is the firm core site closest to the two AWS, were correlated
with those derived from the AWS records, for the period February 2010 – November 2015. We used ERA-Interim near-surface air temperatures extracted for the grid point which is nearest to the GUPA-1 drill site (Table 1) as this is the firn core site closest to the two AWS. Monthly mean air temperatures from both datasets are highly and statistically significantly correlated (R² = 0.99, p-value = 0) allowing to calculate a δ¹⁸O–T relationship for the period 1980-2014 based on seasonal means of ERA-Interim near-surface air temperatures and stacked seasonal means of non-standardized UG δ¹⁸O. The two records show a very high correlation (R² = 0.99, p-value = 0) allowing to calculate a δ¹⁸O–T relationship for the entire period of the UG δ¹⁸O–stack based on seasonal means of ERA-Interim near-surface air temperatures and UG δ¹⁸O. The latter yields δ¹⁸O = 0.128×T + 11.7 (R² = 0.23; p-value = 0.045) that is very similar to the δ¹⁸O–T relationship calculated based on AWS data for the period 2010-2015 (Fig. S13). Thus, independent of the period considered we conclude that increasing air temperatures are generally linked with increasing δ¹⁸O-values. However, as this relationship is only weak, a proper inference of near-surface air temperatures from δ¹⁸O values of precipitation is not yet possible for the UG region. This is due to (1) the shortness of the available near-surface air temperature record and (2) the arbitrary calculation of δ¹⁸O seasonal means assuming that precipitation at the study site is evenly distributed throughout the year.

In order to further test the δ¹⁸O–T relationship, the UG δ¹⁸O–stack (standardized) was spatially correlated with ERA-Interim near-surface air temperatures for the period 1980-2014 (Fig. 9a). No correlation was found with ERA-Interim based near-surface air temperatures at the UG site but with those further to the east (Coats Land and DML; Fig. 1a and 9a). This might be due to the ERA-Interim model not capturing the local small-scale orography of the Ellsworth Mountains well and hence, not truly reflecting the local climate at the UG site but rather the regional climate along the Weddell Sea coast. The large differences between the actual altitudes of the firm core drill sites and the elevations of the respective nearest ERA-Interim grid points (Table 1) ranging from about 100 m (DOTT-1) up to 700 m (PASO-1) might support this hypothesis. A second possible explanation for the observed correlations might be that both Coats Land and DML constitute important moisture source areas from which precipitating air masses approach the UG region. This aspect is further discussed below.

Near-surface air temperatures, if real, most have been small during the last 35 years. Apparently, the UG record is highly susceptible to minor changes in data processing and too short for drawing general conclusions on regional climate change. However, our finding based on standardized data is consistent with the absence of a clear regional warming on the AP since the late 1990s (Turner et al., 2010), although the tipping point from warming to cooling is not visible in the UG dataset. It is also in line with findings from ice cores retrieved from the Ronne–Filchner Ice Shelf and the Weddell Sea sector, respectively, that show no statistically significant trends in their stable water isotope time series (e.g. Foundation Ice Stream [Graf et al., 1999], B v i l l t i e l (Molness et al., 2002, Stenni et al., 2017]). Furthermore, the observation of rather constant stable water isotope time series at UG is consistent with a period of significant warming on the WAIS (Bromwich et al., 2013). A lack of significant regional air temperature change on the AP since the late 1990s (Turner et al., 2010), although the tipping point from warming to cooling is not visible in the UG dataset. It is also in line with the and the FAIS (Turner et al., 2005, Schneider et al., 2006, Smith and Polvani, 2016). For instance, a slightly negative, but statistically not significant trend in air temperature (-0.11 ±0.17 °C) has been observed in the instrumental record of Halley research station (1957-2000) (-0.11 ±0.17 °C; Turner et al., 2005), whereas and no trend has been found at Neumayer research station (1981-2010; Schlosser et al., 2014). However, Medley et al. (2018) have recently shown that near-surface air temperatures in western DML have significantly increased between 1998 and 2016 (+1.15±0.71 °C per decade). In summary, we assume that mean δ¹⁸O values in the UG region capture regional air temperature variations only to some extent during a period of rather constant climate conditions.
4.1.2 Relation of stable water isotopes to meteorological data records

Linear regression between non-standardized seasonal means of UG near-surface air temperatures and UG \( \delta^{18}O \) for the period 2010–2014 (Fig. 9c) revealed a statistically significant positive \( \delta^{18}O \)-T relationship \((\delta^{18}O = 0.175T + 11.6, R^2 = 0.21, \) p-value = 0.03 \((p = 0.05))\). However, a proper inference of near-surface air temperatures from \( \delta^{18}O \) values of precipitation in the UG region is not yet possible. This is due to (1) the shortness of the available near-surface air temperature record and (2) the arbitrary calculation of \( \delta^{18}O \) seasonal means assuming that precipitation at the study site is evenly distributed throughout the year. Nevertheless, the presented \( \delta^{18}O \)-T relationship confirms that \( \delta^{18}O \) values and near-surface air temperatures in the UG region are positively interrelated, i.e. increasing air temperatures imply increasing \( \delta^{18}O \) values. Hence, they provide evidence that mean \( \delta^{18}O \) values in the UG region can indeed be used as a proxy for near-surface air temperature at the site. In order to further test the robustness of this relationship, the UG \( \delta^{18}O \)-stack (standardized) was spatially correlated with ERA-Interim near-surface air temperatures for the period 1980–2014 (Fig. 9c). Surprisingly, no correlation was found with near-surface air temperatures at the UG site, but with near-surface air temperatures further to the east (Coats Land). This might be due to the ERA-Interim model not capturing the local geography of the Ellsworth Mountains well and hence, not truly reflecting the local climate at the UG site, but rather the regional climate along the Weddell Sea coast.

4.1.3 Relation of stable water isotopes to large-scale climate modes and sea ice variability

Mean annual \( \delta^{18}O \) values (UG \( \delta^{18}O \)-stack) exhibit a weak positive correlation with the SAM Index \((r = 0.40, \) p-value = 0.026; Table 3). Stronger contraction of the polar vortex during positive SAM phases facilitates the advection of warm and moist air from mid- and lower latitudes, i.e. from regions with higher SST and lower relative humidity towards Antarctica (Thompson and Wallace, 2000; Thompson and Solomon, 2002; Gillett et al., 2006). Hence atmospheric water vapour with higher \( \delta^{18}O \) values is expected to reach Antarctica (Uemura et al., 2008; Stenni et al., 2010). Spatial correlations with ERA-Interim geopotential heights (850 mbar) calculated for the period 1980–2014 (Fig. 9c) confirm that increased geopotential heights above the mid-latitudes as occurring during positive SAM phases (Thompson and Wallace, 2000; Thompson and Solomon, 2002) imply increased \( \delta^{18}O \) values of precipitation in the UG region. However, non-standardized mean annual \( \delta^{18}O \) values (UG \( \delta^{18}O \)-stack) show no correlation with the SAM Index (Table 3). Furthermore, none of the standardized isotopic values exhibits a significant correlation with the MEI Index (Table 3). Hence, oceanic circulation changes associated with the alternation between El Niño and La Niña events seem to have a detectable, measurable influence on the stable water isotope composition of precipitation in the UG region.

Kohyama and Hartmann (2016) showed that the SAM Index is statistically significantly positively correlated with sea ice extent (SIE) in the Indian Ocean sector of Antarctica. When comparing SIE in the different Antarctic sectors (Weddell Sea, Bellingshausen-Amundsen Sea, Ross Sea, West Pacific, Indian Ocean) with the UG \( \delta^{18}O \) and \( \delta^{18}O \)-stack (standardized), a significant correlation of \( \delta^{18}O \) with SIE in the Indian Ocean sector \((r = 0.315, \) p-value = 0.074; Table 3) is found. However, this correlation might be an artefact and does not necessarily indicate predominant moisture transport from the Indian Ocean sector towards UG. Cluster analysis and seasonal frequency distribution of backward trajectories performed with the HYSPLIT model (Fig. 10 and 11) suggests that the Weddell Sea sector, including the Ronne-Filchner Ice Shelf, is the dominant source region for precipitating air masses reaching the UG site.
Spatial correlations with SIC yield a more specific regional picture of the interplay between sea ice distribution and UG moisture sources. We found that only SIC in the northern Weddell Sea exhibits a strong negative correlation with mean annual δ¹⁸O and d excess values in the UG region (r = -0.6; Fig. 4a), corroborating the results of the backward trajectory analysis. Thus, higher δ¹⁸O and d excess values at the UG site correspond to a reduction in SIC in the northern Weddell Sea, respectively. Consequently, reduced SIC in the northern Weddell Sea implies enhanced availability of proximal moisture which would support higher δ¹⁸O values in the UG region during low SIC phases. For a detailed interpretation of the negative correlation with UG d excess further data on the moisture sources’ relative humidity is needed which is not yet available.

4.2 Spatial and temporal variability of accumulation rates and relation to sea ice and climate modes

4.2.1 Spatial and temporal variability of accumulation rates

For the overlapping period (1999–2013; Table 1) highest accumulation rates are observed at the DOTT-1 site that is located at the lowest elevation and closest to the sea. However, accumulation rates are very similar at the sites of SCH-1, SCH-2, BAL-1 and PASO-1, despite the clear differences in altitude and distance from the sea (Fig. 1b and Table 1). Accumulation rates have decreased at all sites throughout the respective record period, except at the PASO-1 site (Fig. 6). At SCH-1, SCH-2 and BAL-1 accumulation decreased at a rate of -0.002 m w.eq.a⁻¹ yr⁻¹ (p value = 0.032), -0.004 m w.eq.a⁻¹ yr⁻¹ (p value < 0.001) and -0.003 m w.eq.a⁻¹ yr⁻¹ (p value = 0.006), respectively. The decrease is highest at the DOTT-1 site, but not statistically significant (r = -0.005 m w.eq.a⁻¹ yr⁻¹; p value = 0.458). In contrast, accumulation exhibits a slight, albeit statistically significant increase at the PASO-1 site (r = 0.001 m w.eq.a⁻¹ yr⁻¹; p value = 0.032). The observed negative trends in accumulation rates are at the same order of magnitude as those reported by Burdener et al. (2013) for central West Antarctica for the period 1975–2010 (ranging between -0.0022 and -0.0072 m w.eq.a⁻¹) and by Schlosser et al. (2014) for Fimbul Ice Shelf, DML, for the period 1995–2009 (ranging between -0.006 and 0.021 m w.eq.a⁻¹), respectively. However, it seems that snow accumulation in the UG region is not directly related to altitude and distance to the sea. Furthermore, spatially varying accumulation trends likely reflect the strong influence of site-specific characteristics on accumulation rates, in particular the different exposure to wind drift. DOTT-1 and PASO-1 are the former located on an ice rise and the latter located on a high-altitude plateau, might be more exposed to wind drift than the sites of SCH-1, SCH-2 and BAL-1. The latter three are all located within U-shaped glacial valleys stretching from northwest to southeast (Fig. 1b), and, thus, are potentially better protected from the predominant south-westerly winds. Hence, accumulation trends might be better preserved in these records.

Analogously to the UG δ¹⁸O-stack, a composite accumulation time series is constructed and analyzed for the period that comprises at least three core records (1980–2014, excluding GUPA-1; Fig. 8). Based on the annual accumulation rates of all firm cores (excluding GUPA-1) for the period 1980–2014, an average accumulation rate in the UG region of 0.245 ± 0.07 m w.eq.a⁻¹ (n = 148) has been calculated. This value is roughly consistent with accumulation rates determined from stake measurements on UG (79°42'32'' S, 80°12'40''S, 80°56'13''S, 82°55'52''W, 480–814 masl, 2008–2009: up to 0.7 m w.eq.a⁻¹; Rivera et al., 2014), regional atmospheric model outputs (1980–2004: 0.086 ± 0.238 ± 8 m w.eq.a⁻¹, horizontal model resolution: 55 km; van den Broeke et al., 2006) and the closest ITASE (International Trans-Antarctic Scientific Expedition) ice core 01-S (77°03'24.2''S, 89°08'13.2''W, 1246 m asl, 1958–2000: 0.342 m w.eq.a⁻¹; Genthon et al., 2005). It is also in line with accumulation rates reconstructed from firm cores retrieved along a 920 km long
northeast-southwest traverse on the Ronne-Filchner Ice Shelf (from 51°32’W, 77°59.5’S to 59°38.1’W, 84°49.1’S, 65-1191 m asl), that range between 0.09 and 0.18 m w.eq.a⁻¹ (1946-1994; Graf et al., 1999).

From the combining the accumulation records of the individual firn cores (excluding GUPA-1) non-standardized accumulation record sign average accumulation rate in the UG region of 0.25 m w.eq.a⁻¹ has been calculated. This value is roughly consistent with accumulation rates determined from stake measurements on UG (2007-2011: between 0.12 and 0.2 m w.eq.a⁻¹; Rivera et al., 2014) regional atmospheric model output (1980-2001: 0.09, 0.33 m w.eq.a⁻¹; horizontal model resolution: 55 km, van de Broeke et al., 2006) or from the close-up location of Patriot Hills (80°18’ S, 81°22’ W, 1246 m asl as of 1995, 0.1 m w.eq.a⁻¹; Casado et al., 1999) and the closest ITASE (International Trans-Antarctic Scientific Expedition) ice core 01-S1 (77°31’2° E, 8°S, 13°2’W, 1246 m asl as of 1999-2001: 0.39 m w.eq.a⁻¹; Kagehara et al., 2004).

Analogously to the UG δ¹⁸O stack a composite accumulation time series has been constructed from standardized annually averaged data and analysed for the period that comprises at least three core records (1980-2014; excluding GUPA-1; Fig. 8). The UG composite accumulation record derived from both non-standardized and standardized time series shows a small but statistically significant negative trend (Fig. 8; non-standardized: $s = 0.001$ m w.eq.a⁻¹, p-value = 0.006; standardized: $s = 0.020$, p-value = 0.001). This finding is in contrast to the positive precipitation trend observed on the AP (Turner et al., 2005; Fieeler et al., 2015; Thomas et al., 2018) and in coastal Ellsworth Land (Thomas et al., 2013). This finding is in line with Burgener et al. (2013), who observed a statistically significant negative trend in accumulation rates reconstructed from five firn cores from the central WAIS for a similar period as covered by the UG cores (1975-2010; on average 3.8 mm w.eq.a⁻¹). Furthermore, firn and ice-core based studies of the surface mass balance on Firnbul Ice Shelf, DML revealed a negative trend for the second half of the 20th century (Kaczmarska et al., 2004; Schlosser et al., 2014; Alttau et al., 2015). Medley and Thomas (2019) also report a generally decreasing trend in snow accumulation for the EIS since 1979. The negative trend in accumulation rates in the UG region is in contrast to the absence of a long-term trend in accumulation rates in Adelie Land (Goursaud et al., 2017) as well as positive precipitation and accumulation trends observed on the AP (Turner et al., 2005b; Thomas et al., 2008; Fieeler et al., 2015; Thomas et al., 2017), in coastal Ellsworth Land (WAIS, Thomas and Bracegirdle, 2015; Thomas et al., 2015), costal DML (Philippe et al., 2016) and in western DML (EAIS, Medley et al., 2018), respectively, during the 20th and early 21st centuries.

4.3.2 Relation of accumulation rates to sea ice variability and large-scale climate modes

The link between snow accumulation and SIE (SIC) in Antarctica is complex. Generally, the smaller the SIE (SIC) is, i.e. the closer the open water areas are, the more surface level moisture is available and may be transported towards the Antarctic continent causing an increase in snow accumulation (Tkaczenk and Nytrich, 2013; Thomas et al., 2015). Furthermore, higher air temperatures may lead to more open water areas, and warm air can transport more moisture than cold air (Clark and Fritz, 1997). However, these simplistic considerations might be much more complex in specific settings such as the UG region and might be superimposed by manifold factors and processes such as wind directions, wind drift, moisture content of air masses etc.

Backward trajectory analysis revealed that the Weddell Sea sector as well as Coats Land and DML are the most likely strong moisture source regions, for UG in all seasons of the year for UG (Fig. 10 and 4d1) (van de Broeke et al., 2006). This is confirmed by a strong positive correlation (up to $r > 0.6$) of the UG composite accumulation record with ERA-Interim precipitation-evaporation time series for these regions (1980-2014), whereas there is no correlation with the UG site (Fig. 9c). This might be due to post-depositional processes (wind drift, snow removal and/or redeposition) influencing accumulation at the firn core sites, beside the above mentioned incapabilities of the ERA-Interim model. Surprisingly, there does not appear to be a relationship between either SIE or SIC and in the Weddell Sea sector and snow accumulation at UG (Table 2 and Fig. 12c). Instead, there is a weak negative correlation with SIE in the Indian Ocean sector (Table 2) pointing towards increased precipitation and thus snow accumulation at UG during periods of low SIE in the Indian Ocean sector. This relationship is
supported by a significant positive correlation (up to $r > 0.6$) between accumulation at UG and ERA-Interim precipitation-evaporation in the Indian Ocean sector (Fig. 9c).

Indeed, there is a very weak positive correlation of snow accumulation at UG with SIC in the Bellingshausen Sea sector (Fig. 4d). Reduced sea ice in the Bellingshausen Sea sector, and the increased availability of surface level moisture, has been used to explain the increases in snow accumulation along the AP and in coastal Ellsworth Land during the 20th century (Thomas et al., 2015). However, the UG site is considerably distant from the sea-ice edge and, thus, changes in sea ice appear to be less important for snow accumulation in this region. There is no correlation between snow accumulation at UG with either SAM or ENSO (Table 2). This suggests that snow accumulation in the UG region is likely not directly driven by large-scale modes of climate variability and that UG seems to be located in a transition zone between West and East Antarctic climate. The UG composite accumulation record is only weakly correlated with ERA-Interim precipitation-evaporation time series at the site (Fig. 8d). Similar has been found for other firn and ice cores in the region (Thomas et al., 2017). This may be because the models used for the reanalysis are unable to capture the small geography of the Ellsworth Mountains, or be evidence of post-depositional processes at the firn core sites (wind erosion, snow deposition and redistribution).

5. Conclusions

In this study, we examined six firn cores from the Union Glacier region in the Ellsworth Mountains (79°46’ S, 83°24’ W) situated at the northern edge of the West Antarctic Ice Sheet. Based on firn cores, composite time series of $\delta^{18}O$, $\delta D$ and accumulation rates (non-standardized and standardized) were established for the entire Union Glacier region covering periods between 16 and 43 years, the period 1980-2014. A Local Meteoric Water Line was derived (8D = 8.02δ$^{18}O$ + 6.57, $R^2 = 0.99$) from the co-isotopic relationship of all firn cores confirming the preservation of meteoric origin of snow and firm at UG. The original (oceanic) stable water isotope signal during moisture transport towards and snow deposition at UG. Diffusion was found to have only a negligible influence on the stable water isotope records of the UG firm cores. Spatial and temporal variability of accumulation rates is likely to be rather influenced by post-depositional processes, i.e. wind drift, removal and redistribution of snow.

The analysis of signal-to-noise ratios for the UG firm cores (excluding GUPA-1) revealed relatively high values for $\delta^{18}O$ of between 0.60 for the entire record period (1973-2014) and 0.78 for the overlapping period (1999-2013). For accumulation rates, the signal-to-noise ratios for the two periods are lower amounting to 0.29 and 0.32, respectively, and hence, reflecting the strong influence of site-specific characteristics on snow accumulation (e.g. the different exposure to wind drift). The results of the signal-to-noise ratio analysis allowed to stack the single firn core stable water isotope and accumulation rate time series, respectively, for the period 1980-2014 in order to draw conclusions at a regional scale. For the UG composite $\delta^{18}O$ record (UG $\delta^{18}O$-stack) no statistically significant trend was found suggesting that regional changes in near-surface air temperature have been small at least since 1980. The absence of a $\delta^{18}O$-trend in the UG region is consistent with recent findings in the AP region and parts of the EAIS.

The standardized composite UG $\delta^{18}O$-stack record revealed no statistically significant trend suggesting that regional changes in near-surface air temperature have been small at least since 1980. The absence of an isotopic temperature trend in the UG region is consistent with findings in the AP region and other parts of Antarctica. Furthermore, it seems that standardized mean annual $\delta^{18}O$ and $\delta D$ excess values in the UG region (UG $\delta^{18}O$ and $\delta D$ excess stacks) are likely related to sea ice conditions in the northern Weddell Sea. Also, there is a weak positive correlation between mean annual $\delta^{18}O$ excess values and SIE in the Indian Ocean sector. However, no concurrent relation exists with SAM and ENSO. Backward trajectory analysis confirmed suggests that the Weddell Sea sector, and coastal Weddell-Scotia Land and DML are the likely dominant source regions for precipitating air masses reaching the UG site. Mean annual $\delta^{18}O$-values are neither correlated with SAM nor with ENSO, but standardized mean annual $\delta D$ excess values exhibit a weak positive correlation with the SAM.
Index. implying that a more positive SAM facilitates higher $d$ excess values of precipitation in the UG region. However, no statistically significant trend has been found for the UG $d$ excess stack composite $d$ excess record (both non-standardized and standardized) suggesting overall little change in the main moisture sources and the origin of air masses precipitating over the UG region since 1980.

On average mean annual accumulation in the UG region amounts to 0.245 m w.eq $a^{-1}$ with respect to the period in 1980-2014 and in contrast to stable water isotopes, mean annual accumulation in the UG region has slightly decreased during this period since 1980 ( fired-standardized: $-0.031$ m w.eq $a^{-1}$ standardized Sen slope $s = -0.020$). This finding is in line with observations from the central and western WAIS and coastal parts of the EAIS, but contrasts positive precipitation and accumulation trends on the AP, the eastern WAIS and in inner parts of the EAIS. There is no correlation between snow accumulation at UG and SIE (SIC) in the dominant moisture source regions (Weddell Sea, Coats Land, DML), but a weak negative correlation with the Indian Ocean sector was found. There is no direct relationship of mean annual accumulation at UG with either sea ice concentration or large-scale modes of atmospheric variability (SAM or ENSO).

We conclude that this confirms that neither the rapid warming nor the large increases in snow accumulation as observed on the AP and in other coastal regions and the interior of West Antarctica during the last decades have extended inland to the Ellsworth Mountains. Hence, the UG region, although being located at the northern edge of the WAIS and relatively close to the AP, and that the UG region exhibits rather East than West Antarctic climate characteristics.

As the UG firn core records demonstrated to be are highly susceptible to minor changes in data processing, longer records and deeper ice cores are essential to draw general and statistically more significant conclusions on climate change in the UG region.

Author Contribution. F.F. designed the study and carried out the fieldwork supported by D.R.O, K.H. and H.M. performed the stable water analyses of firn cores BAL-1 and PASO-1. K.H. and J.R.M. performed the glacio-chemical analyses of PASO-1. Stable water isotopes of firn cores GUPA-1, DOTT-1 and SCH-1 were measured by F.F. and M.A. Stable water isotope and glacio-chemical analyses of SCH-2 were carried out by L.R.T. High-resolution density profiles of firn cores BAL-1 and PASO-1 were measured by K.H. and J.F.J.A.-N. provided AWS data from Union Glacier. F.F. and D.T. modelled backward trajectories. L.R.T. helped with data standardization and spatial correlation analysis. K.H. was responsible for data analysis, interpretation, and writing of the manuscript supported by H.M., C.S., F.F., L.R.T. and T.O. All authors contributed to data interpretation and the preparation of the final manuscript.

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

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Data Availability.
The data will be made publicly available via: www.pangaea.de.
Figure 1a-b: Location of the UG region within Antarctica (a) and location of the drill sites of the six firm cores (GUPA-1, DOTT-1, SCH-1, SCH-2, BAL-1, PASO-1) within the UG region (b). The red triangles in (b) denote the location of two automatic weather stations on UG (yellow: station Wx7; red: Trigony; further explanations in the text). The background image in (b) was extracted from the Landsat Image Mosaic of Antarctica (LIMA) and the contour lines were obtained from the Radarsat Antarctic Mapping Project Digital Elevation Model, Version 2 (Liu et al., 2015).
Figure 2: Age scale for firn core SCH-2 constructed by counting and inter-matching of maximum peaks (dashed lines) in CFA-derived profiles of stable water isotope composition (δD) and different chemical parameters (H₂O, Cl/Na, MSA and SO₄²⁻). Smoothed 2P is a 2-point running average. Note, that the maxima of the chemical parameters do not necessarily coincide with the respective maxima in δD due to the different seasonality of the proxies.
Figure 3: Age scale for firn core PASO$_{\text{1}}$ constructed by counting and inter-matching of maximum (minimum) peaks (dashed lines) in profiles of stable water isotope composition ($\delta$D, $\delta^{18}O$) as obtained from discrete sample measurements and in CFA$_{\text{1}}$-derived profiles of nssS and nssS/ssNa, respectively. The year of the eruption of Mt. Pinatubo (1991) that is used as tie point for annual layer counting is highlighted. Note, that the maxima of nssS and nssS/ssNa, respectively, do not necessarily coincide with the respective maxima in $\delta$D due to the different seasonality of the proxies.
Figure 4: Composite record of mean daily and mean monthly air temperatures recorded at two nearby Union Glacier AWS sites (stations: Wx7, Arigony) from February 2010 to March 2018. The mean daily air temperature for the entire composite record period (−21.3°C; dashed black line) and the period overlapping with Union Glacier core records (February 2010 to November 2015; grey bar) are also indicated.

Figure 5a-g: Composite δ18O–isotopic relationships (δ18O vs. δD) based on all individual samples (n = 2348; white dots) of for all six firn cores from Union Glacier with δ18O. For each firn core, the equation and the coefficient of determination (R²) of the linear regression (red dashed line) is shown. The Global Meteoric Water Line (GMWL) is indicated in blue. The composite co–isotopic relationship with its equation and R² that is referred to as the Local Meteoric Water Line (LMWL) of the Union Glacier region is also displayed.
Figure 6: Annual accumulation rates at the drill sites of the six firn cores from Union Glacier for the period covered by the respective firn core. Sen slopes (in m w.eq.a⁻¹y) and p-values are given for all firn cores indicating that accumulation has decreased at most sites since the beginning of the record period.
Figure 7: Profiles of the stable water isotope composition ($\delta^{18}O$) of the six firn cores from Union Glacier with respect to time. Years with prominent maxima above average maxima (warm summers) and minima (cold winters) in $\delta^{18}O$ time series — although not visible in all cores — are highlighted by red and blue shading, respectively. The peak in summer 2002 is the only maximum found in all cores.

Prominent maxima in $\delta^{18}O$ time series of UG firn cores are found in 1991, 1997, 2002, 2006 and 2007 (Fig. 7). The above-average warm peak in summer 2002 is the only maximum found in all cores. Prominent minima occur — although not visible in all cores — in the years 1995, 2001, 2004, 2010 and 2014.
Figure 8: Composite records of mean annual $\delta^{18}O$, d excess and snow accumulation in the UG region for the period 1980-2014 derived from both non-standardized (grey) and standardized data (black; excluding firm core GUPA-1). For $\delta^{18}O$ the composite record derived from non-standardized annually averaged data (grey) is also displayed as it exhibits a worth mentioning statistically significant positive trend. Sen slopes ($s$) and p-values are given for each record. Only mean annual snow accumulation exhibits a statistically significant negative trend for both non-standardized and standardized data.
Figure 9a-c: Spatial correlation of annually averaged ERA-Interim (a) near-surface air temperatures (2 m), (b) geopotential heights (850 mb) and (c) precipitation-evaporation with standardized mean annual (a) $\delta^{18}$O, (b) $d$ excess and (c) snow accumulation in the UG region for the period 1980-2014 (excluding firm core GUPA-1). All time series were detrended before calculating spatial correlations. The red star denotes the location of the UG region. Only statistically significant correlations (p-value < 0.05) are displayed. For (b) August-July annual averages (winter-winter) were considered as spatial correlations appear more significant than for December-November annual averages (calendar year).
Figure 10a-d: Density distribution of 3-day backward trajectories transporting precipitating air masses towards the UG region (red star) as calculated for each season (DJF, MAM, JJA, SON) for the period 2010–2014 using the model HYSPLIT.
Figure 11: Seasonal frequency distribution of single 5-day backward trajectories during precipitation events extracted from ERA-Interim time series of daily precipitation for the UG region for the period 2010–2015 using the HYSPLIT model. In total 121 precipitation events with ⩾1% of the mean annual accumulation (~2.5 mm d⁻¹) were considered for this analysis performed with ACC. The red star denotes the location of the UG region.

Figure 1: Cluster analysis of 5-day backward trajectories transporting air masses towards the UG region as calculated for all days with precipitation events (in total 121, represented by thin grey lines) for the period 2010–2015 using the model HYSPLIT. Bold lines represent main transport pathways calculated as percentage (%) of all trajectories associated with the respective cluster.
Figure 11a-c: Spatial correlations of standardized mean annual (a) $\delta^{18}O$, (b) d excess and (c) snow accumulation in the UG region with mean annual sea ice concentrations in the Weddell and Bellingshausen Sea sectors for the period 1980-2014 (excluding firn core GUPA-1). For the calculations all time series were detrended and December-November annual averages (calendar year) were considered. The red star denotes the location of the UG region. Only statistically significant correlations ($p$-value < 0.05) are shown.
The red star denotes the location of the UG region. Only statistically significant correlations (p-value < 5%) are shown.
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Table 1: Details on drill locations and basic statistics of the stable water isotope composition and accumulation rates of the six firm cores retrieved from Union Glacier. Basic statistics are also given for the composite stable water isotope and accumulation records spanning the period 1980–2014. In addition, minimum, mean and maximum values of stable oxygen isotope annual means and accumulation rates are given for the period covered by all cores (1999–2013).
Table 7: Dating results for the six firn cores from Union Glacier based on annual layer counting (stable water isotopes and glaciochemistry) and core inter-matching taking SC1a_2 as reference.

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Coordinates (standard)

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Dilling date  

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Schriftdaten (Times New Roman, 9 Pt., English (Australia))
Table 3: Results of cross-correlation analysis for standardized stable water isotope and accumulation composite records from Union Glacier and time series of SAM Index, Multivariate ENSO Index (MEI) and sea ice extent (SIE) in five different Antarctic sectors (annual means). Cross-correlations were calculated considering the record period that is covered by a minimum of three firn cores (1980–2014, excluding firm core GUPA-1). Prominent correlations with a low p-value (< 0.1) are marked bold and if statistically significant (p-value < 0.01, α = 0.05) in red and bold. Prominent correlations are marked bold and if statistically significant (p-value < 0.01, α = 0.05) in red and bold.

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<th>d excess</th>
<th>Accumulation</th>
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<th>MEI Weddell</th>
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References


Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A.C.M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer,


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