**Reply to the 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 firn core GUPA-1 (Chapter 3.3, p 7) and further when we compare the accumulation rates of single firn cores (Chapter 4.2.1, p 10). Chapter 4.2.1 (p 10) starts with an extensive comparison of the different firn 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 bal- ance 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 firn 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-2firn 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* $SO_4^{2-}$*, nor all stable water isotope peaks are considered for the chronology of SCH-2. In general, we consider* $H_2O_2$ *as most reliable parameter for dating as it is directly connected to the insolation cycles (thus to solar radiation). Most maxima and minima in* $H_2O_2$*correspond to maxima/minima in the dD record (a temperature proxy), supporting the* $H_2O_2$*-based dating. In contrast, MSA and* $SO_4^{2-}$ *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* $H_2O_2$ *with MSA and* $SO_4^{2-}$ *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 idependent 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 ($\delta^{18}O/\delta D$ 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.*

| *Firn Core* | | *Winter Minima ($\delta^{18}O/\delta D$)* | *Summer Maxima ($\delta^{18}O/\delta D$)* | *ALC uncertainty (years)* | *Period* | *Total number of years (summer maxima)* | *Offset with respect to ALC dating (Min /Max summer maxima)* |
|---|---|---|---|---|---|---|---|
| *GUPA–1* | *Min* | *18* | *18* | *±3.5* | *1989–2014* | *26* | *+8/+1* |
| | *Max* | *25* | *25* | | | | |
| *DOTT–1* | *Min* | *18* | *19* | *±1* | *1999–2014* | *16* | *-3/-5* |
| | *Max* | *20* | *21* | | | | |
| *SCH–1* | *Min* | *35* | *35* | *±2* | *1986–2014* | *29* | *-6/-10* |
| | *Max* | *39* | *39* | | | | |
| *SCH–2* | *Min* | *40* | *40* | *±5* | *1977–2015* | *39* | *-1/-11* |
| | *Max* | *50* | *50* | | | | |
| *BAL–1* | *Min* | *28* | *28* | *±6.5/±6* | *1980–2015* | *36* | *+8/-4* |
| | *Max* | *41* | *40* | | | | |
| *PASO–1* | *Min* | *37* | *36* | *±4* | *1973–2015* | *43* | *+7/-1* |
| | *Max* | *45* | *44* | | | | |

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.*

*Münch, T. and Laepple, T.: What climate signal is contained in decadal- to centennial-scale isotope variations from Antarctic ice cores?, Clim. Past, 14, 2053-2070, doi: 10.5194/cp-14-2053-2018, 2018.*

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 youcite 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*

*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).*

*Laepple, T., Münch, T., Casado, M., Hoerhold, M., Landais, A. and Kipfstuhl, S.: On the similarity and apparent cycles of isotopic variations in East Antarctic snow pits, The Cryosphere, 12, 169–187, doi:10.5194/tc-12-169-2018, 2018.*

Discussion - I suggest to begin by discussing potential noises (see above), before dis- cussing 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 $\delta^{18}O$ 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 l12: 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 l15: 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 emphazing 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, ie 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):*

$nssS = S - ssNa*(S/Na)_{seawater}$

*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.*

*Bowen, H.J.M.: Environmental chemistry of the elements. Academic Press. London. New York. 1979.*

*Röthlisberger, R., Mulvaney, R., Wolff, E.W., Hutterli, M.A., Bigler, M., Sommer, S. and Jouzel, J.: Dust and sea salt variability in central East Antarctica (Dome C) over the last 45 kyrs and its implications for southern high-latitude climate, Geophys. Res. Lett., 29, doi:10.1029/2002GL015186, 2002.*

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 firn 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 $H_2O_2$, nssS and stable water isotopes for dating only. Accordingly, the dating sequence is: annual layer counting using $H_2O_2$ (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, $SO_4^{2-}$, 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 firn 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 l18: 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. summers). Stable water isotope maxima between two dashed lines have not been included in the ALC (i.e. due to the* $H_2O_2$ *[SCH-2] or nssS [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 l17: 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, forALC we counted a minimum and maximum number of stable water isotope peaks in all firn cores which brackens 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 δD 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, (firn 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 l24: P5 l23: 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 inhomogenities 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, J. Hydrol., 349, 350-363, doi:10.1016/j.jhydrol.2007.11.009, 2008.*

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 re-calculation 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 devide 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-1 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:*** *"t" 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 $\delta^{18}O$ 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 firn cores as the difference between the firn 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 firn-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), firn 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 firn cores' co-isotopic relationships to the supplements (S3a-f).*

*Fernandoy, F., Meyer, H., Oerter, H., Wilhelms, F., Graf, W. and Schwander, J.: Temporal and spatial variation of stable-isotope ratios and accumulation rates in the hinterland of Neumayer station, East Antarctica, J. Glaciol., 56, 673-687, doi: 10.3189/002214310793146296, 2010.*

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 firn 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–1and 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 l5 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 dO18 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 dO18 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 d excess 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 d excess trend is negative. The BAL–1 d excess 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 l14 to l16: 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 $\delta^{18}$O 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 $\delta^{18}$O 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 $\delta^{18}$O annual* *means (S3) reveals statistically significant trends only for cores SCH–1 ($s = +0.039$ ‰ $a^{-1}$, p-value $< 0.05$) and BAL–1 ($s = +0.054$ ‰ $a^{-1}$, p-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 δ-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–square 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.*

*Sen, P.K.: Estimates of the Regression Coefficient Based on Kendall’s Tau. J.Am.Stat.Assoc.. 63. 1379-1389. 1968.*

*Theil, H.: A Rank-Invariant Method of Linear and Polynomial Regression Analysis. Proceedings of the Royal Netherlands Academy of Sciences. 53. 386-392. 1950*

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* $\delta^{18}O$ *variability is explained by near-surface air temperature though.*

P9 l12: 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 l15-16: 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 restructured the chapter. We conclude that the isotope-temperature relationship is weak and give reasons for this. A part of the* $\delta^{18}O$ *variability is explained by near surface air temperature though. This was changed consistently throughout the text.*

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 l5: 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 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 $\delta^{18}O$ and $\delta D$, 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.*

*Burgener, L., Rupper, S., Koenig, L., Forster, R., Christensen, W.F., Williams, J., Koutnik, M., Miège, C., Steig, E.J., Tingey, D., Keeler, D. and Riley, L.: An observed negative trend in West Antarctic accumulation rates from 1975 to 2010: Evidence from new observed and simulated records, J. Geophys. Res.–Atmos., 118, 4205–4216, doi:10.1002/jgrd.50362, 2013.*

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 $\delta^{18}O$ as we think, that it is worth mentioning that it reveals a statistically significant positive trend. This has also been stated in the manuscript. Concenring the use of cityscape vectors see answer above (Figure 6).*

Table 2:  Periods for reconstruction are given it 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

Agosta, C., Amory, C., Kittel, C., Orsi, A., Favier, V., Gallée, H., van den Broeke, M. R., Lenaerts, J. T. M., van Wessem, J. M., and Fettweis, X.: Estimation of the Antarctic surface mass balance using MAR (1979-2015) and identification of domi- nant processes, The Cryosphere Discuss., 2018, 1-22, 10.5194/tc-2018-76, 2018.

Caiazzo, L., Becagli, S., Frosini, D., Giardi, F., Severi, M., Traversi, R., and Udisti, R.: Spatial and temporal variability of snow chemical composition and accumulation rate at Talos Dome site (East Antarctica), Science of the Total Environment, 550, 418-430, 2016.

Schotterer U., Stichler W., Ginot P. (2004): The Influence of Post-Depositional Effects on Ice Core Studies: Examples From the Alps, Andes, and Altai. In: DeWayne Cecil L., Green J.R., Thompson L.G. (eds) Earth Paleoenvironments: Records Preserved in Mid- and Low-Latitude Glaciers. Developments in Paleoenvironmental Research, vol 9, pp. 39-59, Springer, Dordrecht.

Goursaud, S., Masson-Delmotte, V., Favier, V., Preunkert, S., Fily, M., Gallée, H., Jourdain, B., Legrand, M., Magand, O., and Minster, B.: A 60-year ice-core record of regional climate from Adélie Land, coastal Antarctica, The Cryosphere, 11, 343-362, 2017.

Goursaud, S., Masson-Delmotte, V., Favier, V., Orsi, A., and Werner, M.: Water stable isotope spatio-temporal variability in Antarctica in 1960–2013: observa- tions and simulations from the ECHAM5-wiso atmospheric general circulation model, Clim. Past, 14, 923-946, 10.5194/cp-14-923-2018, 2018a.

Goursaud, S., Masson- Delmotte, V., Favier, V., Preunkert, S., Legrand, M., Minster, B., and Werner, M.: Chal- lenges associated with the climatic interpretation of water stable isotope records from a highly resolved firn core from Adélie Land, coastal Antarctica, The Cryosphere Dis- cuss., 2018, 1-55, 10.5194/tc-2018-121, 2018b.

Johnsen, S. J., Clausen, H. B., Cuffey, K. M., Hoffmann, G., Schwander, J., and Creyts, T.: Diffusion of stable isotopes in polar firn and ice: the isotope effect in firn diffusion, Physics of ice core records, 2000, 121-140.

Jones, J. M., Gille, S. T., Goosse, H., Abram, N. J., Canziani, P. O., Charman, D. J., Clem, K. R., Crosta, X., De Lavergne, C., and Eisenman, I.: Assessing recent trends in high-latitude Southern Hemisphere surface climate, Nature Climate Change, 6, 917-926, 2016.

Jones, T., Cuffey, K., White, J., Steig, E., Buizert, C., Markle, B., McConnell, J., and Sigl, M.: Water isotope diffusion in the WAIS Divide ice core during the Holocene and last glacial, Journal of Geophysical Research: Earth Surface, C10122, 290-309, 2017.

Jourdain, B., and Legrand, M.: Year round records of bulk and size segregated aerosol composition and HCl and HNO3 levels in the Dumont d'Urville (coastal Antarctica) atmosphere: Implications for sea salt aerosol fractionation in the winter and summer, Journal of Geophysical Research: Atmospheres, 107, 1-13, 2002.

Stenni, B., Curran, M. A., Abram, N. J., Orsi, A., Goursaud, S., Masson- Delmotte, V., Neukom, R., Goosse, H., Divine, D., and Van Ommen, T.: Antarctic climate variability on regional and continental scales over the last 2000 years, Climate of the Past, 13, 1609-1634, 2017.

Vega, C. P., Schlosser, E., Divine, D. V., Kohler, J., Martma, T., Eichler, A., Schwikowski, M., and Isaksson, E.: Surface mass balance and water stable isotopes derived from firn cores on three ice rises, Fimbul Ice Shelf, Antarctica, The Cryosphere, 10, 2763-2777, 2016.

Interactive comment on The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-161, 2018.

**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 $km^2$ 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 particulate 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 firn 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 avaiable. 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 EAIS. 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 firn 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* $SO_4^{2-}$ *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."*

*Pasteris, D.R., McConnell, J.R., Das, S.B., Criscitiello, A.S., Evans, M.J., Maselli, O.J., Sigl, M. and Layman, L.: Seasonally resolved ice core records from West Antarctica indicate a sea ice source of sea–salt aerosol and a biomass burning source of ammonium. J. Geophys. Res. Atmos., 119, 9168–9182, doi:10.1002/2013JD020720, 2014.*
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 firn-core drill site available (GUPA-1) covering the period 2010-2018, only. Hence, there is no way to retrieve reliable information from the different firn-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 HYSPLIT backward trajectory calculations further back in time. Thus, we believe that the HYSPLIT 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.*

*Thomas, E. R. and Bracegirdle, T.J.: Improving ice core interpretation using in situ and reanalysis data, J. Geophys. Res., 114, D20116, doi:10.1029/2009JD012263, 2009.*

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 (eg. 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 ith 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 $\delta^{18}O$ 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 $\delta^{18}O$ for the height of its coring position, the $\delta^{18}O$-altitude-relationship becomes statistically significant and the coefficient of determination increases substantially and yields: height = -142 * $\delta^{18}O$ – 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.*

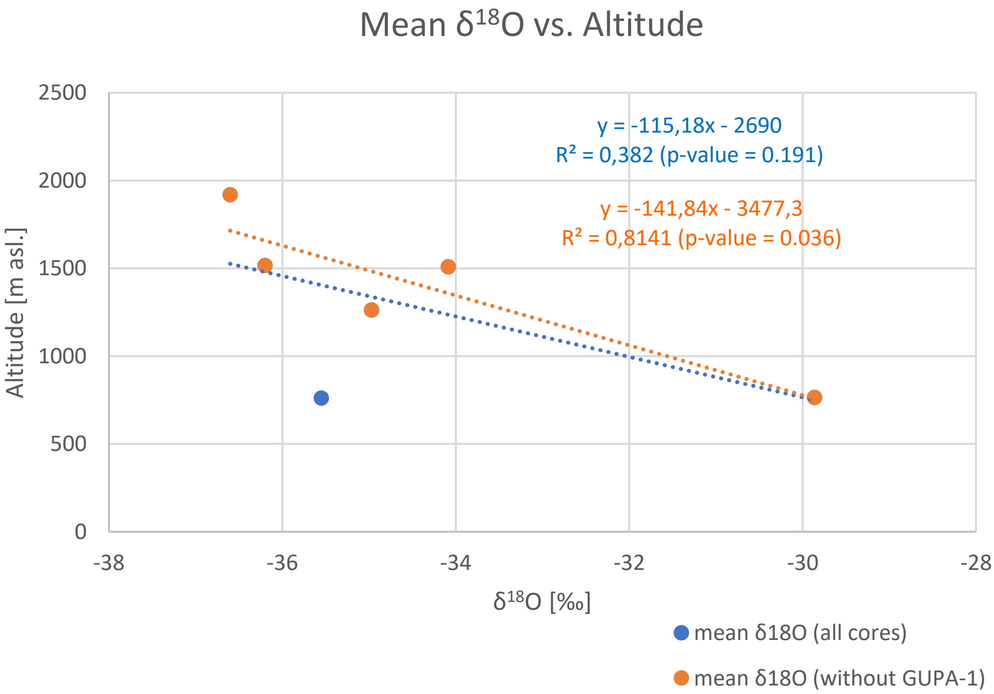


*Figure 1: Relation between mean stable water oxygen compostion and altitude for the UG firn cores considering all six cores (blue) and excluding GUPA-1 (orange), respectively. The equation, the coefficient of determination ($R^2$) and the p-value are given for both linear regressions.*

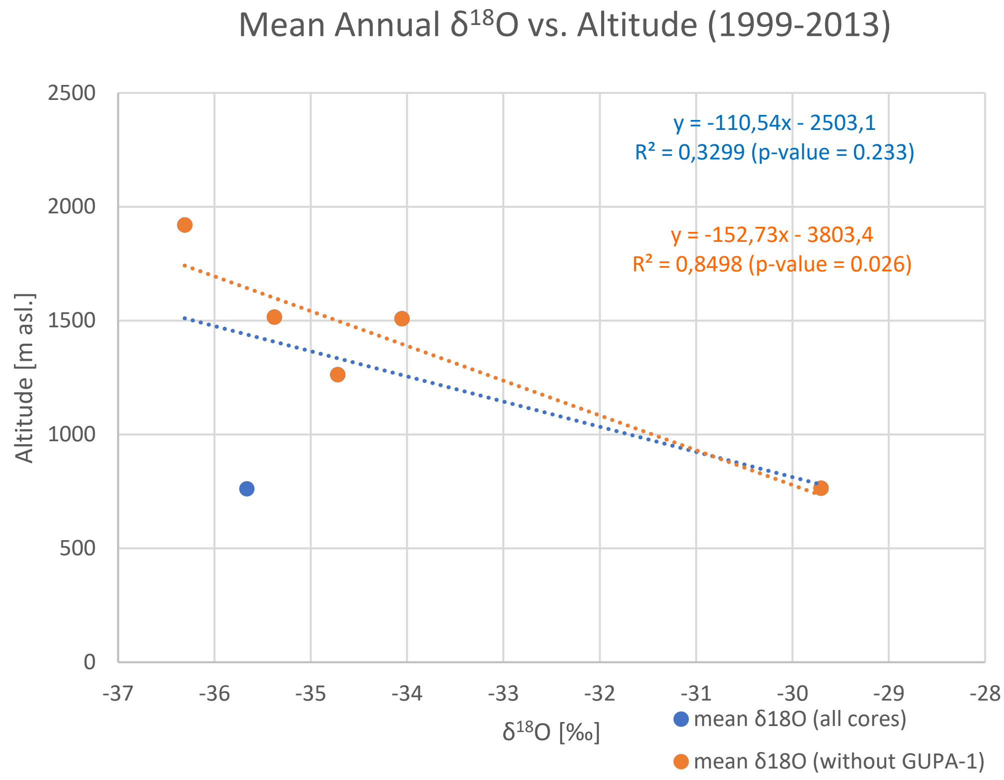


*Figure 2: Relation between mean annual stable water oxygen compostion and altitude for the UG firn cores considering all six cores (blue) and excluding GUPA-1 (orange), respectively, referring to the overlapping period (1999-2013). The equation, the coefficient of determination ($R^2$) and the p-value 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 ($R^2$ = 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 $\delta^{18}$O-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).*

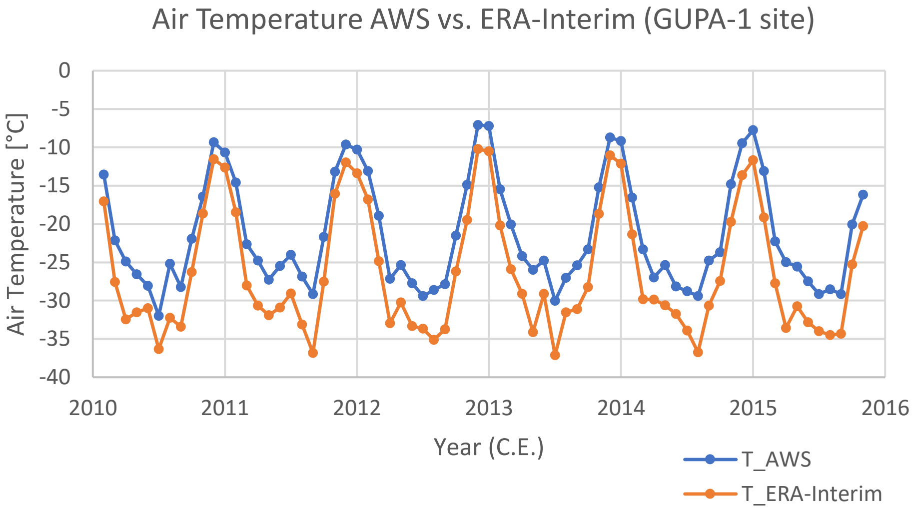


*Figure 3: Comparison between AWS and ERA-Interim monthly mean air temperatures for UG (GUPA-1 drill site) for the period February 2010 – November 2015.*

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-1 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 avaiable. 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.).*

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**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 trayectories for this new version and checked if these are in line with the 3-day trayectories. 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.

Thomas, E. R. and Bracegirdle, T.J.: Improving ice core interpretation using in situ and reanalysis data, J. Geophys. Res., 114, D20116, doi:10.1029/2009JD012263, 2009.

***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.*

*Münch, T. and Laepple, T.: What climate signal is contained in decadal- to centennial-scale isotope variations from Antarctic ice cores?, Clim. Past, 14, 2053-2070, doi: 10.5194/cp-14-2053-2018, 2018.*

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 $\delta^{18}O$ 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.*
*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 $\delta^{18}O$ for the period covered by all cores?

***Answer:*** *We have used only $\delta^{18}O$ 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 firn cores.*

References

Sodemann, H., C. Schwierz, and H. Wernli (2008), Interannual variability of Greenland winter precipitation sources: Lagrangian moisture diagnostic and North Atlantic Oscillation influence. J. Geophys. Res., 113, D03107, doi:10.1029/2007JD008503

# 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 is~~to 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 ($\delta^{18}O$, $\delta D$, 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 isotopes and the d excess ~~composition reveals~~ exhibit 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 sector~~ 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 ~~are~~ 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 ~~are~~ show a weak ~~weakly~~ positive~~ly~~ correlation ~~ed~~ with the SAM.

On average annual snow accumulation in the UG region amounts to about 0.2~~5~~45 m w.~~-~~eq.~~-~~ a$^{-1}$ ~~between~~ in 1980-2014 and ~~1980 and 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

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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

## 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 20$^{th}$ 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. Contemporaneously, precipitation and accumulation rates have significantly increased during the 20$^{th}$ 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 20$^{th}$ 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 Polvani, 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; Stenni et al., 2017). In addition, determined trends are often regionally and/or seasonally contradicting on interannual to decadal or multiannual 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; Stenni 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., 2011; 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; Steig 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; Hosking et al., 2013; Raphael et al., 2015; Burgener 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; Diaz and Markgraf, 1992; Diaz 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 firn 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., 2013) 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, 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 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., 2008), 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 (sub)tropical Pacific (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; Hosking 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 (Karoly, 1989; Diaz and Markgraf, 1992; Diaz and Markgraf, 2000; Turner, 2004; L'Heureux and Thompson, 2006).

Add sector about EAIS!!!

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, supposedly 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; Stenni et al., 2017). However, Steig et al. (2009) 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 thefor most of Antarctic continenta, and, thus proxy data derived from firn 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 (EAIS) data is generally sparse, and little or no long--term meteorological data are available from 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 its susceptibility to destabilization and disintegration under a warming climate (Hellmer et al., 2012; Hellmer et al., 2017), as already observed for ice shelfs 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 to at improve improving our understanding of climate change at the intersection area between the AP, the WAIS and the EAIS based on firn--core stable water isotope data from the Union Glacier (UG) region, located in the Ellsworth Mountains at the northern edge of the WAIS (79°46' S, 83°24' W; 770 m above sea level [asl.asl]; Fig. 1a). Union Glacier (79°46' S, 83°24' W; 770 m above sea level [asl.asl]) 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 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 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 firn 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

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**Formatiert:** Schriftart: (Standard) Times New Roman, Nicht Hervorheben 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 at 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 ones being Union and Schanz Glaciers – –covering an estimated total area of 2561 km$^2$. 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. and tThe bedrock is located below sea level (–-858 m; Rivera et al., 2014).

Here wWe 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 ice-core drill (Backpack Drill; icedrill.ch AG), at different locations ranging between 760 m asl.asl (GUPA–-1 and DOTT–-1) and 1900 m asl.asl (PASO–-1) in altitude. : . GUPA–-1 has beenwas coreddrilled near the ice-landing strip on UG and, DOTT–-1 (comesoriginates -from an ice rise towards the Ronne-Filchner Iice Sshelf. ), 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). ). ) and 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 2.5 cm resolution and analysed for stable water isotopes using a cavity ring–-down spectrometer (L2130–-*i*; Picarro Inc.) coupled to an auto–-sampler (PAL HTC–-xt; 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 per mil (‰) versus VSMOW2. Precision of the measurements is ±better than 0.08 ‰ for $\delta^{18}$O 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 45EP; Los Gatos Research) was used with a precision of being better than 0.1 ‰ for $\delta^{18}$O and 0.8 ‰ for δD (Fernandoy et al., 2018). Each sample was measured twice in different days, using ten repeated injections from which the first four were discarded. on each measurement. 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 ~~c~~m resolution using a Picarro L2130~~–~~-*i* analyser with measurement precision of 0.08 ‰ for $\delta^{18}O$ and 0.5 ‰ for δD. Major ions ($Cl^{-}$, $NO_3^{-}$, $SO_4^{2-}$, $MSA^{-}$, $Na^{+}$, $K^{+}$, $Mg^{2+}$, $Ca^{2+}$) were measured at 0.05 ~~c~~m 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 $H_2O_2$ at high resolution (~1 mm; Continuous Flow Analysis [CFA]); McConnell et al., 2002). In addition, core PASO~~–~~-1 was analysed for liquid conductivity, $H_2O_2$, $NO_3^{-}$, $NH_4^{+}$, 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 Element2 ICP~~–~~-MS instruments. Subsequently, values of ssNa (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 t~~The corrected and calibrated $\delta^{18}O$ and δD values were used to calculate ~~,~~ the d excess ~~was calculated~~ (d excess = δD~~–~~-8*$\delta^{18}O$; Dansgaard, 1964) ~~and~~ and to derive a co~~–~~-isotopic relationship (δD = m* $\delta^{18}O$ + 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 - at a first approximation – can be referred to as LMWL at UG.

## 2.~~3~~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 ($\delta^{18}O$ 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, ~~F~~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 ~~: Methanesulfonic acid (MSA), $SO_4^{2-}$, the Cl/Na~~–~~ratio and~~ on $H_2O_2$ for SCH~~–~~-2 (Fig. 2) and nssS ~~(non~~–~~sea salt S) and the nssS/ssNa (sea~~–~~salt Na)~~–~~ratio~~ for PASO~~–~~-1 (Fig. 3). $H_2O_2$ and nssS ~~as these parameters e~~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 methanesulfonic acid (MSA), $SO_4^{2-}$ and the Cl/Na-ratio were used for corroborating the years identified by ALC of $H_2O_2$ 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~~found via 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 (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. 3)~~. For cores ~~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. ~~were dated based on ALC of stable water isotopes and matching to the SCH~~–~~2 age scale. 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.~~

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~~1~~).

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Composite stable water isotope and accumulation records 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 firn core the same weight and to not overrepresent a certain firn core drill site annually averaged data were standardized ~~(z = x-μ/σ; citation????)~~ before stacking (Stenni et al., 2017; Eq. S4). Linear trends were calculated and tested for their statistical significance using the non-–-parametric Mann-–-Kendall Tau 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 firn cores were estimated according to Fisher et al. (1985; Eq. S5).

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**2.43 Meteorological database and backward trajectory analysis**

Meteorological data from an automatic weather station (AWS) located at the UG ice runway (79°~~47'~~ 46' S, 8~~2~~3°~~53~~16' W, 705 m ~~asl.~~asl; Fig. 1b) covers the ~~a~~ 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.~~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 firn-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 firn core across it's entire length.~~

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~~In addition, we~~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-–-Interim; 1979-2019 ~~onwards~~; spatial resolution: 79 km; 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.

~~We~~ For the comparison with UG stable water isotopes and accumulation rates ~~M~~mean 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://neptune.gsfc.nasa.gov/csb/index.php). 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-–-0079 –- 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 ~~this comparison, we~~ used the Marshall SAM Index (Marshall, 2003) as indicator for the prevailing SAM phase (available at: https://legacy.bas.ac.uk/met/gjma/sam.html) and the Multivariate ENSO Index (MEI; Wolter and Timlin, 1993, 1998) as indicator for the occurrence and strength of El Niño and La Niña events (available at: https://www.esrl.noaa.gov/psd/enso/mei/table.html).

Mean 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://neptune.gsfc.nasa.gov/csb/index.php). 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–-0079 –- 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/nside–-0079; 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 and p–-values at the 95% confidence level. ERA–-Interim reanalysis data were annually averaged and detrended before the analyses.

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 firn core SCH-1 was taken as initial point for the calculation of 5–-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 firn-core drill sites the most more representative for snow fall events in the UG region. Input data for the of 5–-day backward trajectory 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 1061 m asl.asl for the period 2010–-2015 from the nearest grid point for the period 2010–-20145 (resolution: 0.75°x0.75°; available at: http://apps.ecmwf.int/datasets/data/interim–-full–-daily/levtype=sfc/) served as input to extractidentify precipitation events aton a daily scale. We used a minimum threshold corresponding to 1% of the annual accumulation (i.e. ~2.5 mm $d^{-1}$see below), a value that in terms of percentage is is percentually equivalent to the one using a similar procedure as applied applied by Thomas & Bracegirdle (2009). input data for the calculation of 3–-day backward trajectories. The location of the AWS Arigony (see above) corresponding to the drill site of firn core SCH-1GUPA-1 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), Iin total, 121 backward trajectories were calculated corresponding tofor 210 singledaily precipitation events occurring in the period 2010–-201420154. They were then , and subdivided into their respective seasons (DJF, MAM, JJA and SON). . InFurthermore, iIndividual backward trajectories were later combined into four different clusters, that group single 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 is –-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$ms^{-1}$ with a predominant direction from SW (220°). The maximum wind speed recorded was is 29.7 m/s$ms^{-1}$. Generally (> 75%), wWind

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speeds are higher than 1.2 ~~m/s~~$ms^{-1}$ 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.

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### 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 ($\delta^{18}O$) of the six firn cores are displayed with respect to depth in 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). The number of years identified in each core by ALC and the respective period covered is summarized in Table 2.~~ Core DOTT~~–~~-1 (16 years, 1999~~–~~-2014) exhibits the shortest and PASO~~–~~-1 (43 years, 1973~~–~~-2015) ~~t~~the longest record. Note that for age~~–~~-model construction of GUPA~~–~~-1 two years (1990, 2001) and of BAL~~–~~-1 three years (1981, 1983 and~~,~~ 1994) were only identified from ~~by~~ linear interpolation and are not clearly visible in the stable water isotope records due to smoothing ~~of the stable water isotope records~~ 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). ~~Furthermore, f~~For all cores the last year (either 2014 or 2015) was excluded from further ~~the~~ analys~~e~~is 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 ~~isotopic~~ 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 $\delta^{18}O$ and from –-285.9 ‰ (PASO–-1) to –-233.1 ‰ (DOTT–-1) for δD, respectively (~~Table 1). Absolute minimum δ~~–~~-values are found in GUPA~~–~~-1, absolute maximum δ~~–~~-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 records (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 slopes of the co~~–~~-isotopic relationship (Table 1 and S 6a-f) ~~Fig. 5a-g)~~ ~~is~~ is ~~are~~ close to that of the Global Meteoric Water Line (GMWL; Craig, 1961) for all ~~individualall~~ firn cores ranging between 7.94 (GUPA-1) and 8.24 (PASO-1). Hence, the ~~atmospheric meteoric~~ origin ~~of the~~ al (oceanic) 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 δD values are highly correlated ($R^2 \geq 0.98$) with the largest variation in d excess observed for SCH~~–~~-2 (values range from ~~: –~~-5.6 ‰ ~~and~~ to 17.2 ‰). The LMWL of the UG study region was determined as $\delta D = 8.02*\delta^{18}O + 6.57$ ($R^2 = 0.99$; Fig. 5~~g~~).

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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.

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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). ~~Highest mean accumulation rates (≥ 0.28 m w.eq.$a^{-1}$) were found for DOTT–-1and 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.$a^{-1}$). In general,~~

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Formatiert: Nicht Hochgestellt/ Tiefgestellt aAnnual 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, inIn 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 firn.

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; Kaczmarska 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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 firn 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 $\delta^{18}O$, 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 firn 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 rates 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 firn core records allow to deduce temporal changes in stable water isotopes and accumulation rates on a regional scale.

**4.1 2 Spatial and temporal variability of firn core stable water isotope composition and relation to near-surface air temperatures, sea ice and climate modes**

**4.1.2.11 Spatial and temporal variability of stable water isotopes**

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 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, firn 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 $\delta^{18}O$ annual means for the overlapping period (1999–-2013; Table 1 and Fig. S7S3)), 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 greatesthighest altitude and greatest distance from the sea shows lowest lightest mean $\delta^{18}O$ values (-36.43 ‰), whereas the low-altitude firn core DOTT-1, which is situated closest to the sea, displays a distinctly heavierhigher mean stable water isotope isotope composition (-29.7 ‰). However, core SCH-2 exhibits less depleted mean $\delta^{18}O$ 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 $\delta^{18}O$-altitude-relationship calculated from $\delta^{18}O$ annual means for the overlapping period (excluding GUPA-1) yielding: altitude = -152.7*$\delta^{18}O$ - 3803.4 with $R^2$ = 0.85 and p-value = 0.026 (Fig. S12).

The individual firn cores are generally well correlated with each other for $\delta^{18}O$ and δD, for both the maximum overlapping period between two individual cores and the overlapping period (1999-2013; (S49 and S10).). All cores display a common $\delta^{18}O$ maximum in summer 2002 (Fig. 7). The cCorrelation coefficients are highest for nearby firn cores such as SCH-1 and SCH-2 reaching up to r = 0.66 (p-value = 0; 1999-2013: r = 0.58, p-value = 0.025) for $\delta^{18}O$ and r = 0.71 (p-value = 0; 1999-

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2013: r = 0.66, p-value = 0.007) for δD. Only core BAL-1 shows relatively low correlations with all other cores except for SCH-1 (r = 0.44, p-value = 0.019 for $\delta^{18}$O, r = 0.43, p-value = 0.024 for δD; 1999-2013: r = 0.49, p-value = 0.063 for $\delta^{18}$O, r = 0.50, p-value = 0.06 for δD; Tables S9 and S10). The results of the cross-correlation analysis (Tables S9 and S10), the negligible influence of diffusion and ~~r= 0.66 for $\delta^{18}$O and 0.71 for δD.~~ the relatively high signal-to-noise ratios allowed to construct a composite ~~Hence, an overall mean~~ $\delta^{18}$O-record (UG $\delta^{18}$O-stack) ~~has been constructed~~ based on ~~from~~, ~~both for non-standardized and sta~~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 $\delta^{18}$O-stack ~~This allows to draw a~~ a more regional picture of the isotopic characteristics of precipitation at UG can be drawn. ~~without overrepresenting a certain firn core drill site.~~ As a result, ~~From this~~ we found only a negligible positive trend in $\delta^{18}$O which is statistically not significant (s = +0.003, p-value = 0.517). Thus, we infer that at UG regional changes in $\delta^{18}$O 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 [Mulvaney 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 ~~to~~ mentioning that stacking of ~~From the non-standardized UG~~ firn core $\delta^{18}$O- time series without previous standardization (excluding GUPA-1) ~~stack~~ yields a statistically significant positive trend of s = +0.058 ‰ $a^{-1}$ (p-value < 0.0001; Fig. 8). This trend most likely results from the dominance of SCH-1 and BAL-1 as these are the only cores showing statistically significant (positive) trends (S~~3~~7). ~~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 $\delta^{18}$O trend is still preserved which is, however it is not statistically not significant anymore (s = +0.003, p-value = 0.517). From this we infer that the regional increase changes in $\delta^{18}$O 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~~ d excess time series of individual firn cores ha~~s~~ve been inter-compared (Fig. S8). ~~Furthermore, in l~~In line ~~ine~~ with $\delta^{18}$O ~~d18O and dD,~~ the ~~second order parameter~~ d excess does not show clear trends or similar contemporaneous changes among the firn 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 d excess record (UG d excess-stack) that has been calculated for the period 1980-2014 (excluding GUPA-1; Fig. 8) despite ~~Although the~~ the individual firn cores showing no cross-correlations in the d excess (Tables S9 and S10~~S4~~). ~~, a composite d excess record (UG d excess -stack) has been calculated (non-standardized and standardized) and analysed for the period 1980-2014 (Fig. 8). Neither the non-standardized nor the standardized records exhibit a statistically significant trend.~~ Dissimilarities between d excess trends of individual firn cores might be partly explained by the presence of orographic barriers that separate the different drill sites from each other and thus might lead to dissimilarities 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 firn core $\delta^{18}$O and seasonal means of AWS-derived near-surface air temperature for the overlapping period February 2010 - November 2015 (Fig. S13) revealed a statistically significant positive $\delta^{18}$O-T relationship ($\delta^{18}O = 0.175 \cdot T - 31.6$, $R^2 = 0.21$, p-value = 0.03). ~~Linear regression between non-standardized seasonal means of AWS-derived UG near-surface air temperature and UG $\delta^{18}$O for the period 2010-2015 (S86) revealed a statistically significant positive $\delta^{18}$O-T relationship ($\delta^{18}O = 0.175 \cdot T - 31.6$, $R^2 = 0.21$, p-value = 0.03 [α = 0.05]).~~ ~~i.e.~~ increasing air temperatures ~~are generally~~ being linked with increasing $\delta^{18}$O-values. In order to test the $\delta^{18}$O-T relationship for the entire period covered by the UG $\delta^{18}$O-stack (1980-2014), monthly means of ~~ERA-interim~~ ERA-Interim near-surface air temperatures ~~extracted for the GUPA-1 site, that is the firn core site closest to the two AWS,~~ were correlated

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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 ($R^2$ = 0.99, p-value = 0) allowing to calculate a $\delta^{18}$O-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 $\delta^{18}$O. The two records show a very high correlation ($R^2$ = 0.99, p-value = 0) allowing to calculate a $\delta^{18}$O--T relationship for the entire period of the UG $\delta^{18}$O--stack based on seasonal means of ERA-interim near-surface air temperatures and UG $\delta^{18}$O. The latter yields $\delta^{18}$O = 0.128*T--31.7 ($R^2$ = 0.22, p--value = 0 [α = 0.05]) that is very similar to the $\delta^{18}$O--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 $\delta^{18}$O--values. However, as As this relationship is only weak, a proper inference of near--surface air temperatures from $\delta^{18}$O 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 $\delta^{18}$O seasonal means assuming that precipitation at the study site is evenly distributed throughout the year.

In order to further test the $\delta^{18}$O--T relationship, the UG $\delta^{18}$O--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 firn 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 temperature, if real, must have been small during the last 35 years. Apparently, the UG record is highly susceptible to minor changes in data processing and thus 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., 2016), 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], Berkner Island [Mulvaney et al., 2002; Stenni et al., 2017]). tFurthermore, theThe observation of rather constant stable water isotope -isotope time series at UG is are facing a period with significant warming on the WAIS (Bromwich et al., 2013), but no -absence of a clear regional warmingair temperature change on the AP (-on the AP since the late 1990s (Turner et al., 2016), although the tipping point from warming to cooling is not visible in the UG dataset. It is also in line with) and the EAIS (Turner et al., 2005; Schneider et al., 2006; Smith and Polvani, 2016). ; -For instance, aA slightly negative, but statistically not significant trend in air temperature (-0.11±0.47 °C) has been observed in the instrumental record from of Halley research station (1957-2000: (-0.11±0.47 °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 $\delta^{18}$O values in the UG region capture regional air temperature variations only to some extent during a period of rather constant climate conditions.

From time--series analysis of d excess 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 = --



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0.110 ‰ $a^{-1}$, p--value = 0.015) and SCH--1 (s = --0.052 ‰ $a^{-1}$, p--value < 0.0001) the d excess trend is negative. The BAL--1 d excess record exhibits no trend. In order to detect possible changes in the origin of precipitating air masses reaching the UG region a composite d excess record (UG d excess--stack) has been calculated (non--standardized and standardized) and analysed for the period 1980--2014 (Fig. 8). Neither the non--standardized nor the standardized record exhibits a statistically significant trend suggesting little change in the main moisture sources and the origin of air masses precipitating over the UG region since at least 1980.

**4.1.2 Relation of stable water isotopes to meteorological data records**

Linear regression between non--standardized seasonal means of UG near--surface air temperature and UG $\delta^{18}O$ for the period 2010--2015 (S6) revealed a statistically significant positive $\delta^{18}O$--T relationship ($\delta^{18}O = 0.175*T - 31.6$, $R^2 = 0.21$, p--value = 0.03 [$\alpha = 0.05$]). 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. 9a). 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 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.

**4.1.3 2.3 Relation of stable water isotopes to large--scale climate modes and sea ice variability**

Standardized mMean annual d excess values (UG d excess--stack) exhibit a weak positive correlation with the SAM Index (0.40, p--value = 0.026; Table 32). 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 d excess 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. 9bc) 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 d excess values of precipitation in the UG region. However, standardized mean annual δ--values (UG $\delta^{18}O$ [δD]-stack) show no correlation with the SAM Index (Table 32). Furthermore, none of the standardized isotopic values exhibits a significant correlation with the MEI Index (Table 23). Hence, oceanic circulation changes associated with the alternation between El Niño and La Niña events seem to have a detectable no visible 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 d excess-stacks standardized UG stacks of δ--values and d excess, the only (weak)positive correlation is found between UG d excess and SIE in the Indian Ocean sector (0.315, p--value = 0.074; Table 32). 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

(46%) throughout the year, closely followed by Coats Land and DML (35%). The latter finding is consistent with the observation of a positive correlation between the UG $\delta^{18}O$-stack and ERA-Interim near-surface air temperatures in these regions (Fig. 9a; see above). Nevertheless, during winter (JJA) and spring (SON) a small percentage of precipitating air masses reaching UG might also originate from the Indian Ocean sector (Fig. 11) supporting the findings from cross-correlation analysis (Table 2).

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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 standardized mean annual $\delta^{18}O$ and d excess values in the UG region (r < –-0.6; Fig. 11a121a and b) corroborating the results of the backward trajectory analysies. Thus, higher or (lower) $\delta^{18}O$ and d excess values at the UG site correspond to a reduction or (increase) in SIC in the northern Weddell Sea, respectively. Consequently, reduced SIC in the northern Weddell Sea implies enhanced availability of proximal surface level moisture which (Tsukernik and Lynch, 2013) which would support higher δ– -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.

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

#### 4.23.1 Spatial and temporal variability of accumulation rates

For the overlapping period (19989–-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$^{–-1}$ (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). The observed negative trends in accumulation rates are at the same order of magnitude as those reported by Burgener 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, Iit 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 –- 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, here accumulation trends might be better preserved in these records.

Analogously to the UG $\delta^{18}O$–-stack a composite accumulation time series (non-standardized and standardized) has been constructed and analysed 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 firn 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" - 80°12'40"S, 80°56'13" - 82°55'52"W, 460-814 m asl, 2008-2009: up to 0.2 m w.eq.a$^{-1}$; Rivera et al., 2014), regional atmospheric model outputs (1980-2004: 0.086 ±2 - 0.328 ± 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 01-5 (77°03'32.4"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 firn 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 0.182 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 aan 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 outputs (1980-2004: 0.09 - 0.33 m w.eq.a$^{-1}$, horizontal model resolution: 55 km;; van de Broeke et al., 2006), or from the close- by location of Patriot Hills (80°18' S, 81° 22' W, 1246 m asl.asl, 1995: 0.1 m w.eq.a$^{-1}$; Casassa et al., 1998) and the closest ITASE (International Trans- Antarctic Scientific Expedition) ice core 01- 5 (77° 3' 32.4" S, 89° 8' 13,2" W, 1246 m asl.asl, 1780-2001: 0.39 m w.eq.a$^{-1}$; Kaspari et al., 2004).

Analogously to the UG $\delta^{18}O$ 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 smallslightly, 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; Frieler et al., 2015; Thomas et al., 2008; Thomas et al., 2017) and in coastal Ellsworth Land (Thomas et al., 2015). 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 Fimbul Ice Shelf, DML, revealed a negative trend for the second half of the 20th century (Kaczmarska et al., 2004; Schlosser et al., 2014; Altnau et al., 2015). Medley and Thomas (2019) also report a generally decreasing trend in snow accumulation for the EAIS 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 Adélie 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; Frieler 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.

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

The linkage 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 (Tsukernik and Lynch, 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 is the most likely a strong moisture source regions for UG in all seasons of the year for UG (Fig. 10 and 1011)0 and see above). 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 incapacities of the ERA-Interim model. Surprisingly, there does not appear to be a relationship between either SIE or SIC SIC 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

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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).

~~. Instead, there is a~~ Furthermore, there is a very weak positive correlation of snow accumulation at UG with SIC in the Bellingshausen Sea sector (Fig. ~~11c~~12~~1~~c). 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 ~~3~~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. 9b). 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 orography of the Ellsworth Mountains, or be evidence of post-depositional processes at the firn core sites (wind erosion, snow deposition and/or drift).~~

**5. Conclusions**

~~In this study, w~~We examined six firn cores from the Union Glacier region in the Ellsworth Mountains (79º46' S, 83º24' W) situated at the northern edge of the West Antarctic Ice Sheet. ~~Based on~~ For all analysed firn cores, ~~composite~~ time series of δ~~-~~-values, d excess 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 (δD = 8.02*$\delta^{18}$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 firn 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 firn 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 firn 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 isotope-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 δ~~-~~ and d excess values in the UG region (UG $\delta^{18}$O- and 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 d excess values and SIE in the Indian Ocean sector. However, ~~, but no concurrent relation exists with SAM and ENSO.~~ ~~B~~backward trajectory analyse~~i~~s ~~confirm~~ suggests that the Weddell Sea sector, ~~and~~ Coats Land and DML are ~~is~~ the ~~likely~~ dominant source regions for precipitating air masses reaching the UG site. Mean annual δ-values are neither correlated with SAM nor with ENSO, but ~~Standardized m~~mean annual d excess values exhibit a weak positive correlation with ~~the~~ the SAM

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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 periodin 1980-2014 and . In contrast to stable water isotopes, mean annual accumulation in the UG region has slightly decreased during this period since 1980 (non-standardized: -0.001 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 of West Antarctica during the last decades have not 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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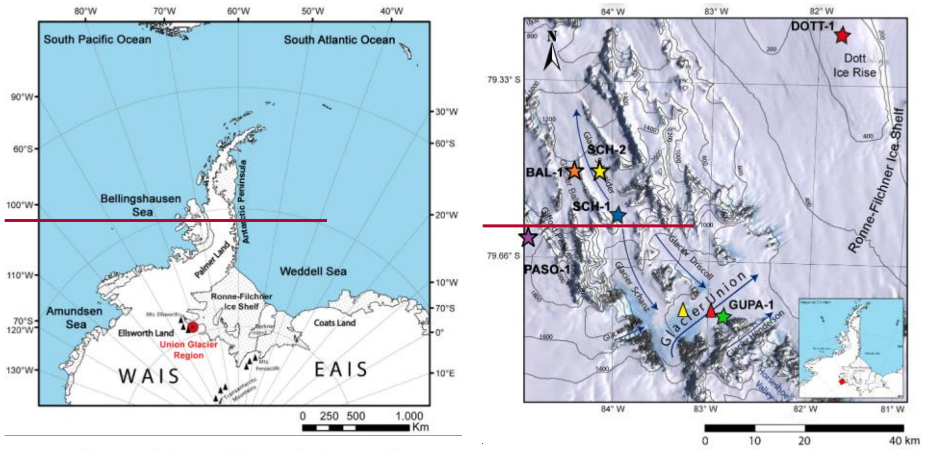
*Data Availability.*

The data will be made publicly available via: www.pangaea.de.



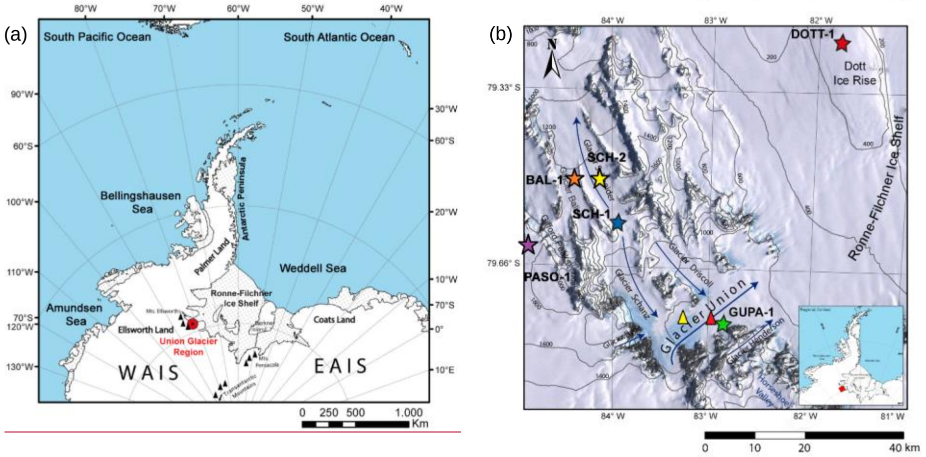




Figure 1a-b: Location of the UG region within Antarctica (a) and location of the drill sites of the six firn cores (GUPA-1, DOTT-1, SCH-1, SCH-2, BAL-1, PASO-1) within the UG region (b). The triangles in (b) denote the location of two automatic weather stations on UG (yellow: station Wx7; red: station Arigony; 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).

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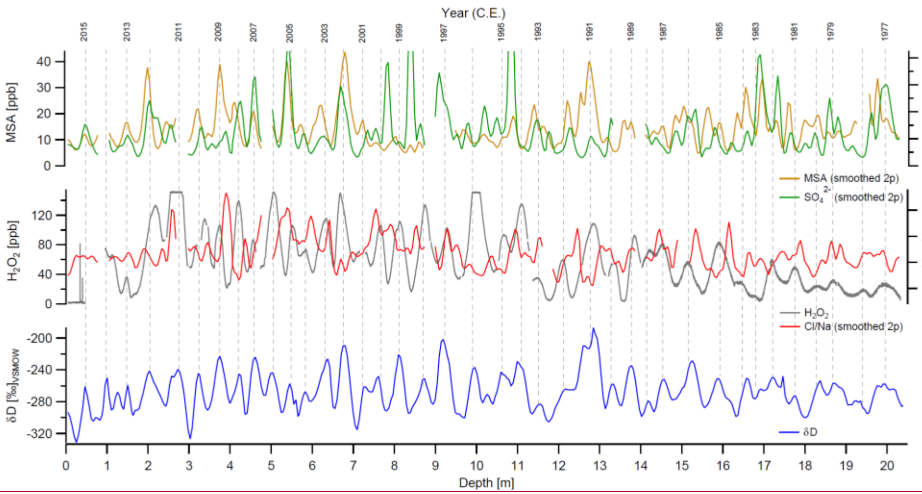


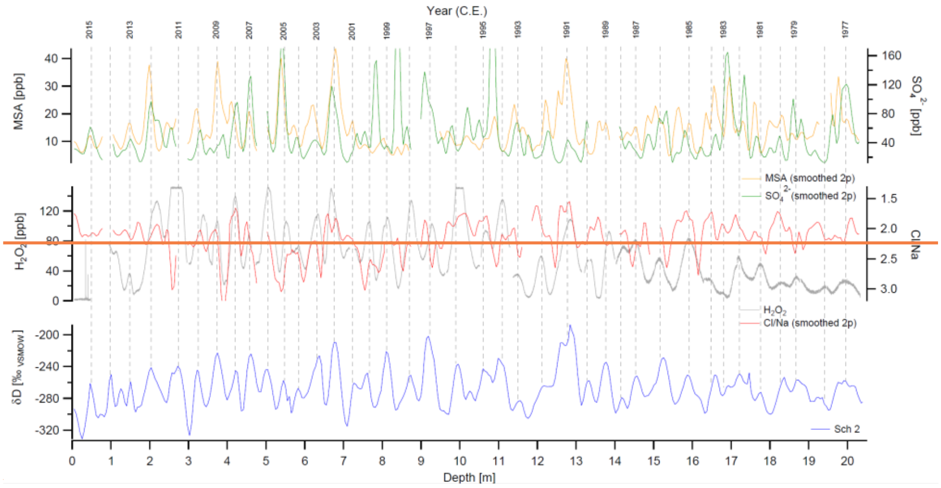
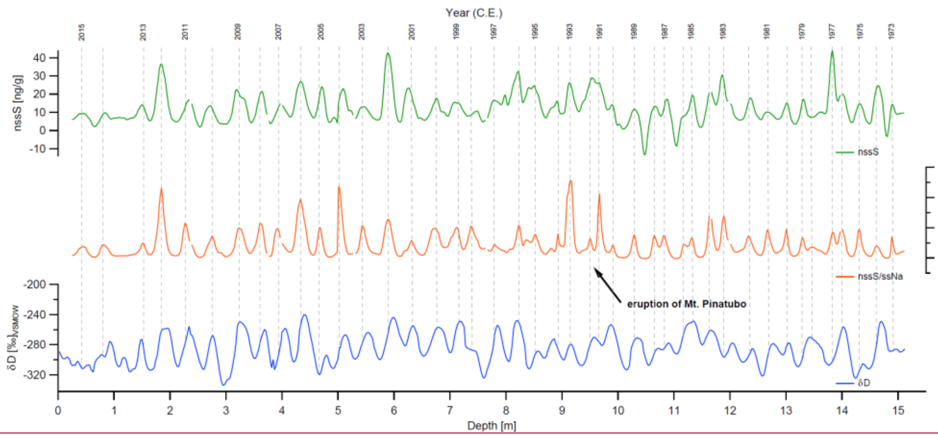



Figure 2: Age scale for firn core SCH-2 constructed by counting and inter-matching of maximum peaks (dashed lines) in CFA-derived profiles of stable water isotope composition (δD) and different chemical parameters ($H_2O_2$, Cl/Na, MSA and $SO_4^{2-}$). Smoothed 2P is a 2-point running average. Note, 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.

~~Age scale for firn core SCH-2 constructed by counting and inter-matching of maximum (minimum) peaks in CFA-derived profiles of stable water isotope composition (δD) and different chemical parameters ($H_2O_2$, Cl/Na, MSA and $SO_4^{2-}$).~~



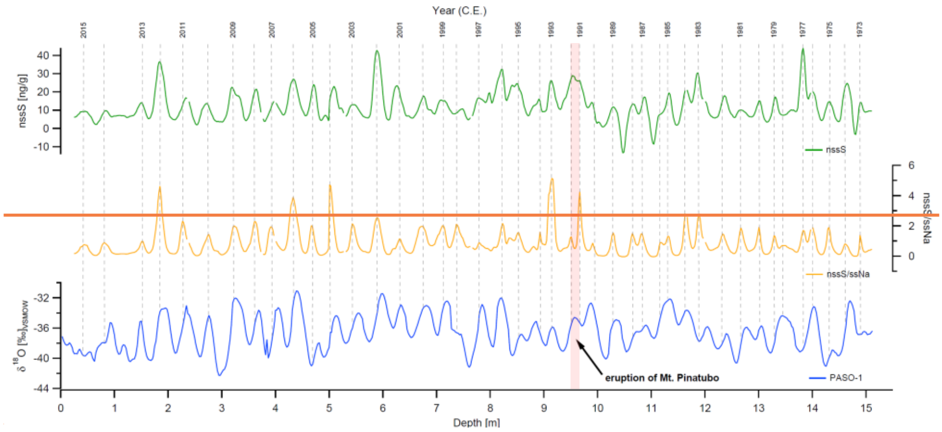
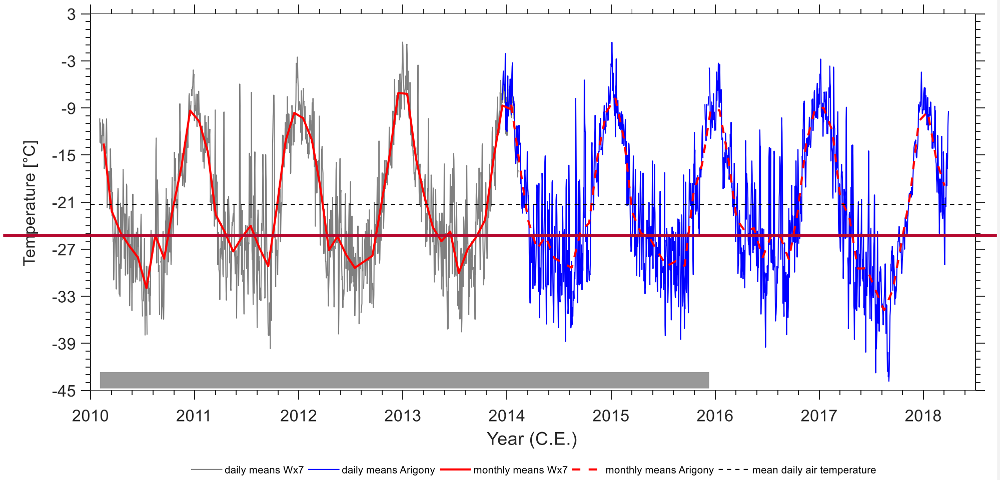



Figure 3: Age scale for firn core PASO--1 constructed by counting and inter--matching of maximum (minimum) peaks (dashed lines) in profiles of stable water isotope composition (δD$\delta^{18}O$) as obtained from discrete sample measurements and in CFA--derived profiles of nssS and nssS/ssNa, respectively. 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 δD due to the different seasonality of the proxies.



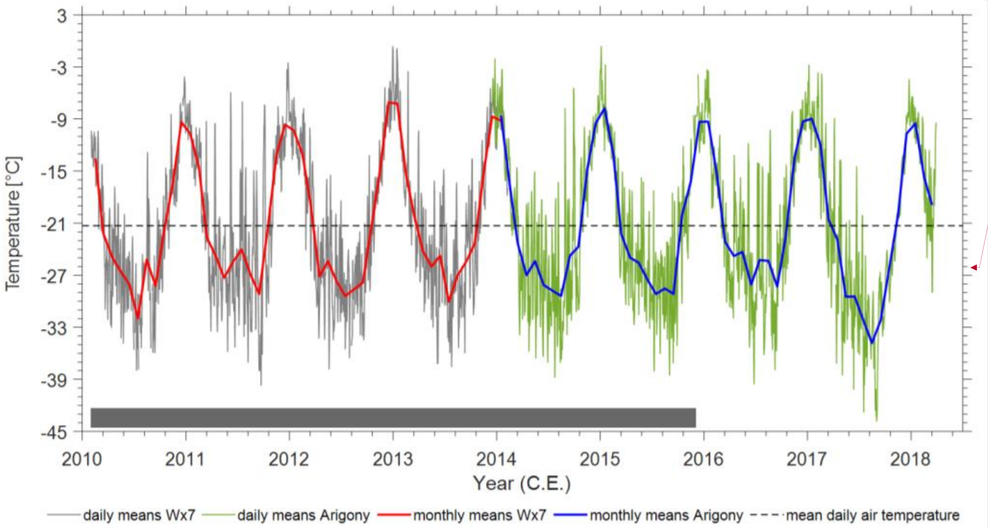



Figure 4: Composite record of mean daily and mean monthly air temperatures recorded at two nearby Union Glacier AWS sites (stations: Wx7, Arigony) from February 2010 to March 2018. The mean daily air temperature for the entire composite record period (~~–~~-21.3°C; dashed black line) and the period overlapping with Union Glacier core records (February 2010 to November 2015; grey bar) are also indicated.

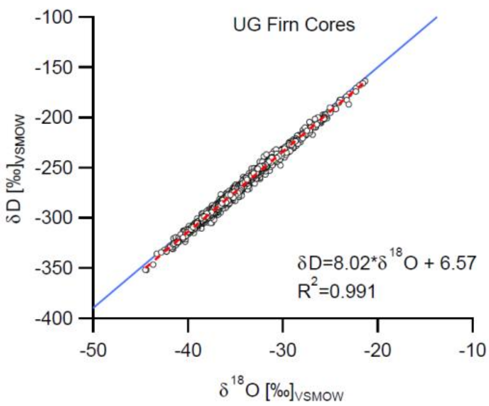



Figure 5~~a-g~~: Composite ~~C~~co~~-~~-isotopic relationship~~s~~ ($\delta^{18}O$ vs. $\delta D$) based on all individual samples (n = 2348; white dots) of ~~for all individual samples of~~ the six firn cores from Union Glacier with ~~(a-f). For each firn core t~~the equation and the coefficient of determination ($R^2$) of the linear regression (red dashed line~~s~~). ~~is shown.~~ The Global Meteoric Water Line (GMWL) is indicated in blue. The composite co~~-~~-isotopic relationship ~~with its equation and $R^2$ that~~ is referred to as the Local Meteoric Water Line (LMWL) of the Union Glacier region. ~~is also displayed (5g).~~

**Formatiert:** Links

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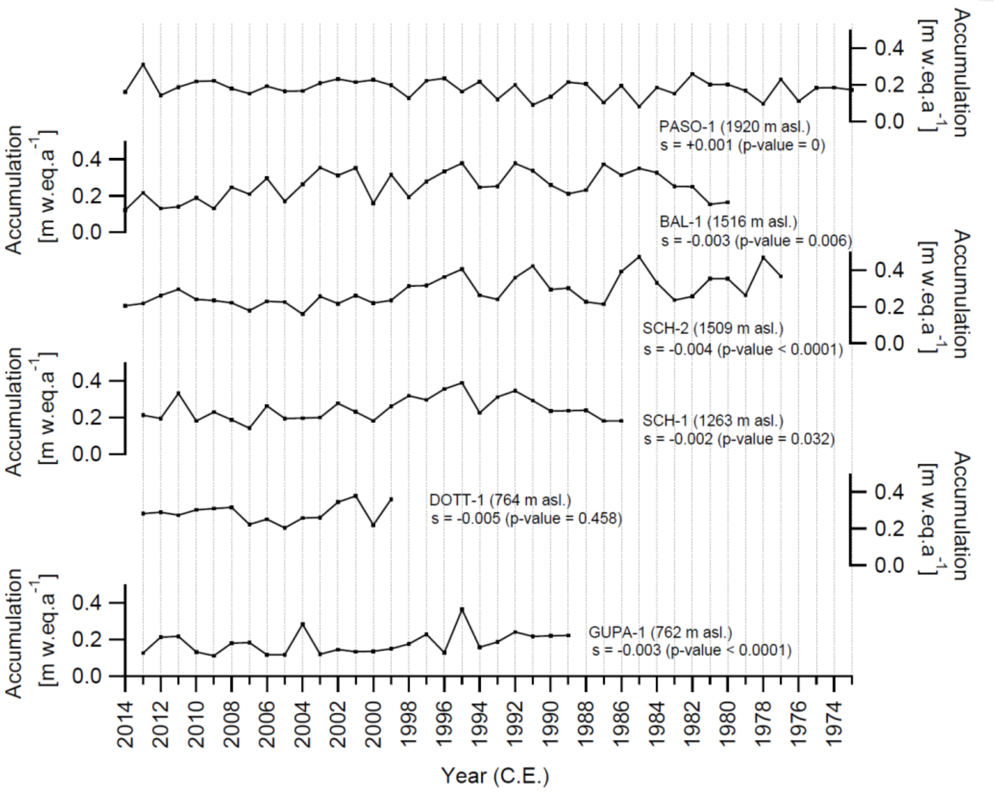


Figure 6: Annual Aaccumulation rates at the drill sites of the six firn cores from Union Glacier for the period covered by the respective firn core. Sen slopes (s in m w.eq.a$^{-1}$)) and p--values are given for all firn cores indicating that accumulation has decreased at most sites since the beginning of the record period.

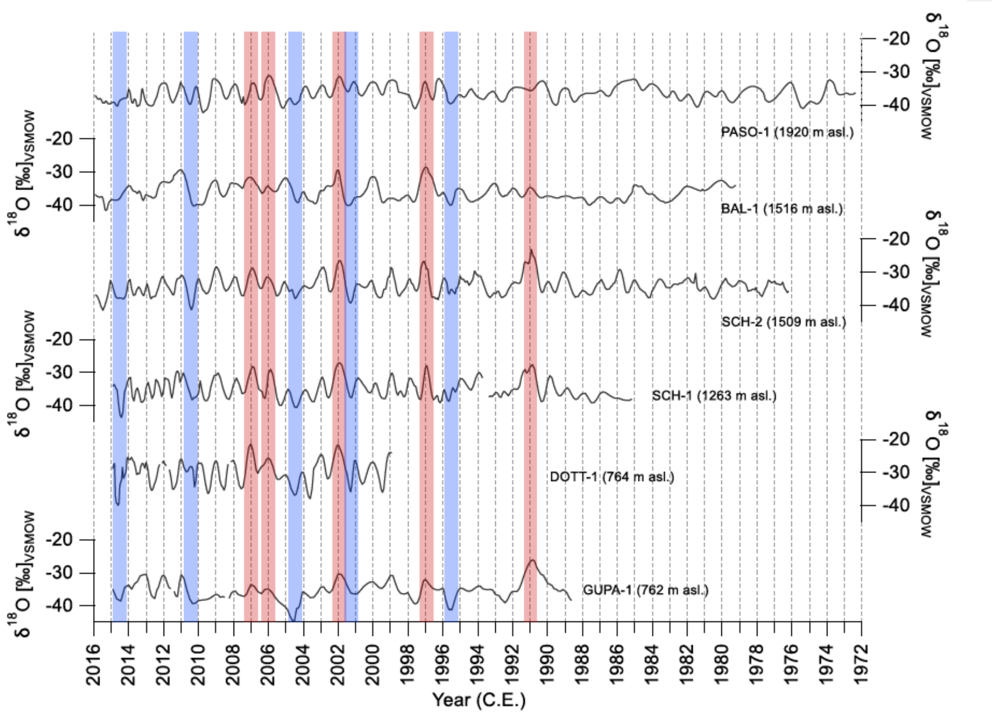


Figure 7: Profiles of the stable water isotope composition ($\delta^{18}O$) of the six firn cores from Union Glacier with respect to time. Years with prominent maxima ~~above‑-average maxima (warm summers)~~ and minima ~~(cold winters)~~ in $\delta^{18}O$‑-time series – although not visible in all cores – 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 ~~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.~~

**Formatiert:** Englisch (Australien)

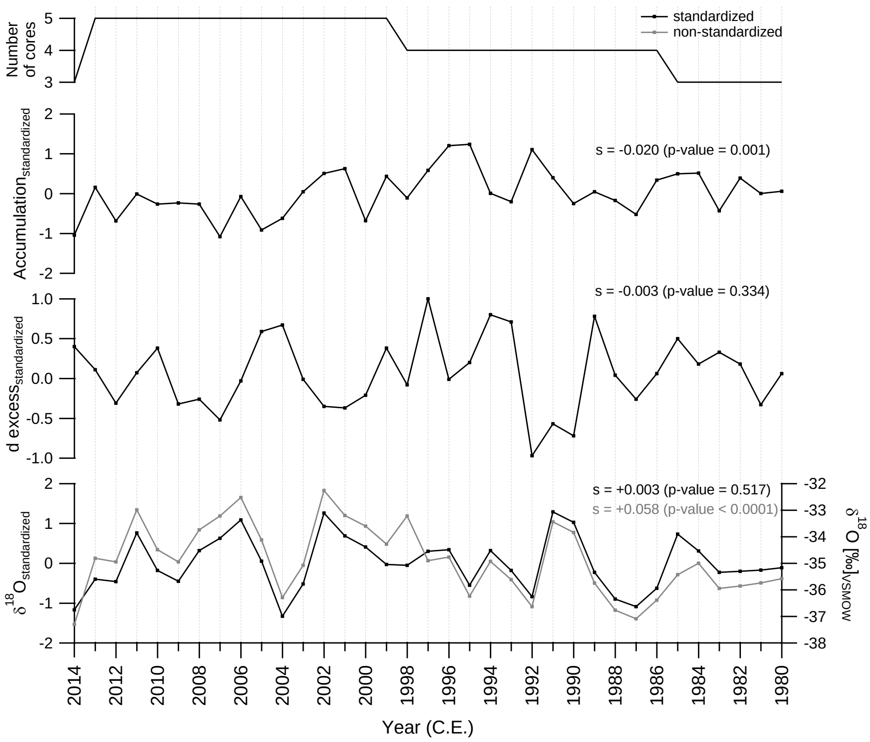


Figure 8: Composite records of mean annual $\delta^{18}O$, d excess and snow accumulation in the UG region for the period 1980-2014 derived from both non-standardized (grey) and from standardized data (black; excluding firn core GUPA-1). For $\delta^{18}O$ the composite record derived from non-standardized 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.

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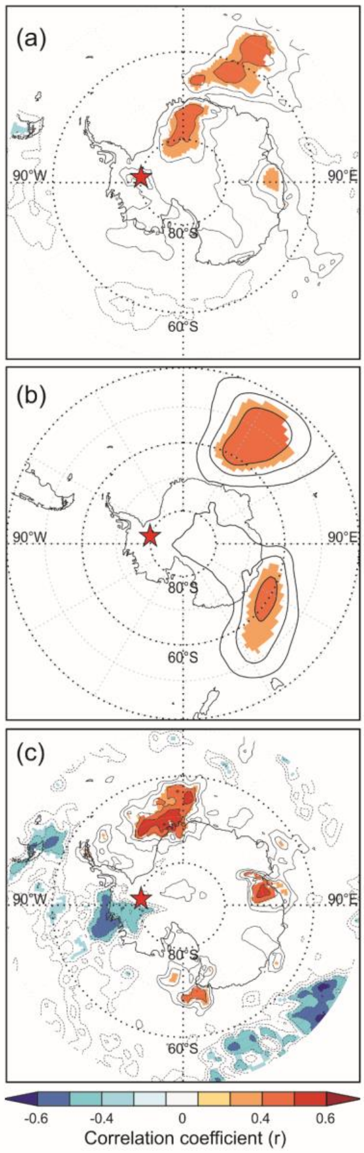


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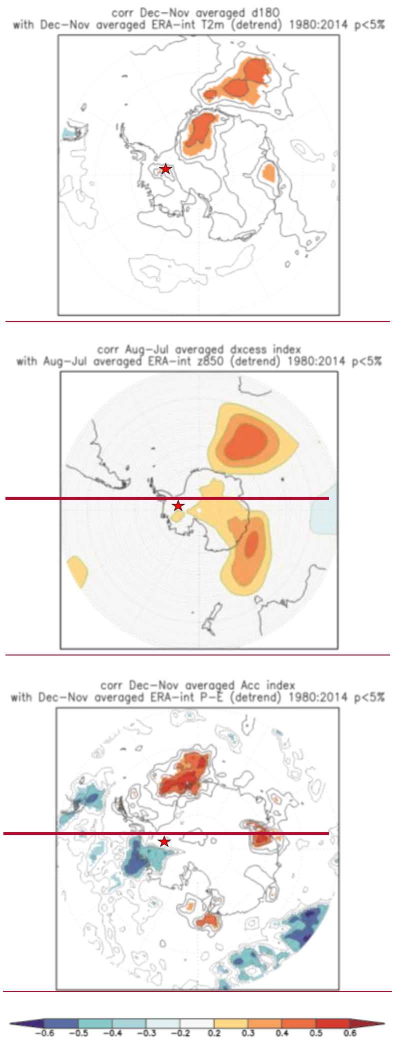


Figure 9a-c: Spatial correlation of annually averaged ERA-InterimERA-Interim (a) near-surface air temperatures (2 m), (b) geopotential heights (850 mbar) and (c) precipitation-evaporation with standardized mean annual (a) $\delta^{18}O$, (b) d excess and (c) snow accumulation in the UG region for the period 1980-2014 (excluding firn 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).

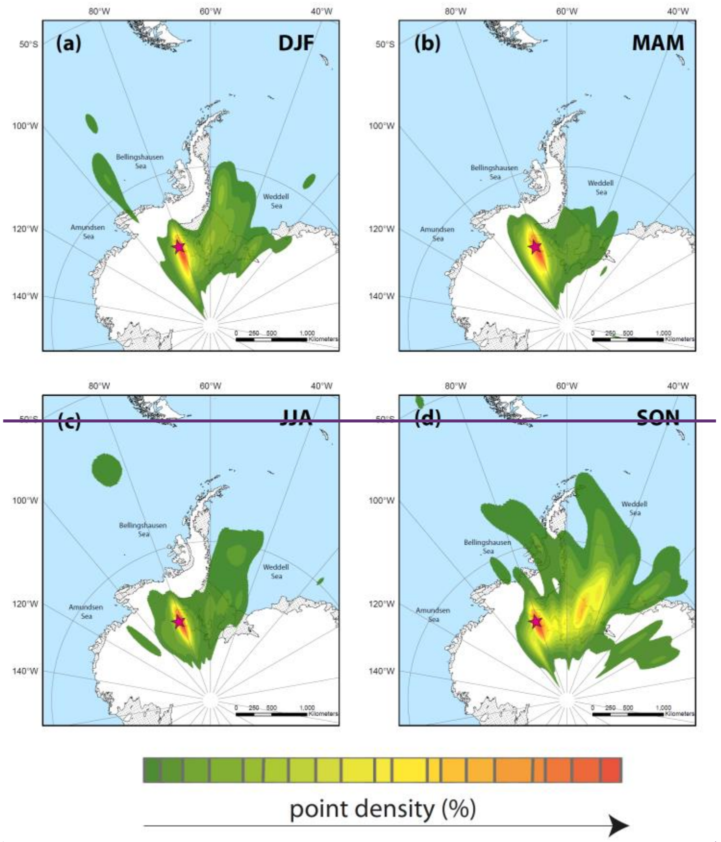


Figure 10a-d: Density distribution of 3-day backward trajectories transporting precipitating air masses towards the UG region (red star) as calculated for each season (DJF, MAM, JJA, SON) for the period 2010–2013 using the model HYSPLIT.

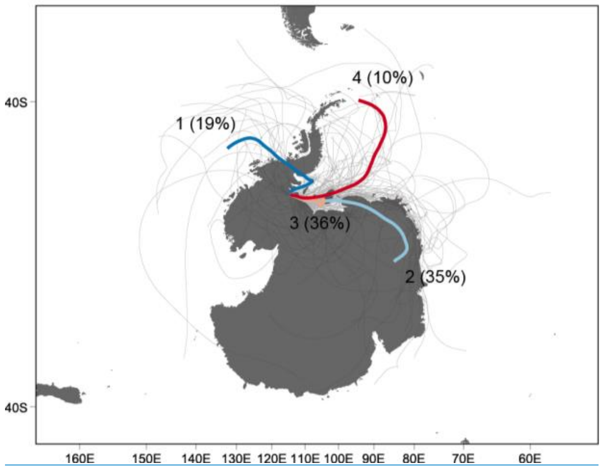


Figure 101: Cluster analysis of 5-day backward trajectories transporting air masses towards the UG region as calculated for all days with precipitation events (in total 121, represented by thin grey lines) for the period 2010-2015 using the model HYSPLIT. Bold lines represent main transport pathways calculated as percentage (%) of all trajectories associated with the respective cluster.

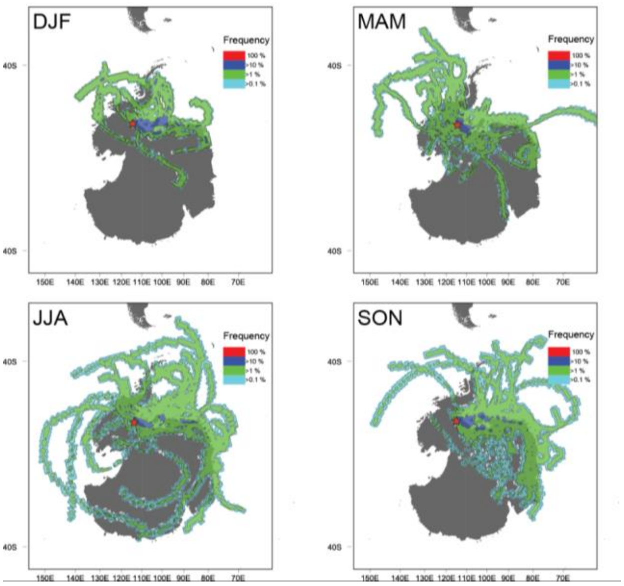


Figure 11: Seasonal frequency distribution of single 5-day backward trajectories during precipitation events extracted from ERA-Interim time series of daily precipitation for the UG region for the period 2010-2015. from ERA--interim reanalysis. In total 121 precipitation events Events with >>1% of the mean annual accumulation (~2.5 mm $d^{-1}$) were considered for this analysis performed with sys, with a total of 121 days of precipitation for the period 2010--2015 using tthe HYSPLIT model. The red star denotes the location of the UG region.

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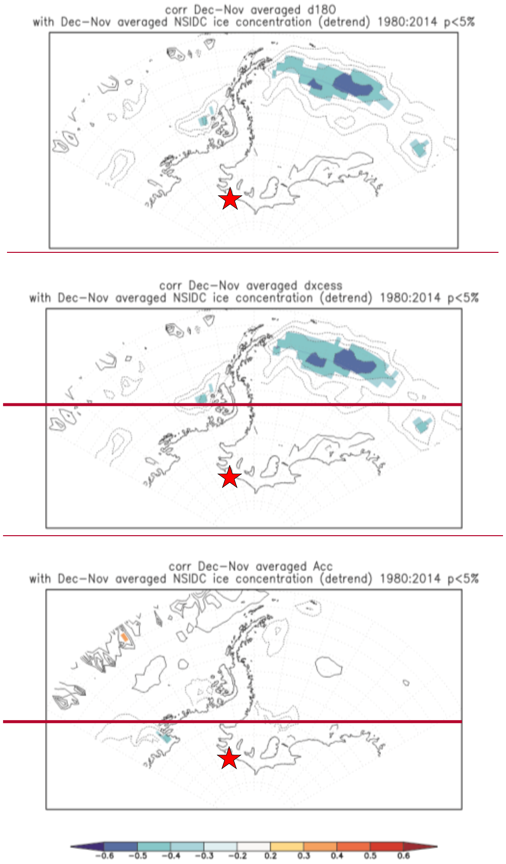
corr Dec–Nov averaged d18O
with Dec–Nov averaged NSIDC ice concentration (detrend) 1980:2014 p<5%
corr Dec–Nov averaged dxcess
with Dec–Nov averaged NSIDC ice concentration (detrend) 1980:2014 p<5%
corr Dec–Nov averaged Acc
with Dec–Nov averaged NSIDC ice concentration (detrend) 1980:2014 p<5%
−0.6 −0.5 −0.4 −0.3 −0.2 0.2 0.3 0.4 0.5 0.6

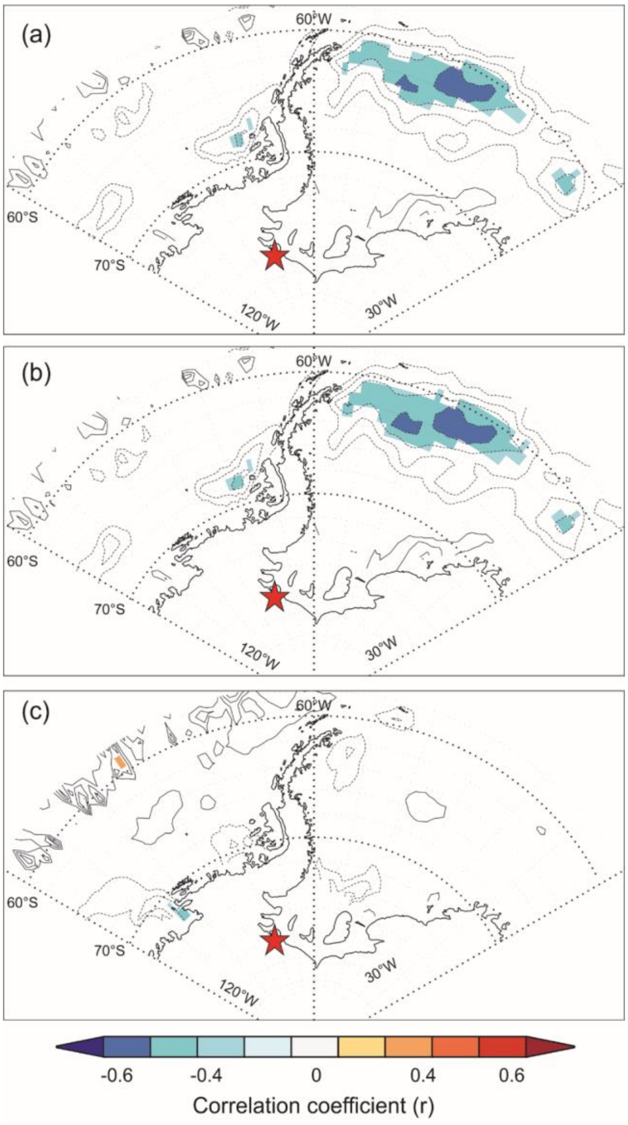


Figure ~~11a~~12~~1a~~-c: Spatial correlations of standardized mean annual (a) $\delta^{18}O$, (b) d excess and (c) snow accumulation in the UG region with mean annual sea ice concentrations in the Weddell and Bellingshausen Sea sectors for the period 1980-2014~~.~~ (excluding firn core GUPA-1). For 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.

**Formatiert:** Zentriert

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The red star denotes the location of the UG region. Only statistically significant correlations (p-value < 5%) are shown.

Table 1: Details on drill locations and basic statistics of the stable water isotope composition and accumulation rates of the six firn 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).

| Firn Core | GUPA--1 | DOTT--1 | SCH--1 | SCH--2 | BAL--1 | PASO--1 |
|---|---|---|---|---|---|---|
| Coordinates | 79°46'07.00"S 82°54'33.44"W | 79°18'38.84"S 81°39'09.33"W | 79°31'14.02"S 84°08'56.48"W | 79°33'17.76"S 84°03'11.46"W | 79°31'27.69"S 84°26'32.09"W | 79°38'00.68"S 85°00'22.51"W |
| Altitude [m asl] | 762 | 764 | 1263 | 1509 | 1516 | 1920 |
| Depth [m] | 9.58 | 9.57 | 14.13 | 20.25 | 17.28 | 15.04 |
| Drilling date | Nov 2014 | Nov 2014 | Nov 2014 | Nov 2015 | Nov 2015 | Nov 2015 |
| Age [period/years] | 1989--2014 (26) | 1999--2014 (16) | 1986--2014 (29) | 1977--2015 (39) | 1980--2015 (36) | 1973--2015 (43) |
| Coordinates and elevation [m asl] of nearest ERA-Interim grid point | 79°30'S 83°15'W 911.3 | 79°30'S 81°45'W 641.5 | 79°30'S 84°00'W 1061.2 | 79°30'S 84°00'W 1061.2 | 79°30'S 84°45'W 1208.4 | 79°30'S 84°45'W 1208.4 |
| δ$^{18}$O [‰] | | | | | | |
| Min | --44.5 | --40.0 | --43.7 | --41.6 | --41.7 | --42.3 |
| **Mean** | **--35.6** | **--29.9** | **--35.0** | **--34.1** | **--36.2** | **--36.6** |
| Max | --26.1 | --21.3 | --27.1 | --23.1 | --28.5 | --31.1 |
| Sdev | 3.1 | 3.9 | 3.1 | 2.8 | 2.5 | 2.3 |
| δD [‰] | | | | | | |
| Min | --352.1 | --314.6 | --346.6 | --331.2 | --330.7 | --333.7 |
| **Mean** | **--278.6** | **--233.1** | **--273.3** | **--268.0** | **--284.1** | **--285.9** |
| Max | --202.5 | --163.9 | --211.2 | --187.1 | --222.3 | --240.2 |
| Sdev | 25.0 | 31.6 | 24.6 | 23.2 | 20.3 | 19.2 |
| d excess [‰] | | | | | | |
| Min | --0.2 | --2.3 | --2.3 | --5.6 | --0.4 | 0.3 |
| **Mean** | **5.8** | **5.8** | **6.5** | **4.9** | **5.5** | **7.0** |
| Max | 11.8 | 10.5 | 15.5 | 17.2 | 9.7 | 11.5 |
| Sdev | 2.6 | 2.2 | 2.6 | 3.7 | 1.6 | 1.7 |
| slope of co--isotopic relationship | 7.94 | 8.09 | 7.95 | 8.19 | 8.05 | 8.24 |
| n (samples) | 190 | 189 | 280 | 418 | 675 | 596 |
| δ$^{18}$O [‰] of annual means for 1999--2013 | | | | | | |
| Min | --41.1 | --33.4 | --37.7 | --36.0 | --38.0 | --38.4 |
| **Mean** | --35.7 | --29.7 | --34.7 | --34.1 | --35.4 | --36.3 |
| Max | --32.5 | --27.0 | --32.3 | --31.7 | --31.5 | --33.8 |
| Accumulation [m w.eq.a$^{-1}$] | 1989--2013 | 1999--2013 | 1986--2013 | 1977--2014 | 1980--2014 | 1973--2014 |
| Min | 0.111 | 0.203 | 0.142 | 0.159 | 0.121 | 0.080 |
| **Mean** | **0.180** | **0.284** | **0.247** | **0.285** | **0.253** | **0.181** |
| Max | 0.364 | 0.378 | 0.390 | 0.472 | 0.378 | 0.311 |
| Sdev | 0.061 | 0.052 | 0.064 | 0.078 | 0.079 | 0.048 |
| Accumulation [m w.eq.a$^{-1}$] for 1999--2013 | | | | | | |
| Min | 0.111 | 0.203 | 0.142 | 0.159 | 0.130 | 0.141 |
| **Mean** | **0.158** | **0.284** | **0.219** | **0.229** | **0.231** | **0.200** |
| Max | 0.284 | 0.378 | 0.333 | 0.295 | 0.353 | 0.311 |

| Firn Core | GUPA-1 | DOTT-1 | SCH-1 | SCH-2 | BAL-1 | PASO-1 |
|---|---|---|---|---|---|---|
| Coordinates | 79°46'07.00''S 82°54'33.44''W | 79°18'38.84''S 81°39'09.33''W | 79°31'14.02''S 84°08'56.48''W | 79°33'17.76''S 84°03'11.46''W | 79°31'27.69''S 84°26'32.09''W | 79°38'00.68''S 85°00'22.51''W |
| Altitude [m a.s.l.] | 762 | 764 | 1263 | 1509 | 1516 | 1920 |
| Depth [m] | 9.58 | 9.57 | 14.13 | 20.25 | 17.28 | 15.04 |
| Drilling date | Nov 2014 | Nov 2014 | Nov 2014 | Nov 2015 | Nov 2015 | Nov 2015 |
| Elevation of nearest ERA-Interim grid point [m asl.asl] | 911.3 | 641.5 | 1061.2 | 1061.2 | 1208.4 | 1208.4 |
| δ18O [‰] | - | - | - | - | - | |
| Min | -44.5 | -40.0 | -43.7 | -41.6 | -41.7 | -42.3 |
| **Mean** | **-35.6** | **-29.9** | **-35.0** | **-34.1** | **-36.2** | **-36.6** |
| Max | -26.1 | -21.3 | -27.1 | -23.1 | -28.5 | -31.1 |
| Sdev | 3.1 | 3.9 | 3.1 | 2.8 | 2.5 | 2.3 |
| δD [‰] | - | | | | | |
| Min | -352.1 | -314.6 | -346.6 | -331.2 | -330.7 | -333.7 |
| **Mean** | **-278.6** | **-233.1** | **-273.3** | **-268.0** | **-284.1** | **-285.9** |
| Max | -202.5 | -163.9 | -211.2 | -187.1 | -222.3 | -240.2 |
| Sdev | 25.0 | 31.6 | 24.6 | 23.2 | 20.3 | 19.2 |
| d excess [‰] | - | | | | | |
| Min | -0.2 | -2.3 | -2.3 | -5.6 | -0.4 | 0.3 |
| **Mean** | **5.8** | **5.8** | **6.5** | **4.9** | **5.5** | **7.0** |
| Max | 11.8 | 10.5 | 15.5 | 17.2 | 9.7 | 11.5 |
| Sdev | 2.6 | 2.2 | 2.6 | 3.7 | 1.6 | 1.7 |
| slope of co-isotopic relationship | 7.94 | 8.09 | 7.95 | 8.19 | 8.05 | 8.24 |
| n (samples) | 190 | 189 | 280 | 418 | 675 | 596 |
| δ18O [‰] of annual means for 1999-2013 | | | | | | |
| Min | -41.1 | -33.4 | -37.7 | -36.0 | -38.0 | -38.4 |
| **Mean** | -35.7 | -29.7 | -34.7 | -34.1 | -35.4 | -36.3 |
| Max | -32.5 | -27.0 | -32.3 | -31.7 | -31.5 | -33.8 |
| Accumulation [m w.eq.a-1] | 1989-2013 | 1999-2013 | 1986-2013 | 1977-2014 | 1980-2014 | 1973-2014 |
| Min | 0.111 | 0.203 | 0.142 | 0.159 | 0.121 | 0.080 |
| **Mean** | **0.180** | **0.284** | **0.247** | **0.285** | **0.253** | **0.181** |
| Max | 0.364 | 0.378 | 0.390 | 0.472 | 0.378 | 0.311 |
| Sdev | 0.061 | 0.052 | 0.064 | 0.078 | 0.079 | 0.048 |
| Accumulation [m w.eq.a-1] for 1999-2013 | | | | | | |
| Min | 0.111 | 0.203 | 0.142 | 0.159 | 0.130 | 0.141 |
| **Mean** | **0.158** | **0.284** | **0.219** | **0.229** | **0.231** | **0.200** |
| Max | 0.284 | 0.378 | 0.333 | 0.295 | 0.353 | 0.311 |

Table 2: Dating results for the six firn cores from Union Glacier based on annual layer counting (stable water isotopes and glacio-chemistry) and core inter-matching taking SCH-2 as reference.

| Firn Core | Period | Total number of years (δ18O/δD summer maxima) |
|---|---|---|

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**Formatierte Tabelle**

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|---|---|---|
| ~~GUPA-1~~ | ~~1989-2014~~ | ~~26~~ |
| ~~DOTT-1~~ | ~~1999-2014~~ | ~~16~~ |
| ~~SCH-1~~ | ~~1986-2014~~ | ~~29~~ |
| ~~SCH-2~~ | ~~1977-2015~~ | ~~39~~ |
| ~~BAL-1~~ | ~~1980-2015~~ | ~~36~~ |
| ~~PASO-1~~ | ~~1973-2015~~ | ~~43~~ |

Table ~~3~~2: 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 firn 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) bold and red. ~~in red and bold.~~ ~~Prominent correlations are marked bold and if statistically significant (p-value < 0.01, α = 0.05) in red and bold.~~

| **1980-2014** | **δ18O** | **δD** | **d excess** | **Accumulation** | **SAM Index** | **MEI** | **SIE Weddell** | **SIE Bellingshausen-Amundsen** | **SIE Indian Ocean** | **SIE West Pacific** | **SIE Ross** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **δ18O** | 1 | **0.995** | -0.214 | 0.194 | -0.089 | 0.200 | -0.247 | -0.116 | -0.036 | 0.061 | 0.116 |
| p-value | 0 | 0 | 0.217 | 0.264 | 0.613 | 0.249 | 0.165 | 0.521 | 0.841 | 0.737 | 0.520 |
| **δD** | | 1 | -0.128 | 0.190 | -0.054 | 0.214 | -0.264 | -0.106 | -0.003 | 0.085 | 0.119 |
| p-value | | 0 | 0.464 | 0.275 | 0.758 | 0.218 | 0.138 | 0.559 | 0.985 | 0.639 | 0.511 |
| **d excess** | | | 1 | -0.071 | **0.376** | 0.024 | -0.205 | 0.103 | **0.315** | 0.169 | -0.068 |
| p-value | | | 0 | 0.687 | 0.026 | 0.890 | 0.253 | 0.570 | 0.074 | 0.348 | 0.707 |
| **Accumulation** | | | | 1 | -0.139 | 0.039 | -0.046 | 0.127 | **-0.310** | -0.024 | -0.143 |
| p-value | | | | 0 | 0.427 | 0.826 | 0.799 | 0.483 | 0.080 | 0.896 | 0.429 |
| **SAM Index** | | | | | 1 | 0.101 | -0.223 | -0.213 | **0.629** | **0.403** | **0.390** |
| p-value | | | | | 0 | 0.563 | 0.211 | 0.233 | 0 | 0.020 | 0.025 |
| **MEI** | | | | | | 1 | 0.165 | 0.171 | **-0.411** | 0.025 | **-0.512** |
| p-value | | | | | | 0 | 0.358 | 0.343 | 0.018 | 0.891 | 0.002 |

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**Formatiert:** Schriftart: Nicht Fett

**References**


Abram, N.J., Mulvaney, R. and Arrowsmith, C.: Environmental signals in a highly resolved ice core from James Ross Island, Antarctica, J. Geophys. Res., 116, D20116, doi:10.1029/2011JD016147, 2011.

Altnau, S., Schlosser, E., Isaksson, E. and Divine, D.: Climatic signals from 76 shallow firn cores in Dronning Maud Land, East Antarctica, The Cryosphere, 9, 925--944, doi:10.5194/tc--9--925--2015, 2015.

Bowen, H.J.M.: Environmental chemistry of the elements, Academic Press, London, New York, 1979.

Bromwich, D.H., Nicolas, J.P., Monaghan, A.J., Lazzara, M.A., Keller, L.M., Weidner, G.A. and Wilson, A.B.: Central West Antarctica among the most rapidly warming regions on Earth, Nat. Geosci., 6, 139–-145, doi:10.1038/NGEO1671, 2013.

Burgener, L., Rupper, S., Koenig, L., Forster, R., Christensen, W.F., Williams, J., Koutnik, M., Miège, C., Steig, E.J., Tingey, D., Keeler, D. and Riley, L.: An observed negative trend in West Antarctic accumulation rates from 1975 to 2010: Evidence from new observed and simulated records, J. Geophys. Res.-- Atmos., 118, 4205--4216, doi:10.1002/jgrd.50362, 2013.

Caiazzo, L., Becagli, S., Frosini, D., Giardi, F., Severi, M., Traversi, R. and Udisti, R.: Spatial and temporal variability of snow chemical composition and accumulation rate at Talos Dome site (Antarctica), Sci. Total. Environ., 550, 418-430, doi: 10.1016/j.scitotenv.2016.01.087, 2016.

Casassa, G., Brecher, H.H., Cárdenas, C. and Rivera, A.: Mass balance of the Antarctic ice sheet at Patriot Hills, Ann. Glaciol., 27, 130–-134, doi:10.3189/1998AoG27-1-130-134, 1998.

Clark, I.D. and Fritz, P.: Environmental Isotopes in Hydrogeology, CRC Press LLC, Boca Raton, New York, USA, 1997.

Comiso, J.: Bootstrap Sea Ice Concentrations from Nimbus–-7 SMMR and DMSP SSM/I–-SSMIS, Version 3 [NSIDC–-0079], Boulder, Colorado, USA, NASA National Snow and Ice Data Center Distributed Active Archive Center, doi:10.5067/7Q8HCCWS4I0R [accessed 23rd July 2018], 2017.

Cook, A.J. and Vaughan, D.G.: Overview of areal changes of the ice shelves on the Antarctic Peninsula over the past 50 years, The Cryosphere, 4, 77–-98, 2010.

Coplen, T. B. and Wassenaar, L.I.: LIMS for Lasers 2015 for achieving long–-term accuracy and precision of $\delta^2$H, $\delta^{17}$O, and $\delta^{18}$O of waters using laser absorption spectrometry, Rapid. Commun. Mass. Sp., 29, 2122–-2130, doi:10.1002/rcm.7372, 2015.

Craig, H.: Isotopic Variations in Meteoric Waters, Science, 133, 1702–-1703, doi:10.1126/science.133.3465.1702, 1961.

Dansgaard, W.: Stable isotopes in precipitation, Tellus, 16, 436–-468, doi:10.1111/j.2153–-3490.1964.tb00181.x, 1964.

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,


**Formatiert:** Schriftart: Nicht Kursiv

**Formatiert:** Schriftart: Nicht Kursiv

**Formatiert:** Schriftart: Nicht Kursiv

**Formatiert:** Schriftart: Nicht Kursiv

**Formatiert:** Schriftart: Nicht Kursiv

A.J., Haimberger, L., Healy, S.B., Hersbach, H., Hólm, E.V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A.P., Monge-Sanz, B.M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay P., Tavolato, C., Thépaut, J.-N. and Vitart, F.: The ~~ERA-Interim~~ERA-Interim reanalysis: configuration and performance of the data assimilation system, Q. J. Roy. Meteor. Soc., 137, 553-597, doi:10.1002/qj.828, 2011.

Diaz, H.F. and Markgraf, V.: El Niño. Historical and Paleoclimatic Aspects of the Southern Oscillation, Cambridge University Press, Cambridge, UK, 1992.

Diaz, H.F. and Markgraf, V.: El Niño and the Southern Oscillation. Multiscale Variability and Global and Regional Impacts, Cambridge University Press, Cambridge, UK, 2000.

Ding, Q., Steig, E.J., Battisti, D.S. and Küttel, M.: Winter warming in West Antarctica caused by central tropical Pacific warming, Nat. Geosci., 4, 398~~–~~-403, doi:10.1038/NGEO1129, 2011.

Draxler, R.R. and Hess, G.D.: An Overview of the HYSPLIT_4 Modelling System for Trajectories, Dispersion, and Deposition, Aust. Meteorol. Mag., 47, 295~~–~~-308, 1998.

Fernandoy, F., Meyer, H., Oerter, H., Wilhelms, F., Graf, W. and Schwander, J.: Temporal and spatial variation of stable-isotope ratios and accumulation rates in the hinterland of Neumayer station, East Antarctica, J. Glaciol., 56, 673-687, doi:10.3189/002214310793146296, 2010.

Fernandoy, F., Tetzner, D., Meyer, H., Gacitúa, G., Hoffmann, K., Falk, U., Lambert, F. and MacDonell, S.: New insights into the use of stable water isotopes at the northern Antarctic Peninsula as a tool for regional climate studies, The Cryosphere, 12, 1069~~–~~-1090, doi:10.5194/tc~~–~~-12~~–~~-1069~~–~~-2018, 2018.

Fisher, D. A., Reeh, N. and Clausen, H. B.: Stratigraphic Noise in Time Series Derived from Ice Cores, Ann. Glaciol., 7, 76-83, doi:10.1017/S0260305500005942, 1985.

Freitag, J., Kipfstuhl, S. and Laepple, T.: Core~~–~~-scale radioscopic imaging: a new method reveals density~~–~~-calcium link in Antarctic firn, J. Glaciol., 59, 1009~~–~~-1014, doi:10.3189/2013JoG13J028, 2013.

Frieler, K., Clark, P.U., He, F., Buizert, C., Reese, R., Ligtenberg, S.R.M., van den Broeke, M.R., Winkelmann, R. and Levermann, A.: Consistent evidence of increasing Antarctic accumulation with warming, Nat. Clim. Change, doi:10.1038/NCLIMATE2574, 2015.

Genthon, C., Krinner, G. and Sacchettini, M.: (2003), Interannual Antarctic tropospheric circulation and precipitation variability, Clim. Dyn., 21, 289--307, doi:10.1007/s00382-003-0329-1, 2003.

Genthon, C., Kaspari, S. and Mayewski, P.A.: Interannual variability of the surface mass balance of West Antarctica from ITASE cores and ERA40 reanalyses, 1958-2000, Clim. Dyn., 24, 759-770, doi:10.1007/s00382-005-0019-2, 2005.

Gillett, N.P., Kell, T.D. and Jones, P.D.: Regional climate impacts of the Southern Annular Mode, Geophys. Res. Lett., 33, L23704, doi:10.1029/2006GL027721, 2006.

**Formatiert:** Spanisch (Chile)

**Formatiert:** Schriftart: (Standard) +Textkörper (Times New Roman), 10 Pt.

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**Formatiert:** Englisch (Großbritannien)

**Formatiert:** Englisch (Großbritannien)

Gillett, N.P., Stone, D.A., Stott, P.A., Nozawa, T., Karpechko, A.Y., Hegerl, G.C., Wehner, M.F. and Jones, P.D.: Attribution of polar warming to human influence, Nat. Geosci., 1, 750–-754, doi:10.1038/ngeo338, 2008.

Goursaud, S., Masson--Delmotte, V., Favier, V., Preunkert, S., Fily, M., Gallée, H., Jourdain, B., Legrand, M., Magand, O., Minster, B. and Werner, M.: A 60--year ice--core record of regional climate from Adélie Land, coastal Antarctica, The Cryosphere, 11, 343--362, doi:10.5194/tc--11--343--2017, 2017.

Graf, W., Moser, H., Oerter, H., Reinwarth, O. and Stichler, W.: Accumulation and Ice-Core Studies on Filchner-Ronne Ice Shelf, Antarctica, Ann. Glaciol., 11, 23-31, doi:10.3189/S0260305500006273, 1988.

Graf, W., Reinwarth, O., Oerter, H., Mayer, C. and Lambrecht, A.: Surface accumulation on Foundation Ice Stream, Antarctica, Ann. Glaciol., 29, 23--28, doi: 10.3189/172756499781820987, 1999.

Graf, W., Oerter, H., Reinwarth, O., Stichler, W., Wilhelms, F., Miller, H. and Mulvaney, R.: Stable-isotope records from Dronning Maud Land, Antarctica, Ann. Glaciol., 35, 195-201, doi: 10.3189/172756402781816492, 2002.

Hellmer, H.H., Kauker, F., Timmermann, R., Determann, J. and Rae, J.: Twenty–-first–-century warming of a large Antarctic ice–-shelf cavity by a redirected coastal current, Nature, 485, 225–-228, doi:10.1038/nature11064, 2012.

Hellmer, H.H., Kauker, F., Timmermann, R. and Hattermann, T.: The Fate of the Southern Weddell Sea Continental Shelf in a Warming Climate, J. Climate, 30, 4337–-4350, doi:10.1175/JCLI–-D–-16–-0420.1, 2017.

Hoshina, Y., Fujita, K., Nakazawa, F., Iizuka, Y., Miyake, T., Hirabayashi, M., Kuramoto, T., Fujita, S., and Motoyama, H.: Effect of accumulation rate on water stable isotopes of near-surface snow in inland Antarctica, J. Geophys. Res., 119, 274-283, doi:10.1002/2013JD020771, 2014.

Hosking, J. S., Orr, A., Marshall, G.J., Turner, J. and Phillips, T.: The influence of the Amundsen–-Bellingshausen Seas Low on the Climate of West Antarctica and Its Representation in Coupled Climate Model Simulations, J. Climate, 26, 6633–-6648, doi:10.1175/JCLI–-D–-12–-00813.1, 2013.

Jones, J.M., Gille, S.T., Goosse, H., Abram, N.J., Canziani, P.O., Charman, D.J., Clem, K.R., Crosta, X., de Lavergne, C., Eisenman, I., England, M.H., Fogt, R.L., Frankcombe, L.M., Marshall, G.J., Masson--Delmotte, V., Morrison, A.K., Orsi, A.J., Raphael, M.N., Renwick, J.A., Schneider, D.P., Simpkins, G.R., Steig, E.J., Stenni, B., Swingedouw, D. and Vance, T.R.: Assessing recent trends in high--latitude Southern Hemisphere surface climate, Nat. Clim., Change, 6, 917--926, doi:10.1038/NCLIMATE3103, 2016.

Joughin, I. and Alley, R.B.: Stability of the West Antarctic ice sheet in a warming world, Nat. Geosci., 4, 506–-513, doi:10.1038/NGEO1194, 2011.

Kaczmarska, M., Isaksson, E., Karlöf, L., Winther, J.-G., Kohler, J., Godtliebsen, F., Ringstad Olsen, L., Hofstede, C.M., van den Broeke, M.R., van de Wal, R.S.W. and Gundestrup, N.: Accumulation variability derived from an ice core from coastal Dronning Maud Land, Antarctica, Ann. Glaciol., 39, 339-345, doi:10.3189/172756404781814186, 2004.

**Formatiert:** Schriftart: Times New Roman

**Feldfunktion geändert**

**Formatiert:** Englisch (Großbritannien)

**Formatiert:** Englisch (Großbritannien)

**Feldfunktion geändert**

**Formatiert:** Schriftart: Times New Roman

Karoly, D.J.: Southern Hemisphere Circulation Features Associated with El Niño–-Southern Oscillation Events, J. Climate, 2, 1239–-1252, doi: 10.1175/1520–-0442(1989)002<1239:SHCFAW>2.0.CO;2, 1989.

Kaspari, S., Mayewski, P.A., Dixon, D.A., Spikes, V.B., Sneed, S.B., Handley, M.J. and Hamilton, G.S.: Climate Variability in West Antarctica derived from annual accumulation–-rate records from ITASE firn/ice cores, Ann. Glaciol., 39, 585–-594, 2004.

Kaufmann, P., Fundel, F., Fischer, H., Bigler, M., Ruth, U., Udisti, R., Hansson, M., de Angelis, M., Barbante, C., Wolff, E.W., Hutterli, M. and Wagenbach, D.: Ammonium and non-sea salt sulfate in the EPICA ice cores as indicator of biological activity in the Southern Ocean, Quaternary Sci. Rev., 29, 313-323, doi:10.1016/j.quascirev.2009.11.009, 2010.

Kendall, M.G.: Rank correlation methods, Griffin, London, UK, 1975.

Kohyama, T. and Hartmann, D.L.: Antarctic Sea Ice Response to Weather and Climate Modes of Variability, J. Climate, 29, 721–-741, doi:10.1175/JCLI–-D–-15–-0301.1, 2016.

Laepple, T., Münch, T., Casado, M., Hoerhold, M., Landais, A. and Kipfstuhl, S.: On the similarity and apparent cycles of isotopic variations in East Antarctic snow pits, The Cryosphere, 12, 169-187, doi:10.5194/tc-12-169-2018, 2018.

Lee, M., Heikes, B.G. and O'Sullivan, D.W.: Hydrogen peroxide and organic hydroperoxide in the troposphere: a review, Atmos. Environ., 34, 3475-3494, doi:10.1016/s1352-2310(99)00432-x, 2000.

Lenaerts, J.T.M., van den Broeke, M.R., Déry, S.J., van Meijgaard, E., van de Berg, W.J., Palm, S.P. and Sanz Rodrigo, J.: Modeling drifting snow in Antarctica with a regional climate model: 1. Methods and model evaluation, J. Geophys. Res., 117, doi:10.1029/2011JD016145, 2012.

Lenaerts, J.T.M. and van den Broeke, M.R.: Modeling drifting snow in Antarctica with a regional climate model: 2. Results, J. Geophys. Res., 117, D05109, doi:10.1029/2010JD015419, 2012.

L'Heureux, M.L. and Thompson, D.W.J.: Observed Relationships between the El Niño–-Southern Oscillation and the Extratropical Zonal–-Mean Circulation, J. Climate, 19, 276–-287, doi:10.1175/JCLI3617.1, 2006.

Limpasuvan, V. and Hartmann, D.L.: Eddies and the annular modes of climate variability, Geophys. Res. Lett., 26, 3133–-3136, 1999.

Liu, H., Jezek, K.C., Li, B. and Zhao, Z.: Radarsat Antarctic Mapping Project Digital Elevation Model, Version 2 [NSIDC-0082], Boulder, Colorado, USA, NASA National Snow and Ice Data Center Distributed Active Archive Center, doi:10.5067/8JKNEW6BFRVD [accessed 3rd August 2018], 2015.

Mann, H.B.: Nonparametric tests against trend, Econometrica, 13, 245–-259, 1945.

Marshall, G.J.: Trends in the Southern Annular Mode from Observations and Reanalyses, J. Climate, 16, 4134–-4143, doi: 10.1175/1520-0442(2003)016<4134:TITSAM>2.0.CO;2, 2003.

**Formatiert:** Englisch (Großbritannien)

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**Feldfunktion geändert**

Marshall, G.J., Orr, A., van Lipzig, N.P.M. and King, J.C.: The Impact of a Changing Southern Hemisphere Annular Mode on Antarctic Peninsula Summer Temperatures. J. Climate, 19, 5388-5404, doi: 10.1175/JCLI3844.1, 2006.

Marshall, G.J.: Half–-century seasonal relationships between the Southern Annular Mode and Antarctic temperatures, Int. J. Climatol., 27, 373–-383, doi:10.1002/joc.1407, 2007.

McConnell, J.R., Lamorey, G.W., Lambert, S.W., Taylor, K.C.: Continuous Ice–-Core Chemical Analyses Using Inductively Coupled Plasma Mass Spectrometry, Environ. Sci. Technol., 36, 7–-11, doi:10.1021/es011088z, 2002.

McConnell, J.R., Edwards, R., Kok, G.L., Flanner, M.G., Zender, C.S., Saltzman, E.S., Banta, J.R., Pasteris, D.R., Carter, M.M., Kahl, J.D.W.: 20th–-Century Industrial Black Carbon Emissions Altered Arctic Climate Forcing, Science, 317, 1381–-1384, doi: 10.1126/science.1144856, 2007.

Medley, B., McConnell, J.R., Neumann, T.A., Reijmer, C.H., Chellman, N., Sigl, M. and Kipfstuhl, S.: Temperature and Snowfall in Western Queen Maud Land Increasing Faster Than Climate Model Projections, Geophys. Res. Lett., 45, doi:10.1002/2017GL075992, 2018.

Medley, B. and Thomas, E.R.: Increased snowfall over the Antarctic Ice Sheet mitigated twentieth--century sea--level rise, Nat. Clim. Change, 9, 34--39, doi:10.1038/s41558--018--0356--x, 2019.

Merlivat, L. and Jouzel, J.: Global Climatic Interpretation of the Deuterium–-Oxygen 18 Relationship for Precipitation, J. Geophys. Res., 84, 5029–-5033, 1979.

Monaghan, A.J., Bromwich, D.H., Fogt, R.L., Wang, S.--H., Mayewski, P.A., Dixon, D.A., Ekaykin, A., Frezzotti, M., Goodwin, I., Isaksson, E., Kaspari, S.D., Morgan, V.I., Oerter, H., Van Ommen, T.D., Van der Veen, C.J. and Wen, J.: Insignificant Change in Antarctic Snowfall Since the International Geophysical Year, Science, 313, 827--831, doi:10.1126/science.1128243, 2006.

Mulvaney, R., Oerter, H., Peel, D.A., Graf, W., Arrowsmith, C., Pasteur, E.C., Knight, B., Littot, G.C. and Miners, W.D.: 1000 year ice–-core records from Berkner Island, Antarctica, Ann. Glaciol., 35, 45–-51, 2002.

Mulvaney, R., Abram, N.J., Hindmarsh, R.C.A., Arrowsmith, C., Fleet, L., Triest, J., Sime, L.C., Alemany, O. and Foord, S.: Recent Antarctic Peninsula warming relative to Holocene climate and ice-shelf history, Nature, 489, 141-144, doi: 10.1038/nature11391, 2012.

Münch, T., Kipfstuhl, S., Freitag, J., Meyer, H. and Laepple, T.: Regional climate signal vs. local noise: a two-dimensional view of water isotopes in Antarctic firn at Kohnen Station, Dronning Maud Land, Clim. Past, 12, 1565-1581, doi:10.5194/cp-12-1565-2016, 2016.

Münch, T. and Laepple, T.: What climate signal is contained in decadal- to centennial-scale isotope variations from Antarctic ice cores?, Clim. Past, 14, 2053-2070, doi:10.5194/cp-14-2053-2018, 2018.


**Formatiert:** Englisch (Großbritannien)

**Formatiert:** Englisch (Großbritannien)

Nicolas, J.P. and Bromwich, D.H.: New Reconstruction of Antarctic Near--Surface Temperatures: Multidecadal Trends and Reliability of Global Reanalyses, J. Climate, 27, 8070--8093, doi:10.1175/JCLI--D--13--00733.1, 2014.

Oerter, H., Wilhelms, F., Jung-Rothenhäusler, F., Göktas, F., Miller, H., Graf, W. and Sommer, S.: Accumulation rates in Dronning Maud Land, Antarctica, as revealed by dielectric-profiling measurements of shallow firn cores, Ann. Glaciol., 30, 27-34, doi:10.3189/172756400781820705, 2000.

Palm, S.P., Yang, Y., Spinhirne, J.D. and Marshak, A.: Satellite remote sensing of blowing snow properties over Antarctica, J. Geophys. Res., 116, D16123, doi:10.1029/2011JD015828, 2011.

Pasteris, D.R., McConnell, J.R., Das, S.B., Criscitiello, A.S., Evans, M.J., Maselli, O.J., Sigl, M. and Layman, L.: Seasonally resolved ice core records from West Antarctica indicate a sea ice source of sea-salt aerosol and a biomass burning source of ammonium. J. Geophys. Res. Atmos., 119, 9168-9182, doi:10.1002/2013JD020720, 2014.

Philippe, M., Tison, J.--L., Fjøsne, K., Hubbard, B., Kjær, H.S., Lenaerts, J.T.M., Drews, R., Sheldon, S.G., De Bondt, K., Claeys, P. and Pattyn, F.: Ice core evidence for a 20th century increase in surface mass balance in coastal Dronning Maud Land, East Antarctica, The Cryosphere, 10, 2501--2516, doi:10.5194/tc--10--2501--2016, 2016.

Pritchard, H.D. and Vaughan, D.G.: Widespread acceleration of tidewater glaciers on the Antarctic Peninsula, J. Geophys. Res., 112, F03S29, doi:10.1029/2006JF000597, 2007.

Rahaman, W., Chatterjee, S., Ejaz, T. and Thamban, M.: Increased influence of ENSO on Antarctic temperature since the Industrial Era, Sci. Rep.--Uk., 9, 6006, doi:10.1038/s41598--019--42499--x, 2019.

Raphael, M.N., Marshall, G.J., Turner, J., Fogt, R.L., Schneider, D., Dixon, D.A., Hosking, J.S., Jones, J.M. and Hobbs, W.R.: The Amundsen Sea Low. Variability, Change, and Impact on Antarctic Climate, Bull. Amer. Meteor. Soc., 97, 111–-121, doi:10.1175/BAMS–-D–-14–-00018.1, 2015.

Rignot, E., Mouginot, J., Morlighem, M., Seroussi, H. and Scheuchl, B.: Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011, Geophys. Res. Lett., 41, 3502–-3509, doi:10.1002/2014GL060140, 2014.

Rivera, A., Zamora, R., Rada, C., Walton, J. and Proctor, S.: Glaciological investigations on Union Glacier, Ellsworth Mountains, West Antarctica, Ann. Glaciol., 51, 91-96, doi:10.3189/172756410791392772, 2010.

Rivera, A., Zamora, R., Uribe, J.A., Jaña, R. and Oberreuter, J.: Recent ice dynamic and surface mass balance of Union Glacier in the West Antarctic Ice Sheet, The Cryosphere, 8, 1445–-1456, doi:10.5194/tc–-8–-1445–-2014, 2014.

Röthlisberger, R., Bigler, M., Hutterli, M., Sommer, S., Stauffer, B., Junghans, H. G., and Wagenbach, D.: Technique for continuous high–-resolution analysis of trace substances in firn and ice cores, Environ. Sci. Technol., 34, 338–-342, 2000.

Röthlisberger, R., Mulvaney, R., Wolff, E.W., Hutterli, M.A., Bigler, M., Sommer, S. and Jouzel, J.: Dust and sea salt variability in central East Antarctica (Dome C) over the last 45 kyrs and its implications for southern high-latitude climate, Geophys. Res. Lett., 29, doi:10.1029/2002GL015186, 2002.

**Feldfunktion geändert**

**Formatiert:** Schriftart: Times New Roman

**Formatiert:** Englisch (Großbritannien)

**Formatiert:** Schriftart: (Standard) +Textkörper (Times New Roman)

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**Formatiert:** Schriftart: Nicht Kursiv

Scambos, T. A., Berthier, E., Haran, T., Shuman, C.A., Cook, A.J., Ligtenberg. S.R.M. and Bohlander, J.: Detailed ice loss pattern in the northern Antarctic Peninsula: widespread decline driven by ice front retreats, The Cryosphere, 8, 2135–-2145, doi:10.5194/tc–-8–-2135–-2014, 2014.

Schlosser, E. and Oerter, H.: Shallow firn cores from Neumayer, Ekströmisen, Antarctica: a comparison of accumulation rates and stable-isotope ratios, Ann. Glaciol., 35, 91-96, doi:10.3189/172756402781816915, 2002.

Schlosser, E., Anschütz, H., Divine, D., Martma, T., Sinisalo, A., Altnau, S. and Isaksson, E.: Recent climate tendencies on an East Antarctic ice shelf inferred from a shallow firn core network, J. Geophys. Res. Atmos., 119, 6549–-6562, doi:10.1002/2013JD020818, 2014.

Schneider, D.P., Steig, E.J., van Ommen, T.D., Dixon, D.A., Mayewski, P.A., Jones, J.M. and Bitz, C.M.: Antarctic temperatures over the past two centuries from ice cores, Geophys. Res. Lett., 33, L16707, doi:10.1029/2006GL027057, 2006.

Sen, P.K.: Estimates of the Regression Coefficient Based on Kendall's Tau, J. Am. Stat. Assoc., 63, 1379–-1389, 1968.

Sigl, M., McConnell, J.R., Layman, L., Maselli, O., McGwire, K., Pasteris, D., Dahl-Jensen, D., Steffensen, J.P., Vinther, B., Edwards, R., Mulvaney, R. and Kipfstuhl, S.: A new bipolar ice core record of volcanism from WAIS Divide and NEEM and implications for climate forcing of the last 2000 years, J. Geophys. Res. Atmos., 118, 1151-1169, doi: 10.1029/2012JD018603, 2013.

Smith, K.L. and Polvani, L.M.: Spatial patterns of recent Antarctic surface temperature trends and the importance of natural variability: lessons from multiple reconstructions and the CMIP5 models, Clim. Dyn., 48, 2653--2670, doi: 10.1007/s00382--016--3230--4, 2017.

Steig, E.J., Schneider, D.P., Rutherford, S.D., Mann, M.E., Comiso, J.C. and Shindell, D.T.: Warming of the Antarctic ice–-sheet surface since the 1957 International Geophysical Year, Nature, 457, 459–-462, doi:10.1038/nature07669, 2009.

Steig, E.J., Ding, Q., White, J.W.C., Küttel, M., Rupper, S.B., Neumann, T.A., Neff, P.D., Gallant, A.J.E., Mayewski, P.A., Taylor, K.C., Hoffmann, G., Dixon, D.A., Schoenemann, S.W., Markle, B.R., Fudge, T.J., Schneider, D.P., Schauer, A.J., Teel, R.P., Vaughn, B.H., Burgener, L., Williams, J. and Korotkikh, E.: Recent climate and ice sheet changes in West Antarctica compared with the past 2,000 years, Nat. Geosci., 6, 372–-375, doi:10.1038/NGEO1778, 2013.

Stein, A.F., Draxler, R.R, Rolph, G.D., Stunder, B.J.B., Cohen, M.D. and Ngan, F.: NOAA's HYSPLIT Atmospheric Transport and Dispersion Modeling System, B. Am. Meteorol. Soc., 96, 2059–-2077, doi:10.1175/BAMS–-D–-14–-00110.1, 2015.

Stenni, B., Masson–-Delmotte, V., Selmo, E., Oerter, H., Meyer, H., Röthlisberger, R., Jouzel, J., Cattani, O., Falourd, S., Fischer, H., Hoffmann, G., Iacumin, P., Johnsen, S.J., Minster, B. and Udisti, R.: The deuterium excess records of EPICA Dome C and Dronning Maud Land ice cores (East Antarctica), Quaternary. Sci. Rev., 29, 146–-159, doi:10.1016/j.quascirev.2009.10.009, 2010.

**Formatiert:** Links

**Formatiert:** Englisch (Großbritannien)

**Formatiert:** Englisch (Großbritannien)

Stenni, B., Curran, M.A.J., Abram, N.J., Orsi, A., Goursaud, S., Masson–-Delmotte, V., Neukom, R., Goosse, H., Divine, D., van Ommen, T., Steig, E.J., Dixon, D.A., Thomas, E.R., Bertler, N.A.N., Isaksson, E., Ekaykin, A., Werner, M. and Frezzotti, M.: Antarctic climate variability on regional and continental scales over the last 2000 years, Clim. Past, 13, 1609–-1634, doi:10.5194/cp–-13–-1609–-2017, 2017.

Stewart, R.W.: The annual cycle of hydrogen peroxide: an indicator of chemical instability?, Atmos. Chem. Phys., 4, 933-946, doi:10.5194/acp-4-933-2004, 2004.

Thomas, E.R., Marshall, G.J. and McConnell, J.R.: A doubling in snow accumulation in the western Antarctic Peninsula since 1850, Geophys. Res. Lett., 35, L01706, doi:10.1029/2007GL032529, 2008.

Thomas, E. R. and Bracegirdle, T.J.: Improving ice core interpretation using in situ and reanalysis data, J. Geophys. Res., 114, D20116, doi:10.1029/2009JD012263, 2009.

Thomas, E.R., Dennis, P.F., Bracegirdle, T.J. and Franzke, C.: Ice core evidence for significant 100–-year regional warming on the Antarctic Peninsula, Geophys. Res. Lett., 36, L20704, doi:10.1029/2009GL040104, 2009.

Thomas, E.R., Bracegirdle, T.J., Turner, J. and Wolff, E.W.: A 308 year record of climate variability in West Antarctica, Geophys. Res. Lett., 40, 5492–-5496, doi:10.1002/2013GL057782, 2013.

Thomas, E.R. and Bracegirdle, T.J.: Precipitation pathways for five new ice core sites in Ellsworth Land, West Antarctica, Clim. Dyn., 44, 2067–-2078, doi:10.1007/s00382–-014–-2213–-6, 2015.

Thomas, E.R., Hosking, J.S., Tuckwell, R.R., Warren, R.A. and Ludlow, E.C.: Twentieth century increase in snowfall in coastal West Antarctica, Geophys. Res. Lett., 42, 9387-9393, doi:10.1002/2015GL065750, 2015.

Thomas, E.R., van Wessem, J.M., Roberts, J., Isaksson, E., Schlosser, E., Fudge, T.J., Vallelonga, P., Medley, B., Lenaerts, J., Bertler, N., van den Broeke, M., Dixon, D.A., Frezzotti, M., Stenni, B., Curran, M. and Ekaykin, A.A.: Regional Antarctic snow accumulation over the past 1000 years, Clim. Past, 13, 1491–-1513, doi:10.5194/cp–-13–-1491–-2017, 2017.

Thompson, D.W.J. and Wallace, J.M.: Annular Modes in the Extratropical Circulation. Part I: Month–-to–-Month Variability, J. Climate, 13, 1000–-1016, doi:10.1175/1520–-0442(2000)013<1000:AMITEC>2.0.CO;2, 2000.

Thompson, D.W.J. and Solomon, S.: Interpretation of Recent Southern Hemisphere Climate Change, Science, 296, 895–-899, doi:10.1126/science.1069270, 2002.

Tsukernik, M and Lynch, A.H.: Atmospheric Meridional Moisture Flux over the Southern Ocean: A Story of the Amundsen Sea, J. Climate, 26, 8055-8064, doi:10.1175/JCLI-D-12-00381.1, 2013.

Turner, J.: The El Niño–-Southern Oscillation and Antarctica, Int. J. Climatol., 24, 1–-31, doi:10.1002/joc.965, 2004.

**Formatiert:** Block, Zeilenabstand: 1,5 Zeilen

**Formatiert:** Schriftart: (Standard) +Textkörper (Times New Roman), 10 Pt.

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Turner, J., Colwell, S.R., Marshall, G.J., Lachlan-Cope, T.A., Carleton, A.M., Jones, P.D., Lagun, V., Reid, P.A. and Iagovkina, S.: Antarctic climate change during the last 50 years, Int. J. Climatol., 25, 279-294, doi:10.1002/joc.1130, 2005a.

Turner, J., Lachlan--Cope, T., Colwell, S. and Marshall, G.J.: A positive trend in western Antarctic Peninsula precipitation over the last 50 years reflecting regional and Antarctic--wide atmospheric circulation changes, Ann. Glaciol., 41, 85--91, doi: 10.3189/172756405781813177, 2005b.

Turner, J., Maksym, T., Phillips, T., Marshall, G.J. and Meredith, M.P.: The impact of changes in sea ice advance on the large winter warming on the western Antarctic Peninsula, Int. J. Climatol., 33, 852-861, doi:10.1002/joc.3474, 2013.

Turner, J., Lu, H., White, I., King, J.C., Phillips, T., Hosking, J.S., Bracegirdle, T.J., Marshall, G.J., Mulvaney, R. and Deb, P.: Absence of 21st century warming on Antarctic Peninsula consistent with natural variability, Nature, 535, 411-415, doi:10.1038/nature18645, 2016.

Uemura, R., Matsui, Y., Yoshimura, K., Motoyama, H. and Yoshida, N.: Evidence of deuterium excess in water vapor as an indicator of ocean surface conditions, J. Geophys. Res., 113, D19114, doi:10.1029/2008JD010209, 2008.

van den Broeke, M., van de Berg, W.J. and van Meijgaard, E.: Snowfall in coastal West Antarctica much greater than previously assumed, Geophys. Res. Lett., 33, L02505, doi:10.1029/2005GL025239, 2006.

van Geldern, R. and Barth, J.A.C.: Optimization of instrument setup and post-run corrections for oxygen and hydrogen stable isotope measurements of water by isotope ratio infrared spectroscopy (IRIS), Limnol. Oceanogr. Meth., 10, 1024-1036, doi:10.4319/lom.2012.10.1024, 2012.

Vaughan, D.G., Marshall, G.J., Connolley, W.M., Parkinson, C., Mulvaney, R., Hodgson, D.A., King, J.C., Pudsey, C.J. and Turner, J.: Recent rapid regional climate warming on the Antarctic Peninsula, Climate Change, 60, 243-274, 2003.

Vega, C.P., Schlosser, E., Divine, D.V., Kohler, J., Martma, T., Eichler, A., Schwikowski, M. and Isaksson, E.: Surface mass balance and water stable isotopes derived from firn cores on three ice rises, Fimbul Ice Shelf, Antarctica, The Cryosphere, 10, 2763-2777, doi:10.5194/tc-10-2763-2016, 2016.

Vega, C.P., Isaksson, E., Schlosser, E., Divine, D., Martma, T., Mulvaney, R., Eichler, A. and Schwikowski-Gigar, M.: Variability of sea salts in ice and firn cores from Fimbul Ice Shelf, Dronning Maud Land, Antarctica. The Cryosphere, 12, 1681-1697, doi:10.5194/tc-12-1681-2018, 2018.

Wolter, K. and Timlin, M.S.: Monitoring ENSO in COADS with a Seasonally Adjusted Principal Component Index, in: Proceedings of the 17th Climate Diagnostics Workshop, Norman, Oklahoma, USA, 18-23 October 1992, 52-57, 1993.

Wolter, K. and Timlin, M.S.: Measuring the strength of ENSO events: How does 1997/98 rank?, Weather, 53, 315-324, 1998.

Yue, S. and Wang, C.Y.: The Mann-Kendall Test Modified by Effective Sample Size to Detect Trend in Serially Correlated Hydrological Series, Water. Resour. Manag., 18, 201-218, doi:10.1023/B:WARM.0000043140.61082.60, 2004.



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