Point-by-point response to the reviews

Final response on "Climatic signals from 76 shallow firn cores in Dronning Maud Land, East Antarctica" by S. Altnau et. al

To Anonymous Referee #1

AC: We thank all referees for their efforts and the constructive criticism.

The manuscript submitted by Altnau et al. present a compilation of surface mass balance (SMB) and water isotopic records from 76 shallow cores in the sector of Dronning Maud Land after a separation in different sectors. The main conclusion is that there is a clear difference in the relative variations of SMB and d18O of ice between the coast and the plateau, the plateau showing coherent variations of SMB and d18O since d18O is controlled by Rayleigh distillation and thermodynamic effects while on the coast, atmospheric circulation effects create strong unrelated variations of SMB and d18Oice. In general, this compilation is interesting and should be published. Still, there are several comments that should be taken into account to improve the manuscript that has too many figures and lacks from some clear conclusions:

- It seems that all data from this paper are already published. Still, it would also be nice to mention what is really new in this study compared to previous studies and what is the real novelty of this study. –

AC: We stated this in the paper and believe it was understandable, as Ref. #2 wrote: "The authors gave proper credit to related work and clearly indicated their own new/original contribution."

The main conclusions of the paper are not clear except the difference between the behaviors of d18O vs SMB in the plateau and on the coast.

AC: Those are the main conclusions, plus the reasons for it.

In particular, the link with the SAM is totally unclear

AC: True. It is not clear, that's what we wrote. We only discuss possible explanations for the relationship of SAM to SMB and δ^{18}O.
If the referee meant that our explanations are unclear: We thought about giving a more detailed explanation of the meteorological conditions we discuss. However, although we fully support the requirement that a paper should be self-contained and a scientist, who works in the field, should be able to understand it without reading 5 other papers, we believe that ice core studies are highly interdisciplinary and we assume that the readers,

who work with ice cores and climate, have (should have) some basic knowledge in meteorology. (We don't explain e.g. snow metamorphosis in each ice core paper either.) Thus we concluded that more detailed explanations would destroy the structure of the paper and deter from our main points. We re-wrote the discussion and conclusion section, but refrained from explaining basic meteorological terms. (see changes in a marked-up manuscript version)

and the conclusion part of the paper should be rewritten. It is not clear from what is written if the SAM has or not any influence on the ice d18O or SMB in coastal area since contradictory conclusions are presented. The authors also seem annoyed by a lack of clear signal with sentences such as "The reasons are not yet entirely clear". I do not see any problem to have a signal that is not clear or inexistent

AC: We never wrote anything that contradicts this. If we did not think the comparison was worthwhile we would not have included it in the paper. On the contrary, we wrote that the lack of correlation between SAM index, air temperature and $?^{18}O$ is highly interesting. We think the comment of Referee 1 is not very objective and we do not understand why Ref.1 should think/write that we are annoyed.

but the conclusion should be written more clearly to avoid a false take-home message.

AC: We re-wrote the discussion and conclusion section. (see marked-up manuscript version) However, we *discuss* different influences on and explanation possibilities for the non-existent correlation between SAM index and the other variables, but we cannot give a definite explanation that could be part of the *conclusion*.

- A discussion on how post-deposition effects also affect d18O of snow is missing (only post deposition noise on SMB is mentioned).

AC: We fully agree here and added some information and references about post-depositional processes in the discussion. (marked-up manuscript version l. 488 – l.494)

- Part 5.2.1 (and 5.2.2) could be rewritten for more clarity. More should be explained on the 11 cross-correlations and what are exactly the 3 cross-correlations of d18O that are significant. What does it mean? What conclusions can be driven for the different sites? For the meaning of the d18O signal in shallow ice cores?

AC: We rearranged this section since the paragraph with the cross-correlation makes more sense following the description of Fig. 6. Furthermore, we noticed that we had a typing error when we cross-checked the calculation for the cross-correlations. Instead of three statistically significant cross-correlations **nine** cross-correlations between the smoothed records (5 year running mean) are found to be statistically significant. This indicates that the temporal variability of $\delta^{18}O$ shows a relatively similar behaviour in most cores, which is in accordance to Figure 6.

p.5976 l. 1-10:

~~Only three of eleven cross-correlations between the detrended composite records of and also three cross-correlations between the smoothed records (5 year running mean) are~~

~~found to be statistically significant at the 95 % confidence level according to t test. For the latter reduction in the number of degrees of freedom was taken into account for calculating the significance.~~

The stable isotope ratio for Ekström (Fig. 6a and b) and Fimbul (Fig. 6c) Ice Shelves is characterized by values generally lower than the multidecadal average during the periods 1950 to the mid-1960s and the 1980s, whereas the 1970s exhibits values above the mean. Ritscherflya (Fig. 6d) has only a short record, but agrees well with Ekström and Fimbul for the given period. For the last 20 years the smoothed record of $\delta^{18}O$ shows little variation. The $\delta^{18}O$ of the plateau cores (Fig. 6e) behaves similar to the ice shelf cores, with the exception of slightly higher values around 1960. The similar temporal variability between the different drilling sites is supported by the calculation of cross-correlations. Only three of eleven cross-correlations between the detrended composite records of $\delta^{18}O$, but nine cross-correlations between the smoothed records (5-year running mean) are found to be statistically significant at the 95% confidence level according to Student's t test. ~~For the latter, reduction in the number of degrees of freedom was taken into account for calculating the significance.~~

There are too many figures in this part (and the following) that are only briefly mentioned and do not seem central for the final conclusion of the paper. Either some figures should be deleted or the text should be more explicit on what can
be learnt from these figures.

AC: We don't think there are too many figures. Particularly Fig. 5 and Fig. 7 give some valuable information to the reader at first glance and do not need more explicit explanation in the text. Therefore we prefer to keep these figures. We made some small changes in the description of Figure 6 in accordance to a comment of Referee #3.

- Some typing mistakes should be corrected (e.g. "Eat" instead of "East" on p. 5966).

AC: Done.

Final response "Climatic signals from 76 shallow firn cores in Dronning Maud Land, East Antarctica" by S. Altnau et. al

To Anonymous Referee #2

The paper compiled surface mass balance (SMB) data and water isotope ($\delta^{18}O$) data from 76 shallow firn cores in Dronning Maud Land, East Antarctica. The authors made composite of these cores for several regions categorized geographically on the ice shelves, plateau regions and regions in between. Both spatial distributions and temporal variations were investigated with assessment of statistical significance. They found that temporal variations are contrasted between regions on the ice shelves and plateau regions. They discussed possible reasons for the contrast, in terms of trends of the Southern Annular Mode (SAM).

In the ongoing discussion about climate change, investigations for detection of possible changes in Antarctica is something that polar scientists must do. So far, compilation of the SMB data and water isotope ($\delta^{18}O$) data were done for each limited ice core(s) core or site group with limited number of sites in Dronning Maud Land. In contrast to earlier studies, this paper attempts to see comprehensively the entire regions in western part of Dronning Maud Land.

This paper addresses scientific questions well within the scope of TC. This paper presents novel compilation of the ground data in one of important regions in East Antarctica. Substantial conclusions are reached with description of statistical limitations. The scientific methods are valid and basically well outlined. The results are basically sufficient to support the interpretations and conclusions. The authors state in their conclusion that "This was the first comprehensive study of this data set from coastal, transitional and interior DML", which I agree.

I suggest in this review that there are rooms for improvement for the description of their compilation and calculations. Otherwise, the paper may not necessarily allow their reproduction by fellow scientists (traceability of results). When I read the paper a few times, it was not easy to understand which site data are used or not for which compilation. For example, please see comments No. 9, 10, 11 and 14 below.

The authors gave proper credit to related work and clearly indicated their own new/original contribution. The title clearly reflects the contents of the paper. The abstract provides a concise and complete summary. The overall presentation is basically well structured and clear, except the rooms of improvements that I suggest in this review. English is not my native language but it seems to me that the language in this paper is good.

Overall, because of the significance and relatively good quality of this work, I suggest that the paper should appear in publication of TC after necessary improvements are made. I would like to encourage authors to improve this paper.

Specific points are commented below with numbers.

AC: We are grateful to Referee # 2 for the thorough review and constructive criticism.

1. This paper did not provide any comments to readers on how precipitation occur in this region, that is, clear sky precipitation, sporadic events of cyclonic activities, occurrence of blocking and redistribution of snow by wind and by sublimation/condensation. Please consider adding short statements for these for a better guide for readers.

AC: We added information about this in the discussion. (see changes in a marked-up manuscript version)

2. Page 5966, lines 4-5.

Please provide definition of shallow cores and medium-deep cores.

AC: We included the total depth/core length of the cores in Table A1.

Reference to Table A1: *...medium-deep cores (see Tab. A1).*

3. Page 5966, a paragraph near the page bottom.

Both Anschütz et al. (2009) and Fujita et al. (2011) investigated at sites outside of the Western DML, that is, outside of any figures in this paper. For a better understanding by readers, another figure for showing wider DML or wider Antarctica with indications of mentioned sites seems useful.

AC: We compare only the sites that are shown on the map. We do not like to add another figure since other reviewers even required to delete some figures and we do not think an additional figure is necessary here.

We gave some additional information in the text:

pp.5966, line 23: *… Dome Fuji (along ID2, Figure 1 and further east).*

4. Page 5966, line 24.

This was supported by a further study of ice core at Dome Fuji using volcanic time markers (Igaras hi et al., 2011). Please consider addition of this paper in the statement.

Igarashi, M., Nakai, Y., Motizuki, Y., Takahashi, K., Motoyama, H., and Makishima, K.: Dating of the Dome Fuji shallow ice core based on a record of volcanic eruptions from AD 1260 to ad 2001, Polar Science, 5, 411-420, doi:10.1016/j.polar.2011.08.001, 2011.

AC: We did not include the paper since Igarashi et al. (2011) dated the shallow firn core on a lower temporal resolution and they examined the accumulation on longer time scales. Additionally they found no clear trend for the considered time period.

5. Page 5966, lines 24-25.

Please confirm if the statement below is really correct.

"This is not confirmed by a study of Frezzotti et al. (2013) who provided a synthesis of Antarctic

SMB during the last 800 years."

These authors Frezzotti et al. (2013) stated in their conclusion "However, a clear increase in accumulation of more than 10%(>300 kgm^{-2} yr^{-1}) has occurred in high-SMB coastal regions and over the highest part of the East Antarctic ice divide since the 1960s." It seems that the central part of DML is the highest part of the East Antarctic ice divide.

AC: We rewrote the sentence/paragraph:

Frezotti (2013) provided a synthesis of Antarctic SMB during the last 800 years. They state that SMB over most of Antarctica do not exhibit an overall clear trend. However, they found *a clear increase in SMB in coastal regions and over the highest part of the East Antarctic ice divide since the 1960s, which confirms the results of Fuijta et al. (2011) but contradicts those of Divine et al. (2009) and Kaczmarska et al. (2004).*

6. Page 5966, line 27.

Where in the East Antarctic Plateau, was it observed? Please specify a region. Otherwise, readers will not understand.

AC: We specified the traverse route in the text:

p. 5966, line 18:

…through DML from the Norwegian base Troll to the South Pole.

p. 5966, line 26:

...SMB changes in ice cores retrieved during the above-mentioned traverse from Troll to South Pole but found that almost all sites...

7. Table A1 in the context of Page 5967 line 5.

Can core depths/lengths be listed? It is informative if you can do it.

AC: The core depth/length is additionally listed in Table 1 now.

8. Page 5967 line 8.

What does "they" mean here, two cores or all cores?

AC: We refer to all cores in this sentence. We rephrased the sentence more clearly:

Spatially the dataset represents the entire western DML.

9. Page 5968 line 4 (Table 1).

Difference between Ekström Ice Shelf and Ekström Ice Shelf (R) was not clear to me. Did you give some explanation to readers somewhere in this paper?

We wrote that we included the six cores derived from Halvarryggen and Søråsen in the Ekström Ice Shelf (R) composite record. Since the cores are strongly influenced by local conditions we stressed that this group has to be considered with care. In accordance with a comment from Reviewer 3 we added a sentence in parentheses that, for the sake of completeness, we do not want to omit these data.

Page 5968 line 6-9:

The second group includes these cores plus six more cores situated on Søråsen and Halvfarryggen (Fernandoy et al., 2010). However, as stated before, these cores are strongly influenced by local conditions, thus this group has to be considered with care.

(For the sake of completeness we did not omit them from our study.)

10. Table1.

For each group of site, please indicate name of the group such as ice shelf name, plateau or something like this. In general, my concern in this paper is that it is hard to understand which site data belong to which geographical category (such as my unknown Ekström Ice Shelf (R)) and how they were used. I think that an addition of such a table (or tables) as supplementary information isuseful both for readers and for future researchers who will recompile the data using additional data of future.

AC: We gave additional information in the caption of Table 1.

"Ice Shelves" corresponds to all cores from Fimbul, Ekström and Riiser-Larsen Ice Shelves. "Ekström (R)" refers to all cores from Ekström Ice Shelf plus the adjacent ridges Søråsen and Halvfarryggen.

11. Page 5968 lines 3-20.

You described several groups as documentation here. Because of complication of many detailed information, I suggest that the authors should provide a supplementary table to explain how grouping and sub-grouping were done. In addition, I hope to see in Figure 1 and other figures that the authors use symbol markers so that readers can see intuitively relations between sites and the authors' grouping of sites.

AC: We provided information about the grouping in the caption of Table 1. We do not think a supplementary table is necessary here.

The cores in Fig. 1 are colour-coded, each sub-group has its own colour. In Fig. 2 it would have been not clear to use circles for the plateau cores: we used crosses because the data points are lying so close together that it would be difficult to distinguish between single circles. On the other hand, crosses would not have been very clear on the map. Therefore we did not use the same symbol markers in all figures.

12. Page 5969 line 26 – Page 5970 line 3.

You stated “*Thus the positive phase of SAM is characterized by strong, mostly zonal westerlies with only low amplitudes of planetary waves. This means little exchange of moisture and energy between mid and high latitudes and consequently a cooling of Antarctica, with the exception of the Antarctic Peninsula, which projects farther north then the rest of the continent* .”

Is this your scientific claim or well-known meaning of SAM? Please clarify. If the latter is the case, please provide reference papers. I did not find such a view in Marshall (2003) paper.

AC: We provided a reference paper by Marshall (2013) in this paragraph to clarify this view.

13. Page 5972 lines 20-21.

You stated “*latitude and elevation effect are closely connected in Antarctica since generally the elevation increases with latitude*.”

This is not a useful rule. It is true only for very limited area in Antarctica. I suggest you to consider to remove this statement and related statements.

I felt that showing the data (SMB and water isotopes) in terms of latitude has little meaning. It is because earlier studies (for example Satow et al. 1999 below) showed examples showing elevation had very strong effects.

I agree that angle of insolation (that is, latitude) potentially have some effects to SMB and water isotopes. But I do not believe that such a faint effect can be visible in simple X-Y plot here. With simple X-Y plot here, we simply see elevation dependency of data through distortion of incompatibility between latitude and elevation. Nothing more can be seen.

Rather, I can see that you did not analyze the data in terms of continentality (distance from open ocean) or relative location in terms of wind-lee or windward side of ice divide. In Figure 3a, deviation of the data points from the regression line seem to mean such effects, which you did not examine.

Satow, K., Watanabe, O., Shoji, H., and Motoyama, H.: The relationship among accumulation rate, stable isotope ratio and surface temperature on the plateau of East Dronning Maud Land, Antarctica, Polar Meteorol. Glaciol., 13, 43-52, 1999.

AC: We agree that this is not as straightforward as we claimed. We removed this statement and related statements:

p. 5972 line 19: remove the word "latitude"

We removed the paragraph line 20 -line 25. We also removed Figure 3b and the paragraph where we discuss the figure.

14. Figures 2, 3 and 4

I suggest that you use the common symbol markers for the same sites in these 3 figures, to improve readers better understanding.

AC: We explained our choice of symbol markers above.

15. Page 5976 lines 15–17.

You stated "*The Little Ice Age (LIA), a colder period widely seen in the Northern Hemisphere between 1650 and 1850 is not clearly present in DML. In a 1000 years chronology from Amundsenisen (Graf et al., 2002)*."

Around here, it is not clear whether the statements are based on data in this work (Figure 8), citation (Graf et al. 2002) or both. Please clarify. If readers need to see Figure 8, please specify which feature in the figure readers should see.

AC: We rewrote this sentence:

Our study covers only the second half of the LIA and the relatively cool period in the second half of the 19th century (seen in Fig. 8) cannot clearly be related to the LIA in the Northern Hemisphere.

17. Page 5977 lines 21–25.

I did not understand well your logic at these lines.

You term "atmospheric flow". It seems to me, in any case, moisture transport occurs due to atmospheric flow from lower latitude, occurring due to cyclonic activities or occurrence of blocking, by which precipitation is induced both in inland and on ice shelves. It seems to me that a main difference between ice shelves and plateau sites is flat land or presence of large scale slope. By a term of "atmospheric flow", do you mean that flow of moisture on topographically flat area? Please make me (and readers) understand.

AC: "Atmospheric flow conditions" means the general pattern of the atmospheric circulation, e.g. more zonal/meridional flow, location and movement of cyclones etc. We thought about giving a more detailed explanation of the meteorological conditions we disuss. However, although we fully support the requirement that a paper should be self-contained and a scientist, who works in the corresponding field, should be able to understand it without reading 5 other papers, we believe that ice core studies are highly interdisciplinary and we assume that the readers, who work with ice cores and climate, have (should have) some basic knowledge in meteorology. (We don't explain e.g. snow metamorphosis in each ice core paper either.) Thus we concluded that more detailed explanations would destroy the structure of the paper and deter from our main points. We re-wrote the discussion and conclusion section, but refrained from explaining basic meteorological terms.

18. Page 5977 line 26 – Page 5978 line 4. Generally accepted views? Then, citation?

AC: We refer to Marshall (2013) where he described the effects of the positive/negative phase of the SAM index to the energy and moisture exchange between high and midlatitudes.

19. Page 5978 lines 20 – 23.

You showed the effects of increasing altitude in this paper. But you did not show any effects of decreasing incidence angle of solar radiation (meaning decreasing temperature) or increasing continentality (meaning less moisture available). The statement is much more than you really showed with data. The statement should be given differently.

AC: We deleted the part about the latitude dependence.

20. Page 5979 line 29 – Page 5980 line 4.

Your statement is that cyclonic activities do not necessary increase precipitation on ice shelves.

Is there no possibility that present sampling (statistical handling of sites) are still insufficient with some probability? If we try to access the SMB data and water isotope data with better statistical sampling what we do? Perhaps such information is useful for readers.

AC: The sampling issue in the case of Antarctica is a somewhat trivial to answer: there is so few data (also on SMB) that hardly one can have a risk of oversampling doing any field work. The more the better. With the available data we cannot state whether this is a sampling problem or a lack of correlation (causal link) in the nature itself. Better sampling (more data) of course would help to decrease the number of working hypotheses.

21. Discussion and conclusion in general.

Discussions are often mixtures of the data, citation and speculation. Because of this condition of the mixture, it is sometimes hard for me to understand basis of each statement. The item just above (Page 5978 lines 20 – 23) is one of such examples. Please be careful to tell to readers basis of each statement. Please clarify the statement is based on data, citation or speculation.

AC: We re-wrote the whole discussion and conclusion.

22. Recent significant papers.

I suggest that the authors consider to mention some of recent significant papers on water isotopes in the paper. They are Steen-Larsen et al. (2014) and Hoshina et al. (2014) as follows. The former showed that there is strong exchanges of water isotopes between snow and air at NEEM. It should surely occur in Antarctica. The latter showed that there is a strong post-depositional alternation of water isotopes. Both papers mean that exchanges of moisture between air and snow play important role to determine water isotope fixed as ice core data.

Steen-Larsen, H. C., Masson-Delmotte, V., Hirabayashi, M., Winkler, R., Satow, K., Prie, F., Bayou, N., Brun, E., Cuffey, K. M., Dahl-Jensen, D., Dumont, M., Guillevic, M., Kipfstuhl, S., Landais, A., Popp, T., Risi, C., Steffen, K., Stenni, B., and Sveinbjornsdottir, A. E.: What controls the isotopic composition of greenland surface snow?, Clim. Past., 10, 377-392,

10.5194/cp-10-377-2014, 2014.

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, Journal of Geophysical Research-Atmospheres, 119, 274-

283, 10.1002/2013jd020771, 2014.

AC: We fully agree that post-depositional processes are important. We re-wrote the discussion and conclusion section and included information on post-depositional processes (including the suggested references) (see changes in a marked-up manuscript version)

Final response on "Climatic signals from 76 shallow firn cores in Dronning Maud Land, East Antarctica" by S. Altnau et. al

To Anonymous Referee #3

AC: We are very grateful to Referee # 3 for the thorough review and we especially appreciate the good structure of the review.

This paper is a valuable analysis of climatic data from Dronning Maud Land. Records of oxygen isotope and surface mass balance variations in firn cores have been collected from many different sources. By stacking groups of these records together, the authors have reduced the signal-to-noise ratio and derived new information from data previously analysed in isolation. The paper is certainly worth publication but could perhaps be improved by some re-balancing of the material. My personal feeling is that the first sections (1-4) are a bit too detailed, while the results and discussion sections (5 and 6) could do with a stronger

structure. Since the sources of the data are acknowledged in Table A1 the authors could perhaps do without a separate Section 3;

where previous authors have made relevant deductions from their data these could be commented on in the Discussion section. I found it quite hard to recall which ideas presented by the authors had already been proposed by others because of the separation between sections 3 and 6.

AC: One of the questions to the reviewers is always, " Does the paper give adequate reference to related work"? Therefore we think that section 3 is necessary. Referee #2 wrote," The authors gave proper credit to related work and clearly indicated their own new/original contribution." We reformulated parts of section 3 to make this even clearer.

I think the number of figures could perhaps be reduced. Figures 5 and 7 do not seem to be essential.

AC: We think that Fig. 5 and 7 are useful to give the reader valuable information about SMB and stable isotope trends at first glance.

I agree with Referee 1 that the comparison with the SAM index is worthwhile reporting, whatever the result.

AC: We never wrote anything that contradicts this. If we did not think the comparison was worthwhile we would not have included it in the paper. On the contrary, we wrote that the lack of correlation between SAM index, air temperature and δ^{18}O is highly interesting. We think the comment of Referee 1 is not very objective and we do not understand why Ref. 1 should think/write that we are annoyed.

It is important to remind the non-specialist reader that Antarctic precipitation does not always increase with warming temperatures even if a clear explanation of what is happening in the coastal regions cannot be derived from the data available so far.

AC: That's what we wrote.

The English is generally excellent, although there are inevitably a few places where minor improvements can be made. I have suggested some possible changes in the detailed comments section below. There is a slight problem of wavering tenses which needs to be sorted out. My own preference is for past work to be described in the past tense but for the new work presented in the paper to be described in the present tense. However, it does not matter what convention is used so long as the authors are consistent.

AC: We fully agree to that and checked the tenses throughout the paper.

Detailed comments

(Suggestions for minor improvements in English are in italics)

p.5962 l.15 *has exhibited*

AC: Done

l.24 *not only is an increase in sea ice observed but also…*

AC: Done

l.26 *observed over the entire..*

AC: Done

p.5963 l.5 How about "This is important because an increase in precipitation, and hence increased surface mass balance (SMB), might mitigate sea level rise."

AC: Done

l.7 *Close monitoring…*

AC: Done

l.12 *are only available since…*

AC: We would like to stress here that they were not available earlier.

l.16 isotope ratio; annual mean SMB…

AC: Done

l.20 *as part of different national… In particular, the pre-site-survey..*

AC: Done

l.23 *hitherto poorly explored…*

AC: Done

l.25 *have been published*

AC: Done.

l.26 *In this study…*

AC: Done

l.27 At this point I would move into the present tense: "the spatial and temporal variations are investigated. Calculation of stacked records helps considerably to improve…

AC: see above. We investigated the spatial and temporal variations, that's done, and then we can show the results. So we prefer past tense here. We guess in this case it is a matter of taste.

p.5964 l.6 The area of the rectangle shown in Figure 1 is c. 960,000 km^2 according to the scale shown. So the area of the western part of DML under discussion must be less than this. Would it be more useful to give this area rather than that of the whole of DML?

AC: Since the borders of DML are not clearly defined, this is just some general information. The study area is not better defined, so we think this is also just a matter of taste.

l.6 *Our study is focused on…*

AC: Done

l.12 *with an area of 33000 km*^{2}

AC: Done

l.20 *After this DML was only visited sporadically…….Systematic data acquisition…*

AC: Done

l.22 I cannot see Neumayer Station on the map

AC: Sorry, it got lost somewhere in the stage of submitting. The label for Neumayer Station was added to the map.

p.5965 l.4 The statement that the cores are not directly comparable is confusing for the reader at this stage since it is not clear whether you are going to include the data in your comparison or not.

AC: We added in the text, that, for the sake of completeness, we did not omit them from our study.

Page 5968 line 9:
(For the sake of completeness we did not omit them from our study.)

l.9 To make this sentence clear you could write " a positive correlation of the Ritscherflya stable isotope ration with the surface air temperature at Halley" .

AC: Done

l.10 This is all a bit confusing for the reader – what exactly is the point being made by this paragraph? Is there a connection between meterorological conditions at a coastal station and in the inland region or not? Bear in mind that the reader does not know until p.5969 l.11 that you do not think Halley is representative of your coastal ice shelves because of the presence of the ice-covered Weddell Sea.

AC: We deleted the sentence about the connection between meteorological conditions at Halley and the ice core properties.

l.9-10: *…large spatial and temporal variability (Isaksson and Karlén, 1994a, b; Isaksson et al., 1996) .*

We delete the next two sentences (see marked-up manuscript version).

l.24 *when the SAM is…*

AC: Done

l.27 *as part of*

AC: Done

p. 5966 l.5 *The area was found to be…*

AC: Done

l.24 *study by Frezotti…*

AC: We rewrote this paragraph according to the comments of Ref. #2.

Frezotti (2013) provided a synthesis of Antarctic SMB during the last 800 years. They state that SMB over most of Antarctica do not exhibit an overall clear trend. However, they found a clear increase in SMB in coastal regions and over the highest part of the East Antarctic ice divide since the 1960s, which confirms the results of Fuijta et al. (2011) but contradicts those of Divine et al. (2009) and Kaczmarska et al. (2004).

l.27 East Antarctic Plateau

AC: Done

l.28 *but found that almost all sites*

AC: We rewrote the paragraph:

...SMB changes in ice cores retrieved during the above-mentioned traverse from Troll to South Pole but found that almost all sites...

p.5967 l.3 *ice cores obtained during…*

AC: Done

l.11 As a matter of interest what were the chemical species determined by the

Continuous Flow Analysis?

AC: With the CFA e.g. Ammonium, Calcium, Sodium were determined. More information:

Sommer, S., Wagenbach, D., Mulvaney, R., and Fischer, H.: Glacio-chemical study spanning

the past 2 kyr on the three ice cores from Dronning Maud Land, Antarctica, 2. Seasonally resolved chemical records, J. Geophys. Res., 105, 29423–29433, doi:10.1029/2000JD900450, 2000b. 5966

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

We add this information on p. 5967 in line 13 :

Continuous flow analysis allowed fast analysis of ammonium, calcium, sodium along the ice core with an high spatial resolution (Röthlisberger et al., 2000a; Sommer et al., 2000b).

l.20 Do you mean "**annual** values of SMB are poorly correlated" ? If so you could write *Annual values of SMB….are poorly correlated even between cores from the same location….*

AC: Yes, we corrected this: *Annual values of SMB and mean annual $\delta^{18}O$…*

l.22 *due to the effects of wind….. values. Furthermore,….*

AC: Done

p.5968 l.16 *on Amundsenisen…*

AC: Done

l.27 *the percentage deviation from the mean*

AC: We rewrote this: *the relative deviation expressed as a percentage*

p.5969 l.4 *are available. An automatic weather station (AWS) was installed 1.5 km west of Kohnen Station in 1998 and moved to the Station in 2007. In coastal …*

AC: Done

l. 11 *not representative of the climate*

AC: Done

l.14 "no homogenous time series"?

AC: Done

l.17 *thus the data can be used*

AC: Done

l.24 *a SAM index*

AC: This has to be **an** SAM index since S is pronounced "es" and thus starts with a vowel.

p.5970 l.10 I had to go back to the Johnsen et al (1997) paper to work out what was meant here. I suggest you repeat the wording of that paper which is quite precise:

One way of estimating the signal to noise (S/N) variance ratio is by comparing the variance of a stacked record (VAR_S) based on n overlapping records, with the mean of the variances (VAR_M) for the n individual records. The estimate of a single record S/N variance ratio then becomes.....

AC: We do not like to simply take exactly Johnson's words; this is not good style and reminds us of copy-paste methods some authors use, who cannot speak English very well. However, we reformulated the paragraph:

*The signal-to-noise variance ratio (SNVR) of a single record Fi can be estimated (Johnsen et al., 1997) by comparing the variance of a stacked record (VAR_C) **derived** from N individual records to the mean variance of the N individual records **(VAR_M)**:*

l.19 You do not explain here that $F_c = n\ F_i$ although this seems to be the case from Table 2. I wonder if you mean you are comparing F_c and F_i between areas rather than with each other, which is what you appear to be saying in the text?

AC: We reformulated this paragraph:

In Table 2, for each subgroup (Ice shelf cores, plateau cores, and 200-year series of the plateau cores) the SNVR of the single records (mean of all cores of one group) F_i compared to the corresponding composite record Fc is shown. F_c is determined by multiplying F_i with the number of individual cores contained in the composite record.

l.23 why do higher values of mean accumulation mean higher SNVR? Could you expand a little?

AC: We rewrote the paragraph from page 5970 line 22 to page 5971 line 2:

On the plateau, accumulation rates are considerably lower than in the coastal areas. At the same time, the effects of wind scouring and thus disturbance of the annual layers, are larger, which leads to higher variance in the plateau cores than in the coastal cores.

p.5971

l.3 Present tense here? *It turns out that*

AC: We keep past tense here since it describes something that was done (and finished) during our investigation.

l.12 *independent of short-term (interannual) variability. An ANOVA F-test is used to test whether these trends are statistically significant. The period 1950-2000…*

AC: We did not change this. Readers who are not familiar with the F-test won't know the abbreviation ANOVA either, and we think F-test is clear enough.

l.21 Have you said the same thing twice here? Is normalisation and detrending the same as converting into anomalies?

AC: yes, thank you, we deleted the sentence:

~~Prior to estimation of the correlation the series were converted into anomalies with respect to the common period.~~

p.5972 l.1 "The significance of the correlations…. using the standard t- test" is followed at line 6 by "Significance of the cross-correlations…… using Students t test" . This appears to be a duplication.

AC: Again, thanks, we deleted the sentence:

l.5: ~~Significance of the cross-correlations between the composite records was assessed using Students *t* test.~~

l.6: *cannot*

AC: Done

l.12 The font in Figure 2 is rather small and difficult to read without magnifying the figure. Would it be possible to use a larger font for the values?

AC: We put quite some effort into creating these figure. We agree that it is hard to read in the discussion paper. In the final paper, the figure is supposed to have full page-width, which makes it better readable. The number of cores is so high that a larger font size would not increase the clarity of the figure.

l.18 *related to geographical factors*

AC: Done

l.19 *The distance to the coast (continentality)…precipitation. Latitude and elevation effects are….*

AC: We rewrote this paragraph according to the comments of Ref. #2.

p. 5972 line 19: remove the word "latitude"

Further we removed the paragraph line 20-line 25.

p.5973 l.6 *In contrast to other studies… because of differences in moisture transport..*

AC: Done

l.14 *cannot be explained physically.*

AC: Done

l.15 But are the values from these cores shown as points on the graph? If so could they be indicated?

AC: They are not shown on the graph.

l.24 Earlier in the paper you use R^2 rather than write out "coefficient of determination" in full.

AC: We removed Figure 3b and the paragraph where we discuss Figure 3b according to a comment by Referee #2.

p.5974 l.1 *Both Schlosser et al. (2008)and Fujita et al. (2011) note that the main wind direction along ID1 is NE.*

AC: Done

l.7 *lower than on the windward side...... generally lower on the lee side...*

AC: Done

l.12 *however, not as strong (R^2=0.90) as between...*

AC: matter of taste

l.17 I am not quite sure how this diagram works. If the whiskers mark the extreme data points how can the "outliers" be outside the whiskers? Are these "outlier" points excluded from the statistical calculation? If so, maybe you could specify that the whiskers indicate the range of points included in the calculation, not the extreme data points.

AC: We rewrote this paragraph:

The red line indicates the median. The tops and bottoms of each box are the 25th and 75th percentiles; the distances between the tops and bottoms are the interquartile ranges. Whiskers are drawn from the ends of the interquartile ranges to the
furthest observations within the whisker length, the latter corresponding to 1.5 times the interquartile range. Values beyond the whisker length are marked as outliers and plotted as red dots.

p.5975 l.4 *to Student's t test...*

AC: Done

l.9 *agrees well with...*

AC: Done

l.10 The stable isotope ratio is not almost constant year-to-year. The smoothed record

(5-year running mean) shows little variation which is, I think, what you mean.

AC: We rewrote this paragraph:

For the last 20 years the smoothed record of $\delta^{18}O$ shows little variation. The $\delta^{18}O$ of the plateau cores (Fig. 6e) behaves similar to the ice shelf cores, with the exception of slightly higher values around 1960.

p.5976 l.2 It is not clear here whether the previous work involved only some of the cores or only some sections of all of the cores.

AC: The previous work involved only some of the cores. We changed the formulation to *"…with only a subset of the cores"*

l.24 *on two different ice shelves.*

AC: Done

p.5977 l.3 r = 0.59 ? Previously you have used R^2

AC: The correlation coefficient r refers to a measure of the strength of association between two variables. The correlation coefficient is useful as an initial exploratory tool when several variables are being considered. The sign of r gives the direction of the association.

The coefficient of determination is a number that indicates how well data fit a statistical model i.e. a line. This is useful to check how much of the variability in the key response can be explained.

l.7 *A positive correlation between….. is expected because of….*

AC: We did not change this because we do not think this relationship is EXPECTED (at least we don't expect it anymore), but it is ASSUMED in ice core studies, particularly to estimate the accumulation rate using the stable isotope ratio as a temperature proxy. We did not add this explanation in the text since it deters from the topic we are talking about.

l.13 The notation implies that you are going to compare a ratio with the SAM index. I think you mean both $?^{18}$O and SMB will be compared with SAM.

AC: We changed the title of the subsection to:

Possible influence of SAM on δ^{18}O and SMB

Further we rewrote l.13-1.14:

… as a first step, a possible influence of SAM on d18O and SMB was considered.

l.17 Figure 9 actually shows (a) $?^{18}$O, Neumayer temperature and SAM index and (b) SMB, Neumayer pressure and SAM index as a function of time. This allows a comparison to be made by eye, but is not in itself a comparison.

AC: We removed "compare to" and write "together with" in line 19.

p.5978 l.14 It is a matter of choice, but if you choose to use the present tense to describe the analysis in the paper then at this stage the analysis is completed. Therefore you would say… *have been analysed…. This has been the first comprehensive study… Thus it*

has been possible to analyse climatic trends…

AC: As you say, the analysis is **completed**. Present perfect is used for something that started in the past and is still **ongoing**. Thus we cannot use present perfect here.

(We had the same discussion with a native speaker in another review…)

p.5979 l.8 *The origin of precipitation…*

AC: Done

l.11 *In the 200-year records…*

AC: Done

l.12 *However, in this context…. should also be discussed*

AC: Done

l.19 *This suggests that winter accumulation has decreased even more strongly than…*

AC: matter of taste

l.25 Saying "to confirm the hypothesis" is probably better than saying "to prove" it

AC: We changed this:

Recent data alone are not sufficient to confirm this hypothesis.

p.5980 l.19 *for the data set presented here.*

AC: Done

l.25 *As well as firn cores and ….*

AC: matter of taste.

p.5981l.3 *ice core data from the ….*

AC: Done

p.5992 *The standard deviation of the slope is also given*

AC: Done

p.5993 Should the 1950-2000 Plateau trend be in bold type?

AC: This is correct. We changed this in Table A3.

p.6004 The diagram is a bit difficult to understand. Maybe you could separate plateau and ice shelf data i.e. have 4 panels?

AC: We prefer to have plateau and ice shelf cores in the same figure since this facilitates the comparison. It allows to detect immediately periods where SMB or $\delta^{18}O$ of ice shelf and plateau cores are in phase or not. For the final publication, Figure 8 should have full page width and be thus easier to read.

Final response on "Climatic signals from 76 shallow firn cores in Dronning Maud Land, East Antarctica" by S. Altnau et. al

To Anonymous Referee #4

AC: We thank all referees for their efforts and the constructive criticism.

Altnau et al. compile availabe records of 76 shallow firn cores from the western part of Dronning Maud Land to analyze the relationship between the temperature proxy, delta18O, and the surface mass balance. As can be expected from the complex terrain including ice shelves, mountain ranges, ice divides and the plateau considerable differences are found. It is an interesting analysis, well written. I think what I can add as another referee is the following:

The introduction is very detailed. I have the feeling from the title, abstract and introduction the point of your interest is changing climate and recent climate change.
What I am missing in the paper are a few sentences commenting on the massive mass changes in the DML area described by Boening et al. (GRL2012) and the following papers. The years after 2009 are not part of this work, I am aware of this, but you must have looked through lots of records and should be able to tell us whether or not the 2009 mass change event in DML has counterparts during the last 60 or 200 years.

AC: True, the years after 2009 are not part of our study. 2009 was a single year with very wet and warm conditions in East Antarctica, followed by the very dry and cold 2010. Since we were interested in climatic trends, we did not consider single years. It is also difficult to compare data from very different types of measurements.

Reanalysis data: The authors list tells me that you have expertise in the analysis of reanalysis data. There is a 50-60 year long record available. Of course, reanalysis data have lots weaknesses particularly in the polar regions as you mentioned. However, we generally see in the delta-18O a temperature signal. I do not expect a complete reanalysis work but you should be able to say more than Halley the only station with a longer record is too far south. Are the periods showing a positive 18O-trend in the ice core records reflected in the reanalysis data records as periods of positive temperature anomaly? I expect you know more what you tell us.

AC: We do say more than that Halley is too far south. We compare the δ^{18}O and the SMB to measured air temperature at Neumayer Station and find that the latter shows no trend, whereas δ^{18}O and SMB show opposite trends. We think that Neumayer is representative for this coastal part of DML and prefer measurements to reanalysis data. Also Klöwer et al. (2013) state that reanalysis data are not sufficient to access climate trends in Antarctica.

Klöwer, M., T. Jung, G. König-Langlo, T. Semmler, 2013. Aspects of weather parameters at Neumayer station, Antarctica, and their representation in reanalysis and climate model data. Meteor. Zeitschr., doi: 10.1127/0941-2948/2013/0505.

You argue with changes in seasonality. I do not like this argument. It is some form of "deus ex machina" everywhere right. From the Neumayer data E. Schlosser has analyzed you should be able to make a clearer statement if accumulation or whatever may have changed recently if anything has changed.

AC: That is not a clear sentence and hard to understand.

This argument is often used but it is a quite cheap argument and explaining nothing.

AC: The point is not whether Ref. #4 "likes" this argument or not. We believe that to call it a "cheap argument that explains nothing" is a sign for lack of understanding. Seasonality is far away from being a "deus ex machina". There are several studies, in which seasonality is considered in detail (e.g. Schlosser, 1999, Noone et al, 1999).

Little Ice Age Considering that you only present records not older than 200 years it is probably hard to make firm statements about the LIA. Furthermore, the bipolar seesaw may (?) also work on shorter and even decadal time scales then what can we expect to see in a 200 year record as evidence of the LIA.

AC: We deleted the remark about LIA in the discussion and conclusion section. We kept the reference Graf et al. 2002 in the description of Fig. 6, since he investigated longer cores.

No altitude effect on the Ekström ice shelf and the 600 m high ridges east and west of it. I believe that this is easy to understand. The 600 m is cloudy level and the Ekströmisen gets lots or most of its snow from clouds from this level. Don't you think so?

AC: We do not think so. We assume you refer to the lifting condensation level when you say "cloudy level" and there is no reason it should be always at 600m since it depends on the individual dynamics of the frontal systems involved. Also, the cloud layers have different thicknesses and there could be multiple layers. We checked the radiosonde data from Neumayer and found no evidence for your statement. Even if it were true, that the LCL was always at 600m at Neumayer, the air mass would still be orographically lifted when it flowed over the ridges. Orographic precipitation is always a highly complex process and we don't think what we observe is "easy to understand" as Ref. #4 states.

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Climatic signals from 76 shallow firn cores in Dronning Maud Land, East Antarctica

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Abstract. The spatial and temporal distribution of surface mass balance (SMB) and δ^{18}O were investigated in the first comprehensive study of a set of 76 firn cores retrieved by various expeditions during the past three decades in Dronning Maud Land, East Antarctica. The large number of cores was used to calculate stacked records of SMB and δ^{18}O, which considerably increased the signal-to-noise ratio compared to earlier studies and facilitated the detection of climatic signals. Considerable differences between cores from the interior plateau and the coastal cores were found. The δ^{18}O of both the plateau and the ice shelf cores exhibit a slight positive trend over the second half of the 20th century. In the corresponding period, the SMB has a negative trend in the ice shelf cores, but increases on the plateau. Comparison with meteorological data from Neumayer Station revealed that for the ice shelf regions atmospheric dynamic effects are more important than thermodynamics, while on the plateau, the temporal variations of SMB and δ^{18}O occur mostly in parallel, thus can be explained by thermodynamic effects. The Southern Annular Mode (SAM) ~~exhibits~~ has exhibited a positive trend since the mid-1960s, which is assumed to lead to a cooling of East Antarctica. This is not confirmed by the firn core data in our data set. Changes in the atmospheric circulation that result in a changed seasonal distribution of precipitation/accumulation could partly explain the observed features in the ice shelf cores.

1 Introduction

In the ongoing discussion about climate change, the climate of the polar regions is one of the foci of attention. Whereas the enhanced warming that models predict for the polar regions is obvious in the Arctic (Stocker et al., 2013), Antarctica behaves differently. Not only an increase in sea ice extent is observed (Parkinson and Cavalieri, 2012) ~~,~~ but also the expected warming combined with a corresponding increase in precipitation and thus increased surface mass balance is still not ~~seen for~~ observed over the entire Antarctic continent.

Only the wider Antarctic Peninsula region (including parts of West Antarctica) exhibits a large increase in air temperature (Bromwich et al., 2013), accompanied by disintegrating ice shelves and accelerated ice flow (Rignot et al., 2013; Rott et al., 2002). For East Antarctica, no general warming and increase in precipitation is found in surface observational data (Turner et al., 2005; Monaghan et al., 2006, 2008). ~~An increase in Antarctic~~ This is important because an increase in precipitation, and hence increased surface mass balance (SMB), might mitigate sea level rise.

~~A close~~ Close monitoring of changes in both the atmosphere and the cryosphere is necessary in order to detect early signs of climatic change in East Antarctica. In particular, the coastal regions are highly sensitive to any changes, since the temperatures are close to the melting point in summer already in the present climate (King and Turner, 1997).

Instrumental surface air temperature records from the Antarctic continent are available only since the International Geophysical Year (IGY) 1957/58. The number of stations is still limited and most of them are situated at the coast. Thus, to investigate the past climate, we have to rely on firn and ice cores. Temperature information is derived mainly from the stable water isotope ratio~~,~~; annual mean SMB can be calculated from density measurements for cores where annual layers are resolved.

In Dronning Maud Land (DML), East Antarctica (Fig. 1), various expeditions have carried out glaciological field work, including drilling of firn and ice cores in the past decades in the frame of different national and international programmes. ~~Especially~~ In particular, the pre-site-survey expeditions connected to the European Project for Ice Coring in Antarctica (EPICA) (EPICA Community Members, 2006) have increased our knowledge about the ~~so-far~~ hitherto poorly explored DML. Almost 80 cores have been drilled during these expeditions since 1980. However, so far only the results of single expeditions ~~were~~ have been published; no comprehensive study of this unique data set had been carried out. In ~~the presented~~ this study, the spatial and temporal variations of stable isotope ratios and SMB derived from a network of 76 cores were investigated. Calculation of stacked records helped to considerably improve the signal-to-noise ratio. The spatial variations were related to topographic and other geographical features. Possible climatic trends in SMB and δ^{18}O were investigated. Additionally, the relationship between δ^{18}O and SMB and possible influences of the Southern Annular Mode (SAM) as the primary mode of atmospheric variability in the extratropical Southern Hemisphere were analysed.

2 Field area

Dronning Maud Land is situated in East Antarctica approximately between 20° W and 45° E. It covers an area of ca. 2 700 000 km^2. ~~The focus of our study lies~~ Our study is focused on the western part of DML, between 15° W and 10° E (see Fig. 1). DML is bounded by various ice shelves of different sizes. The westernmost ice shelf, for which cores are available for this investigation, is the Riiser-Larsen Ice Shelf with a width of about 400 km. Further east, the Ekström Ice Shelf is found, which is bounded by two N–S stretching ridges, Søråsen and Halvfarryggen. Centred at the Greenwich meridian is the Fimbul Ice Shelf, with an area of 33 000 m^2 one of the largest ice shelves in DML. It extends approximately 100 km in N–S direction and 200 km in E–W direction and is fed by Jutulstraumen, the largest outlet glacier in DML. South of Riiser-Larsen and Ekström Ice Shelves the lower inland region Ritscherflya is situated. A mountain range to the southeast, Heimefrontfjella, separates Ritscherflya from the higher plateau area, the so-called Amundsenisen.

3 Previous work

Early glaciological measurements were carried out in our study area by the British–Swedish–Norwegian Expedition 1949–1952 (Swithinbank, 1957). ~~Afterwards~~Thereafter, DML was ~~visited only~~ only visited sporadically until the early 1980s. ~~A systematic~~ Systematic data acquisition began in the 1980s on Ekström Ice Shelf, connected to the German year-round scientific base Georg-von-Neumayer. Various traverses started at this station since 1986/87 (Miller and Oerter, 1990). Glaciological field work was performed along the traverse routes from Ekström Ice Shelf to Heimefrontfjella and, in the frame of EPICA, to Amundsenisen.

More recently, several shallow firn cores were retrieved at Søråsen and Halvfarryggen (Fernandoy et al., 2010). However, these cores are strongly influenced by local topography and are therefore not directly comparable to the other cores. (For the sake of completeness we did not omit them from our study.)

The lower inland region Ritscherflya was visited during the field season 1988/89 as part of the Swedish Antarctic Research Program (SWEDARP)~~(Isaksson and Karlén, 1994a, b)~~. The SMB and δ^{18}O records generally showed ~~a large variability. A positive correlation of stable isotope ratio and surface air temperature at the British base Halley was found (Isaksson et al., 1996) . The meteorological conditions for records at high altitudes were assumed to be more stable than in coastal areas, which are strongly influenced by cyclonic activity and sea ice extent (Isaksson et al., 1996)~~ large spatial and temporal variability (Isaksson and Karlén, 1994a, b; Isaksson et al., 1996) .

As part of the Norwegian Antarctic Research Expedition (NARE), Norwegian groups investigated the spatial and temporal variability of SMB on a traverse that crossed Fimbul Ice Shelf (e.g. Isaksson and Melvold, 2002 and Melvold et al., 1998). In Austral summer 2000/01, a 100 m deep ice core was retrieved on eastern Fimbul Ice Shelf. The derived accumulation rates showed high temporal variability and a significant negative trend in the 20th century (Kaczmarska et al., 2004).

Divine et al. (2009) used eight firn cores from coastal DML to study the long term changes in accumulation and δ^{18}O in the area and the role of the Southern Annular Mode (SAM) and ENSO

(El Niño–Southern Oscillation) in the temporal variability of δ^{18}O. The study revealed the diverging multidecadal trends in accumulation (decreasing) and δ^{18}O (increasing) in coastal DML. On shorter sub-decadal time scales it was found that the teleconnection of ENSO to the area is stronger in years ~~where~~ when the SAM is in its negative phase.

In Austral summers 2009–2011, eight shallow firn cores were retrieved on Fimbul Ice Shelf during an extensive glaciological field campaign ~~in the frame~~ as part of the project "Fimbul Ice Shelf from top to bottom" that combined glaciological measurements with oceanographic measurements and modelling (http://fimbul.npolar.no). The δ^{18}O exhibited a small positive trend, whereas a negative trend was observed in SMB during the last 30 years (Schlosser et al., 2012; Sinisalo et al., 2013).

The majority of the extensive EPICA pre-site-survey programme was conducted on the high plateau region Amundsenisen. Between 1996 and 1998, a series of shallow firn cores and three medium-deep ice cores (see Tab. A1) were drilled on Amundsenisen. ~~It~~ The area was found to be characterized by a robust deposition system with nearly constant accumulation rates for the last millennium (Isaksson et al., 1996; Oerter et al., 1999, 2000, 2004; Sommer et al., 2000b, a; Graf et al., 2002; Hofstede et al., 2004; Karlöf et al., 2000, 2005). Oerter et al. (1999) calculated a mean value of $57 \pm 15\,\mathrm{kg\,m^{-2}\,a^{-1}}$, with higher values in the western part of Amundsenisen.

Rotschky et al. (2007) used a special interpolation method to derive a surface accumulation map for western DML from firn cores, snow pits, and stake measurements. The accumulation was found to clearly decrease with elevation and distance from the coast, with local maxima and minima on the windward and lee-sides of topographic ridges. This was confirmed by Schlosser et al. (2008) who compared Rotschky's results with data from a mesoscale atmospheric model.

Anschütz et al. (2009) presented data from the Norwegian US Scientific Traverse of East Antarctica TASTE-IDEA, through DML from the Norwegian base Troll to the South Pole, during which some earlier Norwegian drilling sites were revisited. The mean accumulation rate at Sites I and M (Isaksson et al., 1999, see also Fig. 1) has not changed since the earlier measurements. Fujita et al. (2011) investigated the spatial and temporal variability of accumulation in DML using snow pits, firn cores and radar data from an IPY traverse between Kohnen Station and Dome Fuji (along ID2, Figure 1 and further east). They found a positive trend in accumulation for central DML in the past 50 years. ~~This is not confirmed by a study of Frezzotti et al. (2013) who provided a~~ Frezzotti et al. (2013) provided a synthesis of Antarctic SMB during the last 800 years. They stated that SMB over most of Antarctica does not exhibit an overall clear trend. However, they found a clear increase in SMB in coastal regions and over the highest part of the East Antarctic ice divide since the 1960s, which confirms the results of Fujita et al. (2011) but contradicts those of Divine et al. (2009) and Kaczmarska et al. (2004) . Anschütz et al. (2011) used volcanic time markers to investigate century-scale SMB changes in ice cores ~~from the Eat Antarctic Plateau. They found no clear overall trend in SMB, however~~ retrieved during the above-mentioned traverse from Troll to

South Pole but found that almost all sites above 3200 m altitude show a decrease in SMB in the last 50 years.

4 Data and methods

4.1 Shallow firn core data

The available data set consists of 76 shallow firn and ice cores carried out during different field campaigns over a time period of about three decades. Figure 1 shows the location of all firn cores used ~~in~~ during this study. In Table A1 detailed information about each core can be found. The time period covered by the cores ranges from approximately 30 to 200 years, two cores reach an age of 1000 years, one core almost two millennia. Spatially ~~they represent~~ the dataset represents the entire Western DML. In this study, we use SMB and δ^{18}O data. The cores were dated mainly using the seasonality of stable isotope ratios (δ^{18}O, δD), supplemented by dielectric profiling (DEP) (Wilhelms et al., 1998), continuous flow analysis (CFA) (Oerter et al., 2000; Sommer et al., 2000a), and, in the earlier days, electrical conductivity measurements (ECM) (Hammer et al., 1980) and β-activity measurements (Isaksson and Karlén, 1994a, b). Continuous flow analysis allowed fast analysis of ammonium, calcium, and sodium along the ice core with a high resolution (Röthlisberger et al., 2000; Sommer et al., 2000b) . The average dating error for single years is given as approximately ±2 years (Isaksson et al., 1999; Oerter et al., 2000; Schlosser et al., 2012, 2014) for the short cores spanning the last few decades. For the cores covering centennial scales the dating error is larger, but difficult to quantify since it depends not only on accumulation rate, but also on wind scouring that is very irregular and individual.

4.2 Composite records

~~Mean annual~~ Annual values of SMB and mean annual δ^{18}O of different cores are poorly correlated, even records from the same drilling location. This is partly due to the large depositional noise due to ~~wind influence~~the effects of wind, which particularly affects SMB values. ~~Further~~Furthermore, as the annual SMB series generally demonstrate an increased variance at higher frequencies (so-called "blue noise" properties, Fisher et al., 1983), a shift of one or two years due to dating errors can considerably reduce the quality of the correlation when no smoothing of the record is done. In order to reduce depositional noise and enhance the signal-to-noise ratio (see Sect. 4.5.1), stacked records of δ^{18}O and SMB were calculated. For this calculation, the cores were divided into several subgroups, according to geographical region and longest possible common time period covered. Table 1 shows the different core groups and the corresponding time periods and number of cores. The first set of shallow firn cores comprises ten cores drilled in the vicinity of Neumayer Station (Miller and Oerter, 1990; Schlosser and Oerter, 2002a, b). The second group includes these cores plus six more cores situated on Søråsen and Halvfarryggen (Fernandoy et al., 2010). However, as stated before, these cores are strongly influenced by local conditions, thus this group has to be considered with care.

Eight cores retrieved during a recent expedition on Fimbulisen (Schlosser et al., 2012, 2014) together with two older cores from the same area (Kaczmarska et al., 2004) form the third group. All ice shelf cores together were combined in the fourth group. Seven cores from the south-western corner of the study area, Riiser-Larsen Ice Shelf and Ritscherflya, drilled during Austral summer 1988/89 (Isaksson and Karlén, 1994a, b) represent another group.

The last group contains all 30 cores from the Plateau, ~~at~~ on Amundsenisen. The plateau cores cover on average a time period of 200 years; also the three medium-deep cores, B31–B33) are found here. (The data of the plateau and Ekström cores are provided by Alfred-Wegener-Institute (AWI), Helmholtz Center for Polar and Marine Research at www.pangaea.de.) In the discussion of the results we will refer to these sub-groups. Note that the cores shown in orange in Fig. 1, along the Ice Divide 1 are given only for the sake of completeness and are not used in the stacked records due to data loss on annual SMB and mean δ^{18}O from this expedition.

Since the cores are situated in different climatic regions (ice shelf, plateau, and transition zone) with considerable differences in mean precipitation amounts and temperatures, for each core the deviations from the local mean were calculated before averaging over all cores of the corresponding group and time period. For SMB, the relative ~~(percental) deviation from~~ deviation expressed as a percentage of the mean was used, since accumulation rates range from approximately 30 to several hundreds kg m^{-2}.

4.3 Climatological data

To compare the δ^{18}O series with air temperature data, long-term meteorological measurements would be required. For the plateau region of Western Dronning Maud Land, no data from the 20th century are available. An automatic weather station (AWS) ~~has been installed at Kohnen Station not before 2007. However, already in 1998, an automatic weather station had been~~ was installed 1.5 km west of Kohnen Station ~~that was shifted to Kohnen~~ already in 1998 and moved to the station in 2007. In coastal Dronning Maud Land, several year-round stations exist. The first operational meteorological data in DML were provided by the British base Halley, which was established in 1956 on the Brunt Ice Shelf in the frame of the International Geophysical Year 1957/58. Due to its southern location (75° S) at the coast of the ice-covered Weddell Sea, it is not representative ~~for~~ of the climate of the DML ice shelves. The Russian base Novolazarevskaya was built in a partly snow-free oasis, which also exhibits very local features. SANAE, the South African base, was moved several times and has no ~~homogeneous~~ homogenous time series. Thus, the only suitable station for our purpose is the German base Neumayer on Ekström Ice Shelf (see Fig. 1), built in 1981. The climate of Neumayer is typical for the ice shelves of DML and thus the data ~~could~~ can be used for comparison with the ice shelf cores (König-Langlo et al., 1998).

4.4 SAM index

The Southern Annular Mode (SAM) is the principal mode of atmospheric variability of the extratropical Southern Hemisphere. It is revealed as the leading empirical orthogonal function (EOF) in geopotential height, surface pressure, surface temperature, zonal wind and many other atmospheric fields (Marshall, 2003). Since the pressure fields from global reanalyses show relatively large errors in the polar regions, Marshall (2003) defined an SAM index using the mean pressure difference between 40 and 65° S based on observational data. A positive (negative) SAM index corresponds to a strong (weak) meridional pressure gradient. Thus the positive phase of SAM is characterized by strong, mostly zonal westerlies with only low amplitudes of planetary waves. This means little exchange of moisture and energy between mid and high latitudes (Marshall, 2013) and consequently a cooling of Antarctica, with the exception of the Antarctic Peninsula, which projects farther north then the rest of the continent. To examine the possible influence of SAM on accumulation and δ^{18}O of the firn cores, in this study we use the annual SAM index as defined by (Marshall, 2003). The data are provided by the British Antarctic Survey (BAS) at http://www.antarctica.ac.uk/met/gjma/sam.html.

4.5 Statistical methods

4.5.1 Signal-to-noise ratio

The stacked records are also used to investigate the deposition noise of δ^{18}O and SMB. The signal-to-noise variance ratio (SNVR) of a single record F_i can be estimated (Johnsen et al., 1997) by comparing the variance of a stacked record ($\mathrm{VAR_C}$) derived from N individual records to the mean variance of the N individual records ($\mathrm{VAR_M}$):

$$F_\mathrm{i} = [\mathrm{VAR_C} - \mathrm{VAR_M}/N]/[\mathrm{VAR_C} - \mathrm{VAR_M}], \tag{1}$$

with

$\mathrm{VAR_M}$: mean variance of the individual records

$\mathrm{VAR_C}$: Variance of the composite record

N: number of individual records contained in the stacked record

In Table 2, for each subgroup (Ice shelf cores, plateau cores, and the 200 year series of the plateau cores) the SNVR of the single records (mean of all cores of one group) F_i compared to the corresponding composite record F_c is shown~~for the ice shelf cores, the plateau cores, and the 200years series of the plateau cores~~. F_c is determined by multiplying F_i with the number of individual cores contained in the composite record. Generally, the SNVR is higher for the ice shelf cores than for the plateau cores, and, on the plateau also higher for δ^{18}O than for SMB. ~~A higher SNVR for the coastal~~

~~cores is expected due to higher values of mean accumulation there.~~ On the ~~plateau, the combination of lower deposition and stronger wind scouring leads to larger spatial and temporal variability (thus also largerdating uncertainties). This applies to both SMB and data~~plateau, accumulation rates are considerably lower than in the coastal areas. At the same time, the effects of wind scouring and thus disturbance of the annual layers, are larger, which leads to higher variance in the plateau cores than in the coastal cores.

It turned out that it did not make sense to calculate a stacked record of all available cores since the temporal changes of SMB and δ^{18}O were systematically different in the coastal cores and the plateau cores. However, the signal-to-noise ratio in the two large sub-groups of cores in this study ~~was~~ is considerably higher than in earlier studies where a maximum of 12 cores (Oerter et al., 2000) and 16 cores (Graf et al., 2002) was used (see also Sect. 5.2.2).

4.5.2 Trends and correlations

The statistical significance of correlations and trends described in this study is assessed using specific procedures and statistical tests: the linear trends are calculated for time periods of at least 30 years in order to obtain reliable results independent on short-term (interannual) variability. As a testing procedure for statistically significant trends the F test is used. To check the statistical significance, the F test is essentially defined as ratio of the variance of the data "explained" by the model and the "unexplained variance". The period 1950–2000 was chosen as the longest common period covered by a large number of cores. After the year 2000, only data from Fimbul Ice Shelf are available for this study.

In order to reveal possible causal links between the atmospheric forcing, regional SMB and δ^{18}O in annual snow accumulation we calculated cross correlations between the series of SAM, the composite records of δ^{18}O and SMB. Prior to the procedure the series were normalized and detrended for the periods of overlap. ~~Prior to estimation of the correlation the series were converted into anomalies with respect to the common period.~~ First the means and deviation of these means are determined for the common periods of each combination of the composite records. Then these records are detrended, which assumes that there is no link between possible linear trends in the predictor (i.e. SAM) and the predictand (δ^{18}O, SMB). This will yield slightly stronger (weaker) correlations if the trends in the composite records are of opposite (the same) sign. The significance of the correlations is determined using the standard t test. If the original undetrended data were used, this method would assume that the trend in the predictand (δ^{18}O, SMB) is entirely due to the predictor (i.e. SAM). The reality most likely lies somewhere between those two assumptions and a robust causal quantitative relationship between the variables at the time scale of the whole series ~~can not~~ cannot be established. ~~Significance of the cross-correlations between the composite records was assessed using Students t test.~~ The effects of possible autocorrelation in the series were accounted for in the testing procedure via adjustment of the number of degrees of freedom.

5 Results

5.1 Spatial distribution of δ^{18}O and SMB

Figure 2 shows the mean values of δ^{18}O (Fig. 2a) and SMB (Fig. 2b) for each core. Note that the time intervals, for which the averages are calculated, are different. Therefore, spatial differences between the individual cores could partly be due to temporal changes in annual δ^{18}O and SMB. However, we note that the mean values of δ^{18}O and SMB for cores of different age from the same drilling site agree well within the error bounds, particularly on the plateau.

Both δ^{18}O and SMB are strongly related ~~with~~ to geographical factors such as distance to the coast ~~, latitude~~ and elevation. The influence of the distance to the coast, continentality, affects both temperature and precipitation~~; latitude and elevation effect are closely connected in Antarctica since generally the elevation increases with latitude, thus the two single effects are difficult to disentangle. A change in latitude corresponds to a change in solar radiation, whereas the elevation affects the temperature through a vertical lapse-rate. No dependence of SMB and on longitude was found, which is expected due to the zonally homogeneous nature of Antarctic climate~~.

Mean δ^{18}O values range from -49.5 ‰ at the south-eastern corner of the study area on Amundsenisen (elevation almost 3500 m a.s.l.) to a maximum of -18.6 ‰ close to Neumayer Station at an elevation of 30 m a.s.l. A strong linear correlation ($R^2 = 0.98$) is found between the altitude at the drilling location and mean δ^{18}O of the cores. Results displayed in Fig. 3 ~~a~~ suggest an average decrease in δ^{18}O of approximately 8 ‰ km^{-1}. ~~Different from~~ In contrast to other studies, which state that the relationship between altitude and stable isotopes in precipitation depends on the altitude range ~~due to~~ because of differences in moisture transport (e.g. Masson-Delmotte et al., 2008), in our study we find that the same linear relationship holds for the entire range of altitudes covered by the cores (approximately 0–3500 m a.s.l.). A relatively large scattering of data points around the fitted line is observed only for the cores from locations close to sea level. As the three-dimensional moisture transport to Antarctica is not fully understood yet, the altitude range dependence described by Masson-Delmotte et al. (2008) presently cannot be ~~physically explained~~ explained physically.

The cores from Søråsen and Halvfarryggen were not included in the calculation of the δ^{18}O-elevation relationship since the accumulation at these core sites is strongly influenced by local topography. They show mean annual δ^{18}O values similar to the Neumayer cores, which implies no significant altitude effect for these sites. The atmospheric processes that cause these anomalies are not yet understood.

The ~~relationship between and latitude, shown in Fig. 3b, demonstrates a higher scatter around the linear regression line, with the cores from the same region prone to a systematic bias. This can largely be attributed to a latitudinal variability in elevation in the studied sector of DML. However, a clear linear relationship is also found, with a respective coefficient of determination of 0.81.~~

~~The~~ SMB depends mainly on altitude and continentality and is strongly influenced by topographic features. Particularly in the Muehlig–Hofmann-Range (MHG), the local influence or the mountains clearly leads to deviations from the general altitude dependence of SMB. Apart from the effect of the mountain ranges, the larger scale topography, namely the ice divides (dashed lines in Figs. 1 and 2) has an influence on SMB depending on the dominant wind direction. ~~According to Fujita et al. (2011)~~ Both Schlosser et al. (2008) and Fujita et al. (2011) note that the main wind direction along ID1 is NE~~, which was also found by Schlosser et al. (2008)~~. Additionally, Schlosser et al. (2010) showed that during major precipitation events, the flow came more often from the N-NE sector than from the NW. This means that the cores along ID1 are all situated on the lee-side of the ridge. The SMB values found here are generally lower than ~~the values derived from the cores~~ on the wind-ward side of ID2 at similar elevation. Also, SMB ~~at~~ is generally lower on the lee-side of ID2 ~~is mostly slightly lower than at~~ than on the wind-ward side. Even though the difference is relatively small, our findings confirm the results of Fujita et al. (2011), who found that SMB is generally lower at the lee-side of the ice divides in DML.

Figure 4 shows the dependence of SMB on altitude. A linear correlation between SMB and altitude is found, however, not as strong as between δ^{18}O and altitude ($R^2 = 0.90$) due to the generally higher spatial variability of the SMB.

The box plot in Fig. 5 summarizes statistical information on the SMB calculated from the stacked records of the corresponding regional sub-groups of cores. The red line indicates the median~~, the edges of the~~. The tops and bottoms of each box are the 25th and 75th percentiles~~. The most extreme data points are marked by whiskers, outliers (values more than~~; the distances between the tops and bottoms are the interquartile ranges. Whiskers are drawn from the ends of the interquartile ranges to the furthest observations within the whisker length, the latter corresponding to 1.5 times the interquartile range~~from the top or bottom of the box) are~~. Values beyond the whisker length are marked as outliers and plotted as red ~~points~~dots. Again, the group that contains the cores on Halvfarryggen and Søråsen, shows extraordinary amounts of SMB due to the local topographic influence.

5.2 Temporal variability of regional composite records

5.2.1 Stacked records of shallow firn cores

In Fig. 6, 60 year time series of mean annual δ^{18}O and SMB for the different composite records are presented. Both annual means and 5 year running means are shown to highlight the interannual variability. The grey bars on the panels indicate the number of cores used in the calculation of the stacked records.

~~Only three of eleven cross-correlations between the detrended composite records of and also three cross-correlations between the smoothed records (5 year running mean) are found to be statistically~~

~~significant at the 95confidence level according to t test. For the latter reduction in the number of degrees of freedom was taken into account for calculating the significance.~~

The stable isotope ratio for Ekström (Fig. 6a and b) and Fimbul (Fig. 6c) Ice Shelves is characterized by values generally lower than the multidecadal average during the periods 1950 to the mid-1960s and the 1980s, whereas the 1970s exhibits values above the mean. Ritscherflya (Fig. 6d) has only a short record, but agrees well ~~to~~ with Ekström and Fimbul for the given period. ~~The~~ For the last 20 years ~~have almost constant~~ the smoothed record of δ^{18}O ~~in these records. The~~ shows little variation. The δ^{18}O of the plateau cores (Fig. 6e) ~~show a similar behaviour in , with~~ behaves similar to the ice shelf cores, with the exception of slightly higher values around 1960. The similar temporal variability between the different drilling sites is supported by the calculation of cross-correlations. Only three of eleven cross-correlations between the detrended composite records of δ^{18}O but nine cross-correlations between the smoothed records (5 year running mean) are found to be statistically significant at the 95 % confidence level according to Student's t test.

The linear trends in δ^{18}O for the regionally stacked records were calculated for different time periods according to the data availability. The detailed results are given in Table A2. In Fig. 7, linear trends for the composite records of δ^{18}O (Fig. 7a) and SMB (Fig. 7b) are displayed. For the period from 1950 to 2000 δ^{18}O of the ice shelf cores increases significantly (95 % confidence level) by on average 0.18 ‰ decade^{-1}. In the plateau cores this increase is visible, but the positive trend is not statistically significant for the considered period. The largest contribution to this positive trend stems from the period 1950–1980 (see Fig. 6, Table A2), for which also the plateau cores exhibit a significantly positive trend. (The cores from Ritscherflya were excluded for the trend calculation due to the shortness of the data series).

The analysis of the stacked SMB series reveals a generally less uniform picture of temporal changes in the regional SMB: whereas on the plateau, a positive trend in SMB is observed (significant at the 90 % confidence level), the ice shelves show a negative trend, which is statistically significant only on Ekström Ice Shelf with a magnitude of $-4.30\,\mathrm{kg\,m^{-2}\,decade^{-1}}$ for the studied period. For 1980–2009, the negative trend becomes significant for the composite record of all ice shelves ($-7.25\,\mathrm{kg\,m^{-2}\,decade^{-1}}$). The detailed results of the SMB trend analysis are presented in Table A3.

5.2.2 Intermediate-depth ice cores

For Amundsenisen, additional composite records that extend back to 1800 were calculated. This has so far been done with only a ~~part~~ subset of the cores by Oerter et al. (1999, 2000) and Graf et al. (2002). Using a composite of all available cores increases the signal-to-noise variance ratio from 2.2 to 4.1 (δ^{18}O) and from 0.64 to 1.7 (SMB) (see Table 2). Figure 8 illustrates the 11 year running means of the composite time series of δ^{18}O (Fig. 8a) and SMB (Fig. 8b) for the plateau cores and for the two intermediate-depth ice shelf cores, S100 and B04 (see Fig. 1, Table A1) for the time period 1800–1997. In the first half of the 19th century, the δ^{18}O and SMB generally decrease with 0.23 ‰ and $-2.4\,\mathrm{kg\,m^{-2}}$ ($-4.2\,\%$) per decade, respectively. After a minimum around 1850 and again 1885, δ^{18}O increased in the 20th century. The SMB shows positive deviations from the mean in the first part of the 19th century, followed by a longer negative period from approximately 1830 to 1910. Thereafter, small negative deviations occur only during brief time periods, and from the late 70s on, a stronger increase in SMB is observed. The Little Ice Age (LIA), a colder period widely seen in the Northern Hemisphere between 1650 and 1850 is not clearly present in DML. In a 1000-years chronology from Amundsenisen~~(Graf et al., 2002)~~, this period is characterized by strong fluctuations of δ^{18}O and SMB around the mean (Graf et al., 2002) . Our study covers only the second half of the LIA and the relatively cool period in the second half of the 19th century (seen in Fig. 8) cannot clearly be related to the LIA in the Northern Hemisphere.

The two ice shelf cores (B04 and S100) show a fairly different picture. Apart from the first 40 years of the common period, the SMB inferred from the coastal cores and plateau cores exhibit almost opposite trends. For δ^{18}O, the picture is less uniform: periods where coastal and plateau δ^{18}O are in phase vary with anti-phase periods. Note that the ice shelf "composite record" consists of only two cores. However, they show a similar variability at multidecadal scales, although they were drilled ~~at~~ on two different ice shelves.

5.2.3 Relationship between δ^{18}O and SMB

On Amundsenisen, δ^{18}O and SMB show fairly similar long-term temporal variations. For the 200 years series the smoothed records are positively correlated (statistically significant at the 95 % level, $r = 0.59$). Also for the shorter time period 1950–2000, both stable isotope ratio and SMB show positive trends. On the contrary, the ice shelf cores exhibit positive trends of δ^{18}O for this period, whereas SMB has been decreasing. Generally, a positive correlation is assumed between δ^{18}O and SMB due to the linear relationship between δ^{18}O and air temperature and the temperature dependence of the saturation vapour pressure. This means that warmer (colder) air is usually associated to higher (lower) SMB. However, apart from this thermodynamic influence, there are dynamic influences, which seem to be more important for the coastal cores than in the interior and will be discussed in Sect. 6.

5.3 ~~Relationship between~~ Possible influence of SAM on δ^{18}O ~~/SMB~~ and ~~SAM~~SMB

In order to investigate the influence of atmospheric dynamics on our results, as a first step, ~~the relationship between~~ a possible influence of SAM on δ^{18}O ~~/SMB and the SAM~~ and SMB was considered. It has to be kept in mind, though, that SAM typically explains only approximately 35 % of the extratropical Southern Hemisphere climate variability (Marshall, 2007). Figure 9 displays the stacked record of mean annual δ^{18}O (Fig. 9a) and annual SMB (Fig. 9b) from all ice shelf cores ~~compared to~~ together with annual mean 2 m air temperature and surface pressure at Neumayer

Station. The composite record of the ice shelves is chosen since these regions are influenced by low-pressure systems in the circumpolar vortex. Therefore, according to our findings in Sect. 5.2.3, in the present climate they seem to be more influenced by changes in atmospheric flow conditions than the interior plateau. On larger time scales, i.e. glacial–interglacial changes, the interior of the continent is similarly influenced by changes in general atmospheric flow patterns.

The annual SAM index shows a significant positive trend that started around 1965. Generally, both surface pressure and air temperature are supposed to be negatively correlated with the SAM index in East Antarctica since the larger pressure difference that leads to a higher SAM index is mainly caused by lower pressure around Antarctica; the consequently stronger westerlies lead to lower temperatures in East Antarctica due to the reduced meridional heat exchange (Marshall, 2013) . However, whereas Neumayer air temperature only varies slightly around the long-term mean of $-16\,^{\circ}\mathrm{C}$, δ^{18}O exhibits a weak, but statistically significant positive trend of $0.15\,‰\,\mathrm{decade}^{-1}$ for the period 1950–2009. (Note that for the most recent 9 years only cores from Fimbul Ice Shelf contribute to the stacked record). Both features are not in line with the anticipated effect of a more positive SAM index. Surface pressure at Neumayer is statistically significantly negatively correlated with the SAM index ($r = -0.56$), which would be expected, however, there is no trend towards lower pressure during the considered period. When the time series of SAM is detrended, the correlation coefficient increases to $r = -0.74$.

6 Discussion and conclusion

76 shallow firn cores from DML were analysed in order to assess the spatial and temporal variability of water stable isotope ratios (δ^{18}O) and SMB. This was the first comprehensive study of this data set from coastal, transitional and interior DML. The large number of cores reduced depositional noise and enhanced the signal-to-noise variance ratio considerably compared to earlier investigations of subsets of the firn core data. Thus possible climatic trends could be analysed with a higher reliability than previously.

~~Both~~ The temporal variations of δ^{18}O and SMB ~~show a strong latitude dependence, which basically reflects the effects of increasing altitude and decreasing incidence angle of solar radiation (meaning decreasing temperature) as well as increasing continentality (meaning less moisture available). Topographic influences alter this general pattern locally. Temporally, coastal and plateau cores show a distinctly different behaviour~~derived from the plateau cores are distinctly different from those of the coastal cores. The SMB on the inland plateau is positively correlated to the stable isotope ratio, thus seems to be mainly affected by temperature-dependent, thermodynamic influences, namely the saturation vapour pressure. Higher temperatures mean higher saturation vapour pressure, thus more moisture and ~~possibly~~ potentially larger amounts of precipitation. On the contrary, the SMB of the coastal cores does not change in accordance with the changes in δ^{18}O. Precipitation and thus SMB in the coastal areas are dependent on the synoptic activity in the circumpolar trough. Usually precipitation is connected to frontal systems of cyclones moving from west to east north of the coast. Changes in the synoptic activity in and north of the circumpolar trough can have a strong impact on precipitation seasonality as well as precipitation amounts, depending on the strength and location of the trough and the type of the atmospheric circulation (zonal/meridional flow)~~. Origin of precipitation can be strongly influenced by SAM and a change in moisture source influences the isotope fractionation processes and thus .~~ (Schlosser et al., 2010) .

~~In the 200years records of Amundsenisen, no clear evidence for the LIA is found. However, in this context, also dynamic influences~~ Precipitation at the plateau occurs in form of diamond dust on most days of the year. It consists of very fine ice crystals that form due to radiative cooling in almost saturated air. However, it was found that also real snowfall is observed in the interior of the continent. It is connected to advection of warm air due to amplification of Rossby waves and consequent orographic lifting of the air mass. These snowfall events, even though they are rare, can bring up to 50% of the annual accumulation (Schlosser et al., 2010) . Therefore the dynamic influence on stable water isotope ratios and SMB is not restricted to the coastal areas and should be discussed generally. For instance, a considerably lower ratio of winter/summer accumulation during a colder period could lead to higher annual mean δ^{18}O values in the firn core because the contribution of the colder season to the annual mean would be comparatively small. ~~Such a~~ Thus a change in precipitation (and hence accumulation) seasonality ~~would~~ could lead to a ~~positive~~ positive or negative bias in the temperatures derived from δ^{18}O of an ice/firn core~~(Schlosser, 1999; Noone et al., 1999) .~~ , depending on which seasons were preferred (Schlosser, 1999; Noone et al., 1999) .

For the broad relative maximum of δ^{18}O in the second half of the 19th century, the corresponding SMB is still generally lower than the average. This would mean that winter accumulation would have decreased even stronger than summer accumulation. A combination of the thermodynamic effect (generally lower SMB due to lower temperature) and dynamic effects (less precipitation events in winter due to e.g. a more zonal flow or more northern location of the sea ice edge and thus of the frontal zone) could explain the observed features. Recent data alone are not sufficient to ~~proof~~ confirm this hypothesis. More detailed investigations combined with modelling studies are necessary to shed more light on this problem.

The lack of correlation between SAM index, air temperature and δ^{18}O for the ice shelf regions is highly interesting. The reasons are not yet entirely clear. Variations in SMB and its seasonality certainly play an important role here. Stronger westerlies and more intense cyclone activity do not necessarily have to lead to higher accumulation. The coastal areas are always influenced by the synoptic activity in the circumpolar trough. Higher wind speeds and faster moving cyclones alone could lead to ~~a reduced accumulation~~ less accumulation due to reduced duration of precipitation events. Apart from that, a more zonal flow and less meridional exchange of heat and moisture would mean that precipitation amounts for single events were smaller than in a period with negative SAM index. Thus even a higher number of precipitation events would not necessarily lead to a higher SMB. Therefore low SMB values could be due to both dynamic and thermodynamic influences.

For δ^{18}O, a positive SAM means a generally more local moisture source, thus less isotopic fractionation and higher δ^{18}O values than in a period with negative SAM index, even though the temperature might have been relatively low.

Another important factor that influences the stable isotope ratio of Antarctic precipitation is sea ice~~since it~~. It determines the availability of water vapor and has a strong influence on the energy balance of the ocean, thus changing temperature and moisture amounts in the air above the water/ice surface (Noone and Simmonds, 2004). However, in the DML region sea ice does not show any systematic differences in relation to SAM (e.g. Parkinson and Cavalieri, 2012), thus the influence of sea ice on the ice core properties cannot be discussed on the given time scale for the presented data set.

Apart from all factors that affect precipitation it should be kept in mind that also post-depositional processes alter the stable isotope ratio of the snow. Additional to the afore-mentioned redistribution of snow due to wind influence, the sublimation-deposition cycle can change the δ^{18}O values. Diffusion in the pore space due to temperature gradients tends to smooth the seasonal variations (Johnsen , 1977) . Most recent studies (Steen-Larsen et al., 2014; Hoshina et al., 2014) have shown that the interaction of the air in the pore space with the atmospheric layer just above the snow surface is more important than previously thought.

We conclude that, in the last two centuries, conditions in the interior DML have been fairly stable and only weakly influenced by changes in atmospheric dynamics. In the coastal areas, more complex processes are at work and the δ^{18}O and SMB derived from the firn cores cannot be fully explained yet. In order to understand the temporal variability of δ^{18}O, a full understanding of the three-dimensional moisture transport to Antarctica is required. Additionally to firn cores and snow samples, continuous monitoring of the stable isotope ratio of water vapour combined with high-resolution atmospheric modelling would be desirable.

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Table 1. Time periods and number of contributing cores for the composite records for western DML. ”Ice Shelves” corresponds to all cores from Fimbul, Ekström and Riiser-Larsen Ice Shelves. ”Ekström (R)” refers to all cores from Ekström Ice Shelf plus the adjacent ridges Søråsen and Halvfarryggen.

Region	Period	Number of Cores (N)
Fimbul Ice Shelf	1950–2009	9
Ekström Ice Shelf	1950–2001	7
Ekström Ice Shelf (R)	1950–2006	16
Ice Shelves	1950–2009	18
Ritscherflya	1970–1988	6
Plateau	1950–1997	30

Table 2. Signal-to noise variance ratio of δ^{18}O and SMB in the individual records (F_{i}) (N) (see Eq. 1) compared to the composite records (F_{c}). F_{c} is determined by multiplying F_{i} with the number of individual cores contained in the composite record.

Composite record	Parameter	F_{i}	F_{c}
Ice shelves	δ^{18}O	0.35	4.2
	SMB	0.39	4.7
Plateau	δ^{18}O	0.09	2.7
	SMB	0.07	2.1
Plateau	δ^{18}O	0.14	4.1
(200a)	SMB	0.06	1.7

Table A1. Location (latitude, longitude, elevation), total depth, time period and annual mean values of δ^{18}O, δD and SMB for all cores in western Dronning Maud Land (see Fig. 1).

Core label	Latitude	Longitude	Elevation	Total depth	Period	Mean of Parameters			References
						δ^{18}O	δ^{2}H	SMB	
			m	m		‰	‰	$\mathrm{kg\,m^{-2}\,a^{-1}}$	
B04	70°37.00′ S	08°22.00′ W	28	51.7	1892–1981	−20.7	−187	352	Schlosser (1999)
B38	71°09.73′ S	06°41.93′ W	690	84	1960–2006	−20.7		1252	Fernandoy et al. (2010)
B39	71°24.50′ S	09°55.00′ W	655	78.5	1935–2006	−20.1		772	Fernandoy et al. (2010)
E002	70°37′ S	08°22′ W	39	10	1972–1986	−18.6	−146	335	Oerter et al. (1999)
E040	70°56.90′ S	08°31.23′ W	58	9.5	1971–1986	−23.0	−176	294	Oerter et al. (1999)
E70W[1]			70	9.10	1979–1986		−183	295	Oerter et al. (1999)
E090	71°24.10′ S	08°20.83′ W	75	5.1	1969-1986	−24.0	−185	266	Oerter et al. (1999)
E143	71°49.92′ S	08°36.68′ W	298	9	1967-1986		−186	222	Oerter et al. (1999)
E160	71°59.00′ S	08°43.48′ W	559	9.5	1969–1986	−24.9	−195	277	Oerter et al. (1999)
E180	72°09.73′ S	08°49.42′ W	788	10	1973–1986	−25.4	−198	371	Oerter et al. (1999)
FB0189	70°39.52′ S	08°15.15′ W	28	10	1975–1988	−19.6		353	Schlosser (1999)
FB0201	71°12.86′ S	06°47.63′ W	600	16	1995–2001	−20.4		1123	Fernandoy et al. (2010)
FB0202	70°39.34′ S	08°15.22′ W	28	13.2	1980–2001	−20.1	−155	329	Fernandoy et al. (2010)
FB0203	71°27.43′ S	09°51.64′ W	630	14	1996–2001	−20.3		1104	Fernandoy et al. (2010)
FB0702	71°34.08′ S	06°40.02′ W	539	43	1959–2006	−24.2		558	Fernandoy et al. (2010)
FB0704	72°03.84′ S	09°33.50′ W	760	36	1962–2006	−22.8		489	Fernandoy et al. (2010)
G3	69°49.38′ S	00°36.72′ W	57	10	1993–2009	−19.7		295	Schlosser et al. (2012)
G4	70°54.12′ S	00°24.12′ W	66	16.7	1983–2009	−23.7		330	Schlosser et al. (2012)
G5	70°32.70′ S	00°02.46′ W	82	14.5	1983–2009	−21.9		298	Schlosser et al. (2012)
G8	70°24.60′ S	02°00.60′ E	58	10.7	1991–2009	−22.5		282	Schlosser et al. (2014)
LP1	70°13.98′ S	04°48.00′ E	48	11	1992–2009	−20.8		296	Schlosser et al. (2014)
M2	70°18.96′ S	00°06.54′ W	75	17.5	1981–2009	−22.0		314	Schlosser et al. (2012)
S32	70°18.60′ S	00°48.00′ W	53	20	1995–2009	−22.1		339	Schlosser et al. (2014)
S_{20}	70°14.50′ S	04°48.66′ E	63	10	1956–1996	−20.5		271	Isaksson et al. (1999)
S_{100}	70°13.98′ S	04°48.00′ E	48	100	1737–1996	−23.5		268	Kaczmarska et al. (2004)
A(89)	72°39.25′ S	16°38.73′ W	30	10	1975–1988	−21.2		381	Isaksson and Karlén (1994b)
C(89)	72°45.72′ S	14°35.39′ W	70	10	1976–1987	−22.1		414	Isaksson and Karlén (1994b)
D(89)	73°27.39′ S	12°33.45′ W	300	10	1974–1988	−24.4		343	Isaksson and Karlén (1994b)
E(89)	73°35.63′ S	12°25.61′ W	700	10	1973–1988	−25.9		322	Isaksson and Karlén (1994b)
F(89)	73°48.95′ S	12°12.61′ W	800	10	1970–1988	−27.0		258	Isaksson and Karlén (1994b)
G(89)	74°00.84′ S	12°00.99′ W	1200	10	1971–1988	−30.6		283	Isaksson and Karlén (1994b)
H(89)	74°21.08′ S	11°43.35′ W	1200	10	1973–1988	−30.6		318	Isaksson and Karlén (1994b)
B31[5]	74°34.89′ S	03°25.82′ W	2669	91.6	1000–1997	−45.0	−353	61	Oerter et al. (2000)
B32[5]	75°00.14′ S	00°00.42′ E	2882	148.8	167–1997	−45.1	−355	61	Oerter et al. (2000)
B33[5]	75°10.02′ S	06°29.91′ E	3160	71.1	1000–1997	−46.9		45	Oerter et al. (2000)
EPICA[2]	75°00′ S	02°00′ E	2900	20.1	1865–1991	−44.9		77	Isaksson et al. (1996)
FB96DML01[5]	74°51.30′ S	02°33.00′ W	2817	10.1	1895–1995	−43.9	−342	41	Oerter et al. (1999)
FB96DML02[5]	74°58.10′ S	03°55.12′ W	3014	10.8	1919–1995	−45.3	−352	59	Oerter et al. (1999)
FB97DML03[5]	74°29.95′ S	01°57.65′ E	2843	11.6	1941–1996	−43.7	−345	91	Oerter et al. (1999)
FB97DML04[5]	74°23.94′ S	07°13.05′ E	3161	11.7	1905–1996	−47.1	−369	53	Oerter et al. (1999)
FB97DML05[5]	75°00.14′ S	00°00.42′ E	2882	11.2	1930–1996	−44.7	−352	71	Oerter et al. (1999)

Table A1. Continued.

Core label	Latitude	Longitude	Elevation	Total depth	Period	Mean of Parameters			References
						δ^{18}O	δ^2H	SMB	
			m	m		‰	‰	$\mathrm{kg\,m^{-2}\,a^{-1}}$	
FB97DML06[5]	75°00.04′ S	08°00.32′ E	3246	11.8	1899–1996	−47.3	−369	50	Oerter et al. (1999)
FB97DML07[5]	74°34.89′ S	03°25.82′ W	2669	12.1	1908–1996	−44.5	−348	57	Oerter et al. (1999)
FB97DML08[5]	75°45.17′ S	03°16.97′ E	2962	11.4	1919–1996	−47.0	−367	60	Oerter et al. (1999)
FB97DML09[5]	75°56.00′ S	07°12.78′ E	3145	11.1	1897–1996	−48.6	−379	45	Oerter et al. (1999)
FB97DML10[5]	75°13.00′ S	11°21.00′ E	3349	11.3	1900–1996	−49.3	−386	47	Oerter et al. (1999)
FB9802[5]	74°12.30′ S	09°44.50′ W	1439	26.4	1881–1997	−32.5		129	Oerter et al. (2000)
FB9803[5]	74°51.10′ S	08°29.82′ W	2600	29.3	1921–1997	−38.5	−304	206	Oerter et al. (2000)
FB9804[5]	75°15.02′ S	06°00.00′ W	2630	20.6	1801–1997	−42.6		50	Oerter et al. (2000)
FB9805[5]	75°10.04′ S	00°59.70′ W	2840	20	1800–1997	−44.6		48	Oerter et al. (2000)
FB9807[5]	74°59.82′ S	00°02.17′ E	2880	29.6	1758–1997	−44.8		63	Oerter et al. (2000)
FB9808[5]	74°45.04′ S	00°59.99′ E	2860	26.8	1801–1997	−43.7	−343	68	Oerter et al. (2000)
FB9809[5]	74°29.95′ S	01°57.65′ E	2843	32.9	1801–1997	−44.1	−346	88	Oerter et al. (2000)
FB9810[5]	74°40.03′ S	04°00.10′ E	2980	32.2	1801–1997	−46.0		86	Oerter et al. (2000)
FB9811[5]	75°05.04′ S	06°30.00′ E	3160	23.5	1801–1997	−47.9	−375	58	Oerter et al. (2000)
FB9812[5]	75°15.05′ S	06°30.10′ E	3160	16.9	1810–1997	−47.1	−369	40	Oerter et al. (2000)
FB9813[5]	75°10.04′ S	05°00.02′ E	3100	21.3	1800–1997	−46.1		50	Oerter et al. (2000)
FB9814[5]	75°05.02′ S	02°30.06′ E	2970	25.8	1801–1997	−45.5		64	Oerter et al. (2000)
FB9815[5]	74°56.95′ S	01°29.67′ W	2840	21.7	1801–1997	−44.1		53	Oerter et al. (2000)
FB9816[5]	75°00.00′ S	04°29.78′ W	2740	19.7	1800–1997	−43.4		47	Oerter et al. (2000)
FB9817[5]	75°00.04′ S	06°29.90′ W	2680	24.5	1800–1997	−43.1	−339	63	Oerter et al. (2000)
SS9813[5]	74°58.10′ S	03°55.12′ W	3014	21	1801–1997	−46.1			Oerter et al. (2000)
A[3]	71°54.00′ S	03°05.00′ E	1520	13.3	1971–1996	−33.3		135	Isaksson et al. (1999)
B[3]	72°08.01′ S	03°10.51′ E	2044	12.2	1971–1996	−33.4		171	Isaksson et al. (1999)
C[4]	72°15.50′ S	02°53.47′ E	2400		1965–1996	−33.4		123	Isaksson et al. (1999)
D[4]	72°30.50′ S	03°00.00′ E	2610		1965–1996	−38.4		116	Isaksson et al. (1999)
E[3]	72°40.50′ S	03°39.77′ E	2751	10.1	1976–1996	−40.5		59	Isaksson et al. (1999)
F[4]	72°51.50′ S	04°21.08′ E	2840		1965–1996			24	Isaksson et al. (1999)
G[4]	73°02.50′ S	05°02.65′ E	2929		1965–1996	−41.2		30	Isaksson et al. (1999)
H[4]	73°23.50′ S	06°27.63′ E	3074		1965–1996			46	Isaksson et al. (1999)
I[4]	73°43.50′ S	07°56.43′ E	3174		1965–1996	−44.9		53	Isaksson et al. (1999)
J[4]	74°02.50′ S	09°29.50′ E	3268		1965–1996			52	Isaksson et al. (1999)
K[4]	74°21.50′ S	11°06.22′ E	3341		1965–1996	−46.3		44	Isaksson et al. (1999)
L[3]	74°38.50′ S	12°47.45′ E	3406	9	1962–1996	−48.0		41	Isaksson et al. (1999)
M[4]	74°59.50′ S	15°00.10′ E	3453		1965–1996	−49.5		45	Isaksson et al. (1999)
S_{15}	71°11.50′ S	04°35.83′ E	800	15.2	1974–1996	−26.7		244	Isaksson et al. (1999)

[1] Core E70W was drilled 19 km west of Ekström-Traverse 1987. The location is marked on page 187 in Miller and Oerter (1990).
[2] The core was drilled in an area, which has been identified as a potential deep-drilling site by the EPICA research program (Isaksson et al., 1996).
[3] For these cores no SMB data were available. Thus the mean values of SMB (1965–96) were adopted from Isaksson et al. (1999).
[4] For these cores no data were available. Thus the mean values of δ^{18}O and accumulation were adopted from Isaksson et al. (1999).
[5] The data of the plateau and Ekström cores are provided by Alfred-Wegener Institute (AWI) at www.pangaea.de.

Table A2. Linear trends [‰ decade^{-1}] for the stacked records of δ^{18}O. Significant trends according to F test on the 95 % (bold and underlined) and 90 % confidence level (bold) are highlighted. ~~Further, the~~ The standard deviation of the slope is ~~listed~~also given.

	1950–2000	1950–1980	1960–1990	1970–2000	1980–2009
Fimbul Ice Shelf	$\mathbf{0.18 \pm 0.09}$	$\underline{\mathbf{0.53 \pm 0.22}}$	-0.02 ± 0.21	-0.10 ± 0.15	$\mathbf{0.27 \pm 0.16}$
Ekström Ice Shelf	$\mathbf{0.27 \pm 0.14}$	$\underline{\mathbf{0.70 \pm 0.30}}$	-0.21 ± 0.29	0.06 ± 0.27	
Ekström Ice Shelf (R)	$\underline{\mathbf{0.19 \pm 0.08}}$	$\underline{\mathbf{0.62 \pm 0.15}}$	0.20 ± 0.18	-0.07 ± 0.18	$0.16 \pm 0.24^{*}$
Ice Shelves	$\underline{\mathbf{0.18 \pm 0.07}}$	$\underline{\mathbf{0.67 \pm 0.15}}$	-0.09 ± 0.15	-0.14 ± 0.13	$\mathbf{0.28 \pm 0.15}$
Plateau	0.08 ± 0.06	$\underline{\mathbf{0.32 \pm 0.09}}$	-0.07 ± 0.10	0.01 ± 0.15	

* Trend period ends 2006.

Table A3. Linear trends [$\mathrm{kg\,m^{-2}\,decade^{-1}}$] for the stacked records of SMB. Significant trends according to F test on the 95 % (bold and underlined) and 90 % confidence level (bold) are highlighted. ~~Further, the~~ The standard deviation of the slope is ~~listed~~also given.

	1950–2000	1950–1980	1960–1990	1970–2000	1980–2009
Fimbul Ice Shelf	-2.41 ± 2.61	-5.95 ± 6.53	5.81 ± 5.14	-2.50 ± 4.09	-6.26 ± 4.10
Ekström Ice Shelf	$\underline{\mathbf{-4.30 \pm 1.94}}$	0.78 ± 4.04	-3.81 ± 3.66	-4.95 ± 4.46	
Ekström Ice Shelf (R)	0.39 ± 1.42	$\mathbf{5.17 \pm 2.79}$	$\mathbf{-4.41 \pm 2.62}$	1.07 ± 3.12	$-3.83 \pm 4.50^{*}$
Ice Shelves	-2.17 ± 1.77	-2.89 ± 4.28	2.58 ± 3.34	-0.70 ± 2.87	$\mathbf{-7.25 \pm 3.69}$
Plateau	1.43 ± 0.79	-0.59 ± 1.54	0.44 ± 1.50	$\underline{\mathbf{5.23 \pm 1.35}}$	

* Trend period ends 2006.

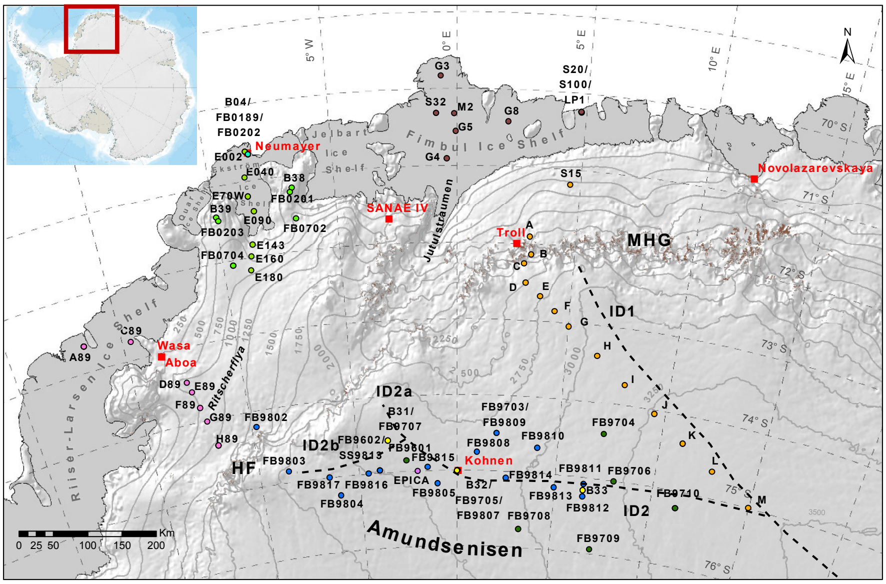

Figure 1. Firn and ice core drill locations in western Dronning Maud Land used in this study (Table A1). Grey lines display the topography with increments of 250 m (MHG: Mühlig–Hofmann Gebirge, HF: Heimefrontfjella, ID: Ice divide). Antarctic research stations are labeled in red. Topographic data are used from Antarctic Digital Database (ADD).

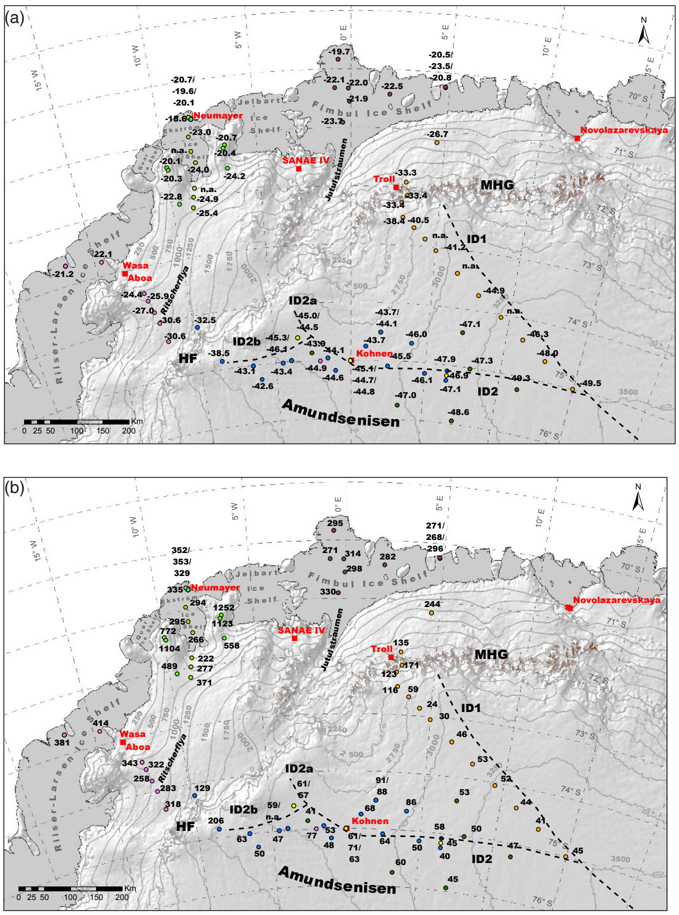

Figure 2. (a) Mean annual δ^{18}O [‰] for the complete time series of each core. Labels in **(a)** and **(b)** are arranged in the same way as in Fig. 1 (NA: not available). **(b)** Mean annual SMB [$\mathrm{kg\,m^{-2}}$] for all firn and ice cores (NA: not available).

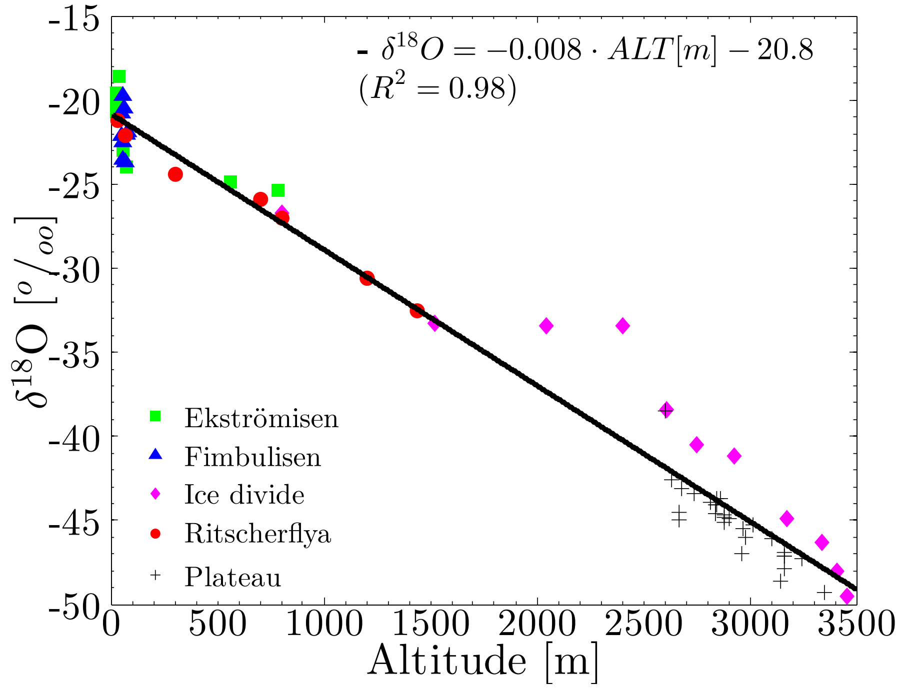

Figure 3. Core average δ^{18}O plotted vs. core site altitude~~(a) and latitude (b)~~. Solid black lines show the respective linear fits to the data. Cores from different regions of the study area are shown in different colours and symbols.

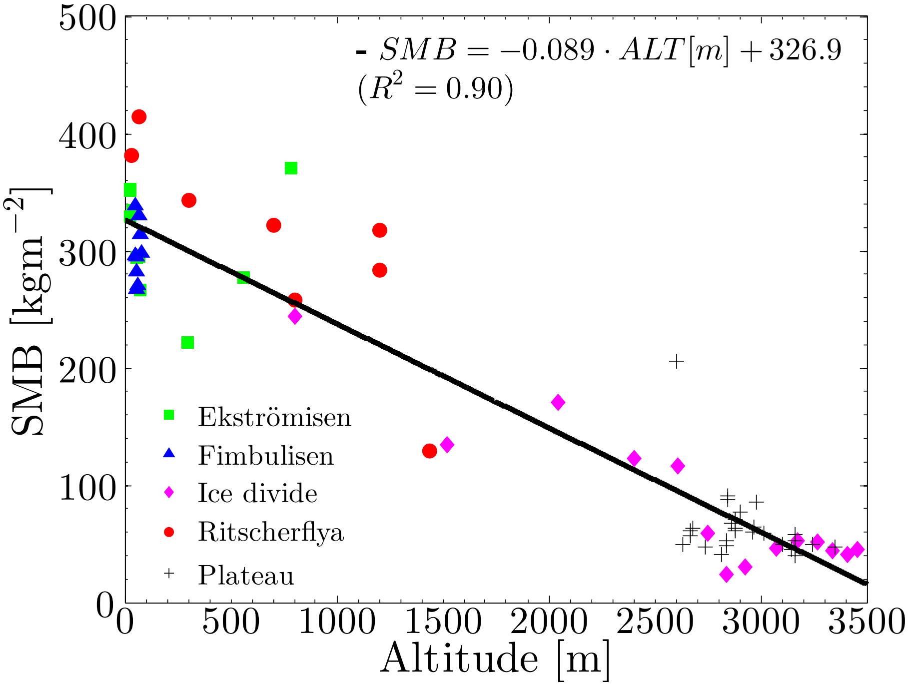

Figure 4. Core average SMB plotted vs. core site altitude. Solid black lines show the respective linear fit to the data. Cores from different regions of the study area are shown in different colours and symbols.

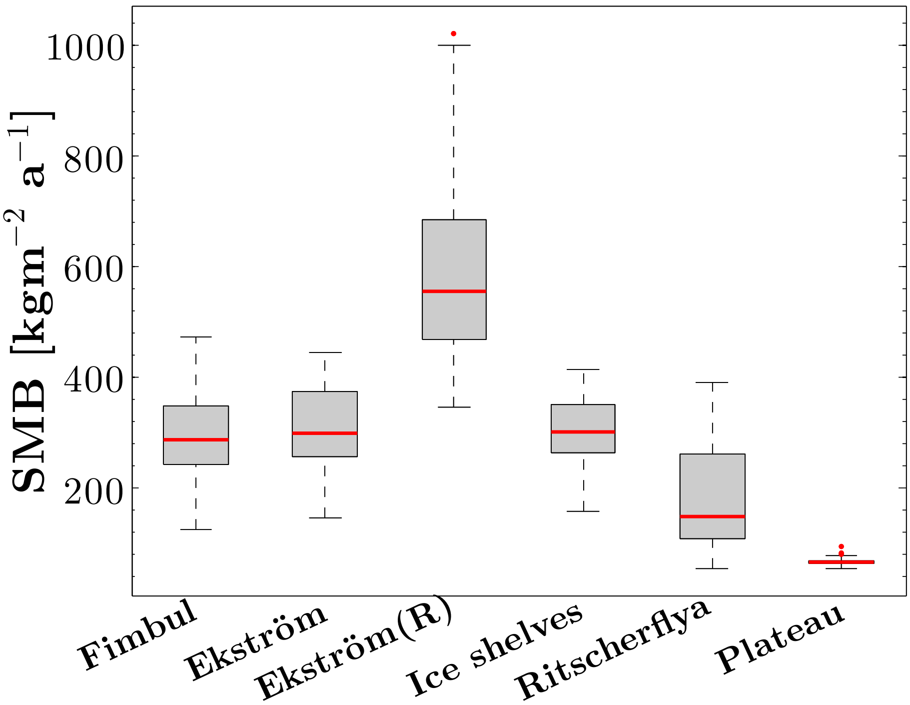

Figure 5. Box plot for the SMB of the stacked records. The red line indicates the median. The tops and ~~the edges~~ bottoms of ~~the~~ each box are the 25th and 75th percentiles; the distances between the tops and bottoms are the interquartile ranges. ~~The whiskers extend~~ Whiskers are drawn from the ends of the interquartile ranges to the ~~most extrem data points~~furthest observations within the whisker length, the latter corresponding to 1.5 times the interquartile range. ~~Outliers~~ Values beyond the whisker length are marked as outliers and plotted ~~individually~~ as red ~~points~~dots.

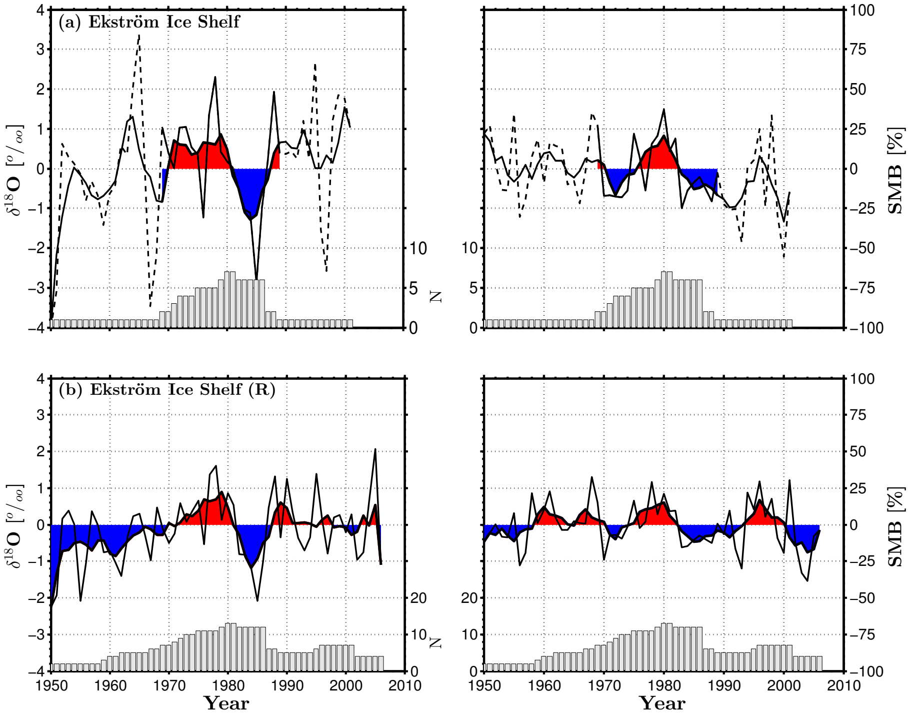

Figure 6.

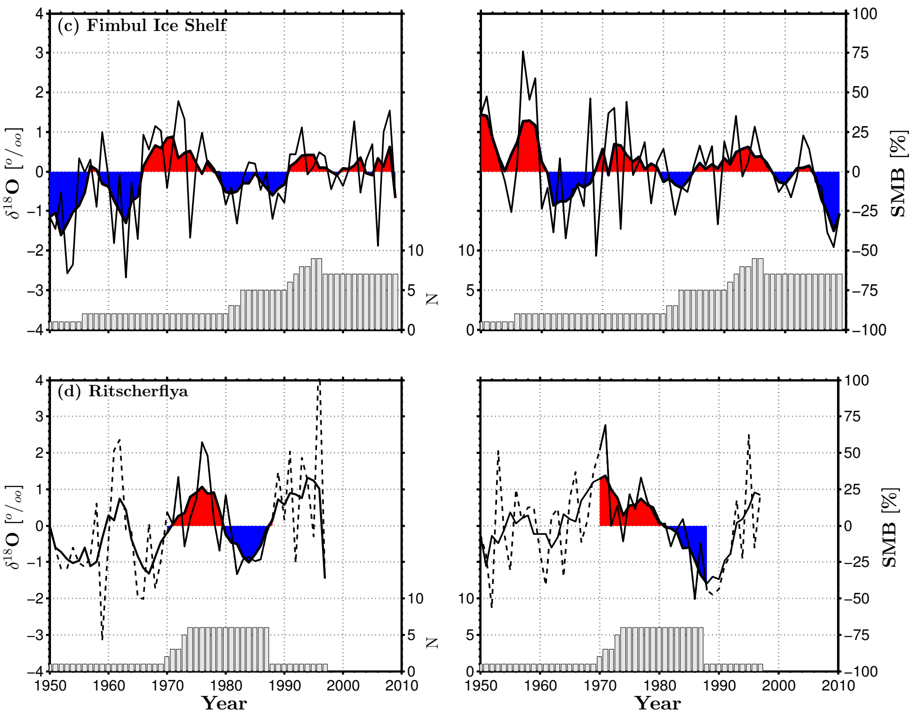

Figure 6.

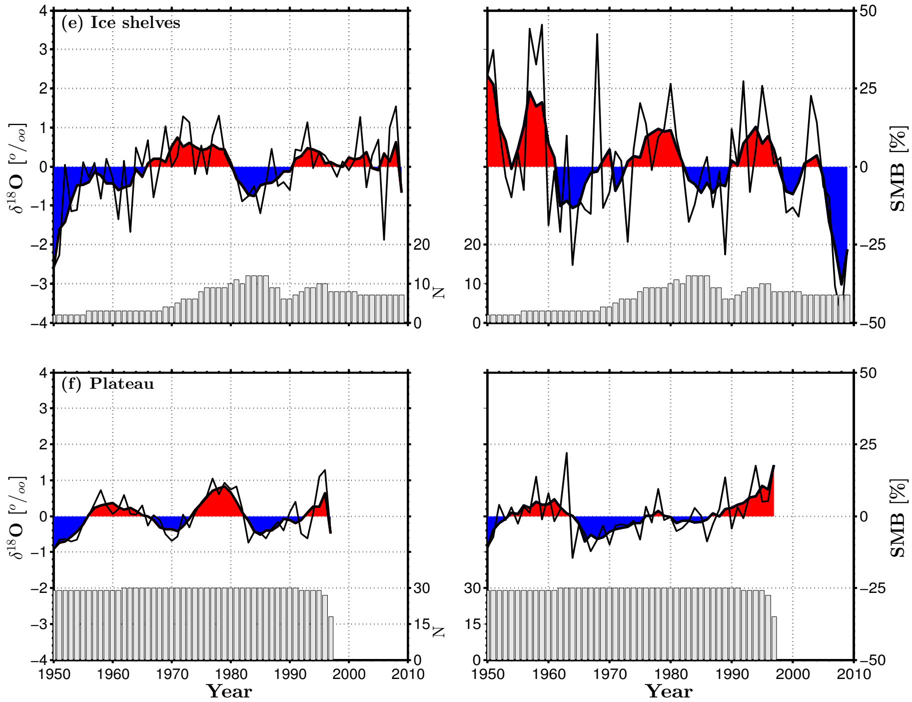

Figure 6.

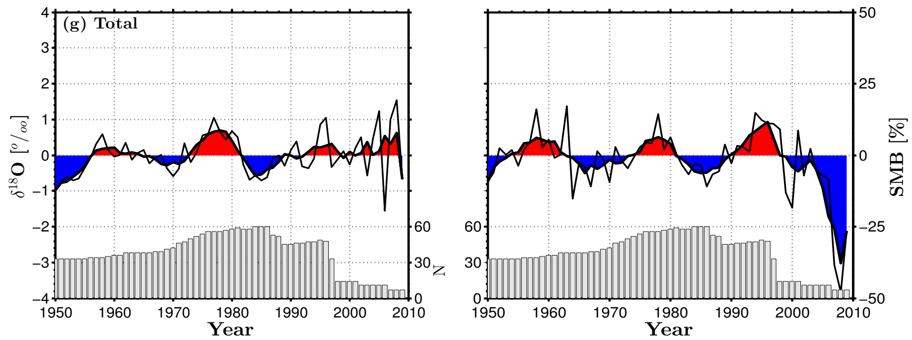

Figure 6. Composite records of δ^{18}O as deviation from the mean [‰] (left) and the SMB as deviation from the mean [%] (right): **(a)** Ekström Ice Shelf, **(b)** Ekström Ice Shelf and adjacent ridges, **(c)** Fimbul Ice Shelf, **(d)** Ritscherflya, **(e)** Shelf ice (all), **(f)** Plateau and **(g)** Total. Also shown is a 5 year moving average (thick red and black lines). The gray bars indicate the number of cores that contribute to the composite records. The shaded areas represent time periods with positive (red) and negative (blue) deviations from mean.

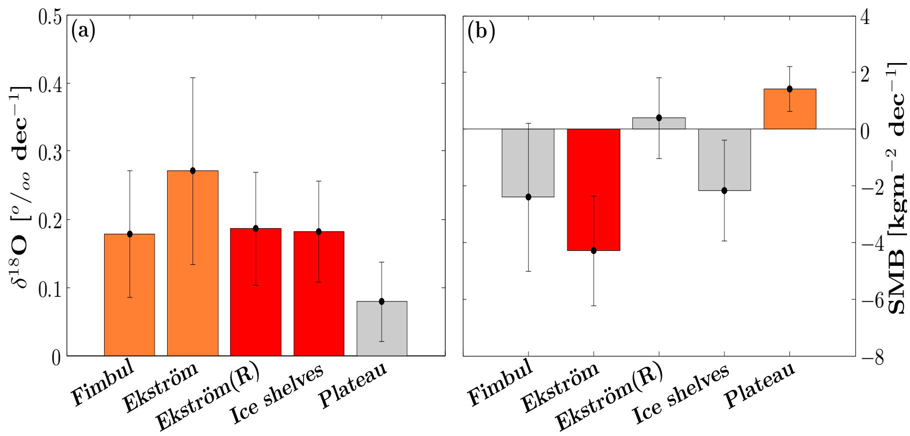

Figure 7. Linear trends for composite records of **(a)** δ^{18}O and **(b)** SMB per decade between 1950–2000. Statistically significant trends on the 95 % (90 %) confidence level according to F test are shown as red (orange) bars. Trends with lower significance are coloured in grey. The black error bars represent the standard deviation of the slope.

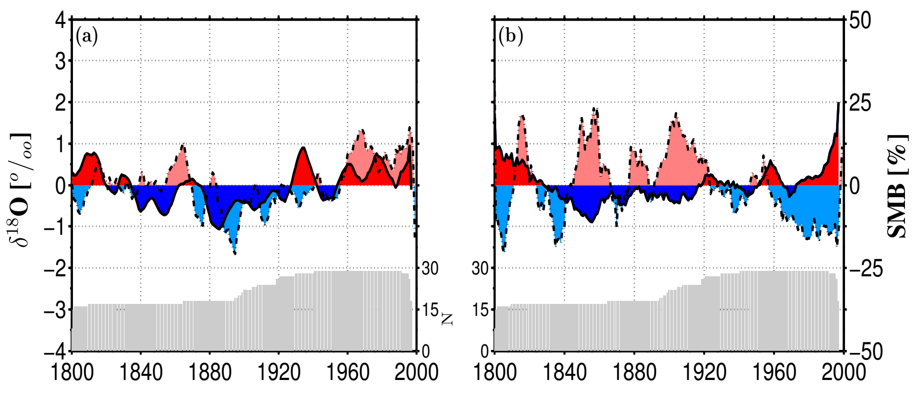

Figure 8. Composite records (11 year moving average) of: **(a)** δ^{18}O as deviation from the mean [‰] and **(b)** SMB as deviation from the mean [%] for the plateau (solid line) and coastal region (dashed) for the last two centuries. The grey bars indicate the number of cores that contribute to the composite record of the plateau. The ice shelf record consists only of S100 and B04. Shading: time periods with positive (red) and negative (blue) deviations from the mean.

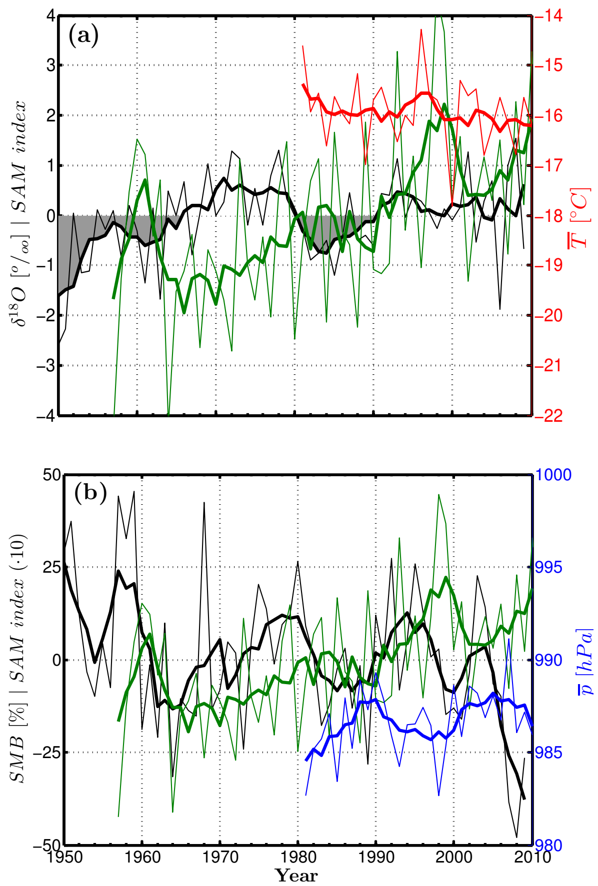

Figure 9. (a) Time series of mean annual δ^{18}O of composite record Ice Shelves (black), annual mean air temperature of Neumayer station (red) and annual SAM index (green). **(b)** Mean annual SMB of composite record Ice Shelves (black), annual mean pressure of Neumayer station (blue), and annual SAM index (green). Bold lines: 5 year moving average.