Comments to Reviewer #1

We thank the reviewer for the thorough review and the constructive criticism. In the following responses we address each point. The corrected parts of the manuscript are included in blue.

Interactive comment on "Precipitation regime and stable oxygen isotopes at Dome C, East Antarctica – a comparison of two extreme years 2009 and 2010" by E. Schlosser et al.

Anonymous Referee #1

Received and published: 27 November 2015

Review of 'Precipitation regime and stable oxygen isotopes at Dome C, East Antarctica: A comparison of two extreme years 2009 and 2010' by Schlosser et al.

This is a nice paper which contributes to the understanding of the observed stable water isotope ratios in precipitation at Dome C. The analysis is conducted for only two years but those years sizeable differences in metrological parameters at the Dome. This has allowed a detailed investigation of the del differences between the two years, and have revealed subtleties which might have otherwise gone unnoticed.
A key aspect of the paper is that synoptic behavior is analysed to inform the particular processes which, on short time scales, govern the del signals. The authors make clear the importance and relevance of understanding the isotopic chemistry for single events, and allow them to unravel the complexity of fractionation history on way to Dome C.
I would like to see the authors revise, in some modest but important ways. These are itemised below.

p 30475, l 9 In this relevant broad overview of the continental mass balance recent analysis of Harig, C., and F. J. Simons, 2015: Accelerated West Antarctic ice mass loss continues to outpace East Antarctic gains. Earth and Planetary Science Letters, 415, 134-141, doi: 10.1016/j.epsl.2015.01.029 should be cited.

Done

p 30475, l 16 To be completely unambiguous as to what Dansgaard showed, should change 'linear relationship' to 'linear spatial relationship'. Important to differentiate this from the temporal relationship discussed below.

We agree and have changed this.

water are used primarily. A linear spatial relationship has been found between mean annual stable isotope ratios in Antarctic precipitation and annual mean air temperature

p 30476, l. 25 Include here also reference to Noone et al., 1998: Implications for the interpretation of ice-core isotope data from analysis of modelled Antarctic precipitation. Ann. Glaciol., 27, 398-402

We added this reference.

p 30476, l. 25 On modeling approach add Noone and co-authors, 2002: 'Associations between d18O of water and climate parameters in a simulation of atmospheric circulation for 1979-95'. J. Clim., 15, 3150-3169.

We added this reference.

p 30482, l. 21-22 Please present citations in order of year of publication.

Corrected

p 30483, l. 14-15 Please reword this. At its simplest the 'coreless winter' is associated with the balance of the net OLR and the atmospheric energy transports into the Antarctic region. This balance is reached quite quickly once the Sun has disappeared.

We rephrased this and also added Schwerdtfeger and King and Turner as references.

The mean annual cycle exhibits the typical coreless winter (van Loon, 1967) with a distinct temperature maximum in summer (December/January), which has no counterpart in winter, where the months May to August show relatively similar values. This is due to a combination of the local surface radiation balance and warm air intrusions. During the first part of the polar night, with the lack of short-wave radiation, anequilibrium of downwelling and upwelling longwave radiation is reached; advection of relatively warm air from lower latitudes further reduces the possibility for cooling. Thus the temperature does not decrease significantly after May (King and Turner, 1997; Schwerdtfeger 1984).

p 30483, l. 21 Negative sign missing here. That is, '54.9C' should be '- 54.9C'

Done

p 30484, l. 1 Would be clearer to replace 'barely exceed -70C' with 'are rarely lower than -70C'.

Done

p 30485, l. 1 'available' better word than 'given'

Done

p 30485, l. 5 and on to next page This section on the synoptics would warrant mention of Warm Conveyor Belts and what their potential role might be. Catto, J. L., E. Madonna, et al, 2015: Global relationship between fronts and warm conveyor belts and the impact on extreme precipitation. J. of Clim., 8411-8429 (his Fig. 6) shows a case of a WCB originating just to the south of Australia and terminating in the Dome C region. Whether or not a WCB is involved in a specific precipitation event will greatly influence the del O18 at the deposition site (via depletion during ascent). A few words should be devoted to this important aspect here.

Since WCB are usually a phenomenon related to frontal systems and the precipitation at Dome C mostly stems from (non-frontal) orographic lifting of moist air masses, we don't think we can imply that WCB processes are present here. We do appreciate the advice and will keep this in mind for further studies. It is very interesting, actually, if there is a *combination of the two effects at play sometimes, but a real analysis of this is beyond the scope of the present study, which mainly deals with the differences of the atmospheric conditions in 2009 and 2010. Adiscussion of WCBs in this extreme high-latitude setting would have a rather speculative character. We would like to investigate this properly before publishing anything about it. Note that a study about all precipitation events at Dome C during the measurement period is in preparation. (We suspect that WCBs could be more important for the other deep drilling site Kohnen, which is closer to the coast and sometimes influenced by frontal systems.)*

p 30486, l. 19 Make clear how many iterations were performed with Mark Stoelinga's scheme at each time step. Comment on the convergence.

We have added this information in the text. Actually, in the first submitted version, we had used the formulation "simple trajectory model", which made the editor doubt that it was fully three-dimensional, so we changed that. It still is simple, in that it does not define a threshold for convergence. However, given all the uncertainties in trajectory calculations, it seemed to be exact enough for practical use for our purposes. We added some information about the estimate of the moisture source, according to Reviewer #3's comments. This is really just an estimate, not an exact determination, and we also never use trajectories alone, without cross-checking with the general atmospheric flow.

The time step we used was 600s. For simplicity's sake, RIP does not define a threshold for convergence, but simply does two iterations for each time step, which turned out to be exact enough in the praxis for our purposes.

p 30488, l. 14 'Marshall' (and in caption of Fig. 8)

Done

p 30488, l. 24 and on top of next page When seen in the broader perspective the difference between the winter and spring SAMs in these two consecutive years is not particularly great. For example, the change in spring SAM from 2001 to 2002 (see, e.g., recent analysis of Simmonds, 2015 - Comparing and contrasting the behaviour of Arctic and Antarctic sea ice over the 35-year period 1979-2013. Ann. Glaciol., 56(69), 18-28) was much greater. I suggest this be mentioned here, and that the direct links between the SAM and the ridges in a given sector need not be a straightforward as the authors appear to be suggesting.

We thank the reviewer for this input, and we reformulated this paragraph. The Simmonds Annals paper is very interesting, but in this case we would still like to refer to the original work by G. Marshall.

The differences between 2009 and 2010 are not extraordinarily high compared to other years (e.g. 2001/2002 as seen at http://www.nerc-bas.ac.uk/public/icd/gjma/newsam.spr.pdf), however, qualitatively they are in agreement with the observed flow pattern. Furthermore, it should be kept in mind that SAM explains only about one third of the atmospheric variability in the Southern Hemisphere (Marshall, 2007) and that the SAM index alone gives no information about the location of respective ridges and troughs in a highly meridional flow pattern..

p 30489, l. 21-25 I like this part of the paper dealing with k=3. However, the index defined by Raphael is based on points fixed in space. Hence it is not able to fully capture (or can misrepresent) phase shifts in the zonal direction. I don't see this as a great problem here, but it is important to mention there are other approaches which are not phase-locked, such as that of Irving ett al, 2015: A novel approach to diagnosing Southern Hemisphere planetary wave activity and its influence on regional climate variability. Jour. Clim., 28, 9041-9057.

Irving et al. (2015) was not published at the time our paper was written. We have added this reference now.

We agree with the reviewer that the ZW3 index used here does not fully capture the shift in phase of the wave. Raphael (2004) recognised this and did note that the net effect is a small reduction in the amplitude of the wave but the sign of the index is not influenced. We added this in the text, too.

p 30490, l. 21-25 I am not sure what 'globally averaged' means here.

We removed the "globally averaged". That was just a thought while writing and came in by mistake, it actually referred to the mean value of d=10, which we did not mention)

p 30491, l. 1 (Discussion and conclusion) This section presents a nice closing discussion and conclusions. However, I would like to see the authors emphasise a little more the importance of the synoptics, and how they directly influence temperature and moisture flow. That is, that there is, at best, a tenuous DIRECT physical link between temperature and depletion. The point is essentially made in the Abstract but should be reinforced here.

We have rewritten this.

Looking towards future work, the results here indicate that a combination of process studies using recent data and modelling of the atmospheric flow conditions on larger time scales will lead to a better quantitative interpretation of ice core data. Apart from the factors influencing precipitation itself, it has become clear recently that post-depositional processes between snowfall events are more important than previously thought because additionally to processes within the snowpack the interaction between the uppermost parts of the snowpack and the atmosphere is very intense (Steen-Larsen et al., 2013). Parallel measurements of stable isotope ratios of water vapour and surface now, combined with meteorological data will give more insight into these processes in Antarctica.

Altogether, this means that the relationship between air temperature and stable isotopes of Antarctic precipitation/ice is anything else but straightforward, since the isotope ratio measured in an ice core (or in the snow) is the result of a complex precipitation history that is strongly influenced by the synoptics and general atmospheric flow conditions, followed by post-depositional processes. Without thorough knowledge of all the processes involved a quantitatively correct derivation of paleo temperatures from ice core stable water isotopes is thus not possible.

p 30495, l. 5-6 EPICA community members, 2004: Eight glacial cycles from an Antarctic ice core. Nature, 429, 623-628, doi: 10.1038/nature02599.

We have added the doi.

p 30499, l. 7-9 The web address give here points to the EARLIER version of Mark Stoelinga's software package (namely version 4). The appropriate citation for Version 4.5 is Stoelinga, M. T., 2009: A Users' Guide to RIP Version 4.5: A Program for Visualizing Mesoscale Model Output. University of Washington. http://www2.mmm.ucar.edu/wrf/users/docs/ripug.htm.

We have updated this, thanks.

Comments to Reviewer #2

We thank the reviewer for the constructive comments that have helped to improve the manuscript. In the following, our comments are written in *italic.*

Manuscript # 2015_734 entitled ‘Precipitation regime and stable oxygen isotopes at Dome C, East Antarctica
– a comparison of two extreme years 2009 and 2010’.

This aim of this paper is to compare the precipitation at Dome C in East Antarctica for two years, 2009 and 2010. The authors present a clear and concise analysis of the circulation differences and their relationship with observed precipitation.

Comments

1. Abstract: Please define SAM and ZW3.

Done

2. Page 30477, line 14. Please define w.e.

Done

3. Page 30478, line 2. What is the word ‘synoptics’ referring to in this section?

We changed this to “large-scale circulation patterns”.

4. Page 30478, line 22-24. Could the authors explain in more detail the sentence that precipitation is ‘formed close to the upper boundary of the temperature inversion layer assuming that the largest moisture amounts are found where the air temperature is highest’? Which inversion layer is this referring to and why is the air temperature high there?

We added information in the text that this is a very simplified assumption widely used in ice core studies.

assuming that the largest moisture amounts are found where the air temperature is highest (Jouzel and Merlivat, 1984). This is a very simplified view that is, however, widely used in ice core studies. It assumes that there are basically no multiple temperature inversions and that humidity is only dependent on temperature through the Clausius-Clapeyron equation, which describes the temperature dependence of vapour pressure. This would mean that humidity and temperature inversions would always have a similar profile. However, more recent studies have shown that humidity inversions are parallel to the temperature inversion only in 50% of the cases, and often multiple humidity (and temperature) inversions occur

5. Page 30479, line 12. Does ‘accumulation’ refer to precipitation accumulation?

We changed this to “precipitation”.

6. Page 30479, line 21. Are the authors claiming that it is not plausible to get high moisture levels above 500hPa? Frontal systems can transport moisture up to the tropopause in the warm conveyor belt airflow. This seems inconsistent with the author’s statement.

Wwe are not claiming this. However, precipitation at Dome C is usually not connected to frontal systems whereas WCBs mostly are. Our statement referred to the low humidity values calculated along the 300hPa trajectories. That does not mean that no substantial amount of moisture is found above 500hPa, but we assume that the flow at 500hPa is representative for a thicker layer. We added this in the text.

7. Page 30483, line 10. What do the authors mean by 'mean annual course'?

Mean annual cycle. We have changed this.

8. Page 30484, line 10. Could the authors expand their reasons for thinking that there is an error in the observation of diamond dust for this event? Is this a systematic error in the observations or a single occurrence? If it is a systematic bias in the observations, would this affect the results?

We have added some information in the text to explain better. We do not think this is a systematic bias in the observation since only a few comparable events occurred during the observation period.

A very high value precipitation value of 1.36 mm on 9 February 2010, followed by 0.67 mm on 10 February, both classified as diamond dust from the photographic crystal analysis, stems from only one event around 9 February. These values should be considered with care given the high error possibilities of the measurements. Considering the extremely low density of diamond dust, a diamond dust amount of more than 1mm/day seems to be unlikely. However, the model data do show a precipitation event connected to warm air advection from the north (see below) for this day, which would indicate the occurrence of snowfall rather than diamond dust. Most likely a mixture of crystal types was found during this event with the diamond dust on top of the snow crystals, which possibly led to the classification of the event as diamond dust. (Note that the crystal classification was carried out purely from photographs by an expert at the Avalanche Institute in Italy and that snow crystals are also comparatively small at the temperatures prevailing at Dome C).

9. Page 30485, line 17. A forecast bust of 25% seems to be very large. Are these missing precipitation events typically with low precipitation rates, just above the threshold, or are more substantial precipitation events missing?

It should be kept in mind that "substantial" precipitation still means daily sums of usually clearly less than 1mm. It cannot be expected that the model represents cases of increased diamond dust precipitation since diamond dust is not parameterized in the model. But, comparison of AMPS data with AWS data in Dronning Maud Land, including the deep drilling site Kohnen (EPICA DML) yielded a very good agreement between AMPS and AWS data for precipitation events, which were usually characterized by an increase in temperature and wind speed, sometimes also a decrease in pressure.

10. Page 30486, line 25. How was the 'main moisture source' defined and how were the source regions estimated? Were the trajectories moisture weighted or are they simply the location of the back trajectories 5-days previously?

The trajectories were not moisture weighted. As we have tried to clarify now in the text, we did not take the location of the back-trajectories 5-days previously as the moisture source. This would definitely be too inaccurate and simple, even in the context of our simplified estimate. We also never considered the trajectories alone (as is often found in the literature, particularly for HYSPLIT users), but we have tried to understand the dynamics of the actual synoptic situation and find a plausible likely moisture source area by combination of back-trajectory and synoptics analysis info.

We added information about this in the manuscript.

Note, that the moisture source is not defined as the location of the trajectory five days previous to the precipitation. Instead, for this estimate, the combined information of the trajectories and the 500hPa geopotential height fields is used. Different from the approach of Sodemann and Stohl (2009) and Sodemann et al. (2008), who calculated 20-day back-trajectories, for a 5-day trajectory it is possible to comprehend the dynamics of the synoptic situation that causes the precipitation. That way the trajectory results can be cross-checked with the geopotential height fields. Even though the trajectory not explicitely deals with moistuer, it gives information about the origin of the moist air mass. The northernmost "point" of the trough that causes the northerly flow to Dome C is supposed to be the northern limit of the potential moisture source since no substantial meridional flow is observed north of this limit. (The 500hPa trajectory seems to have some inconsistencies (e.g. kinks) on the 5th day, which should not be over-interpreted). Whereas it is not possible to exactly determine the moisture source (under the simplifying assumption of a single moisture source) with this simple method, the information is sufficient to distinguish between a source in the Southern Ocean and one at middle latitudes, which is most important for ice core interpretation and for simple isotope modeling.

11. Page 30486, line 28. Why do the authors assume that the northernmost point of the trough corresponds to the northern limit of the potential moisture source? Does this assumption rely on steady state conditions, i.e. that streamlines and trajectories are equal?

No, it does not. We have changed the text, also referring to the comments of Rev. #1, to make it clear that we cannot pinpoint the moisture source with the described method. It is only a coarse estimate. However, we think that no matter if conditions are steady state or not, if the main westerlies have been situated south of a certain latitude for several days before the precipitation, neither the streamlines nor the trajectories hint at a moisture source distinctively north of that westerly band.

12. Page 30487, line 1. What do the authors mean by 'inconsistencies'?

Mainly kinks. We have added this in the text (see above).

13. Page 30487, line 11. Please could the authors clarify what they are referring to by the meandering branch and zonal branch of the main flow?

Yes; we have added an explanation in the texts.

It was also found to be typical for precipitation events at Dome C that the main westerly flow is split into a northern branch that remains zonal, whereas the southern branch starts meandering with a strong meriodional component.

14. Page 30487, lines 15-20. The authors present an account of a forecast bust but it is not clear how representative this is of the other missing precipitation events. Please could the authors expand on this section, to put the case-study analysis into context?

We would have to elaborate on this in a separate study that would inlude the entire data set.

15. Page 30488, line 15. Should 'am SAM index' be 'a SAM index'?

Well, this depends on the pronounciation of SAM. We usually pronounce it "es-a-em", which would make it an SAM index. However, we notice that many people pronounce it like the male name "Sam", so we use the indefinite arcticle "a".

16. Section 5.22 and 5.23. The authors link the precipitation differences to modes of variability for the two years in the study. It is not clear why this is done. Are the authors suggesting that predictability of large-scale modes of variability could inform seasonal prediction of Arctic precipitation, or are they going to use these relationships to look at multi-year analysis or changes in a warming climate, or some other reason? How do the differences in SAM and ZW3 compare to other years?

We are simply saying that the precipitation and temperature measured for these extreme periods may be linked to the flow associated with the atmospheric circulation defined by these two modes of variability. Given that the precipitation dataset is only eight or nine years long at the time of writing we could only speculate about prediction/predictability but the potential may be there. Note that in 2006, 2007 and 2008, the index of ZW3 during the period of interest was more variable in sign.

17. Page 30491, line 19. 'locatation' should be 'location'.

Corrected

18. Figure 5. The contour labels on figure 5a are too small to read.

We fully agree. This is due to the old landscape format of ACPD. In the final paper the figure will have the width of a full column and thus be well readable. Unfortunately, this is the case for several of the figures. ACPD layout has been changed for papers submitted after Dec 2015, and the authors now have more influence on the size of the figures by creating the pdf themselves. Thus, this problem should not appear in the future.

19. Page 30493 lines 16-18. The future work section here is very general and brief. It would be nice to discuss in more detail where this analysis could lead.

Fair point. We have added some more information.

Looking towards future work, the results here indicate that a combination of process studies using recent data and modelling of the atmospheric flow conditions on larger time scales will lead to a better quantitative interpretation of ice core data. Apart from the factors influencing precipitation itself, it has become clear recently that post-depositional processes between snowfall events are more important than previously thought because additionally to processes within the snowpack the interaction between the uppermost parts of the snowpack and the atmosphere is very intense (Steen-Larsen et al., 2013). Parallel measurements of stable isotope ratios of water vapour and surface now, combined with meteorological data will give more insight into these processes in Antarctica.

Comments to Reviewer #3

We thank Harald Sodemann for his thorough review that helped to make necessary clarifications. Our response to comments will be written in *italic,* the corrected text in blue.

General remark:

Our study focuses on the differences in the meteorological conditions at Dome C in 2009 and 2010 and the atmospheric flow patterns that explain those differences. This paper is neither meant to be about stable isotopes nor about moisture source analysis, the method of deriving former air temperatures from ice core stable water isotopes is only the motivation for our study. Thus we do not focus or want to be too elaborate about those topics, which will be dealt with in future papers. We rewrote the introduction to clarify this. Because of that rewrite, a number of the review comments would no longer entail particular necessary changes in the manuscript. Also our moisture source estimate is only a coarse estimate, but there are significant differences in the mean moisture sources in those two years, which can clearly be distinguished even with this coarse method.We have tried to clarify this, too.

This study focusses on the differences in the precipitation regime of two contrasting years within the short measuring period, motivated by the consequences different precipitation/flow regimes have on stable isotope interpretation. The stable istopes themselves are only discussed as additional information about the local conditions in the respective years and will be topic of a different study.

Review of "Precipitation regime and stable oxygen isotopes at Dome C, East Antarctica - a comparison of two extreme years 2009 and 2010" submitted to ACP by Schlosser et al.

This paper presents a comparison of two years of field data from a weather station and snow samples at Dome C. The causes for pronounced differences in winter temperatures between the two years are interpreted in the context of meridional vs zonal transport processes. While I think the paper is in general interesting and suitable for publication in ACP, I point out below several issues that require attention. I hope the authors may find these comments helpful for their revisions.

Comments to comments:

Major comments:

1. Literature. The manuscript currently neglects the state of knowledge on moisture transport to Antarctica and the relation between moisture transport and isotopic fractionation from the published literature. The study by Sodemann et al., 2008 in JGR, which provides a detailed analysis on how moisture source conditions, temperature difference, and temperature regime influence stable isotope fractionation during atmospheric moisture transport, should be cited in the introduction. Furthermore, the study by Sodemann and Stohl (2009) in GRL is a widely cited study of the moisture sources of Antarctica that should be taken into account in this manuscript. Further earlier work includes that of Helsen et al. (2007), and several other studies.

We added references, so the interested reader can study this.
In addition, we would like to refer again to our general comment. We want to focus on the different atmospheric conditions in the two years that are being compared and do not want to distract the reader by going into the details about moisture source diagnostics and stable isotopes.

2. Moisture source analysis. The moisture source identification applied here is very simple (and does not take into account the state of the literature, as mentioned in #1). As I understand from the manuscript, the end points of 5-day trajectories are considered as moisture sources, which is far less than the 15 days recommended by Sodemann and Stohl (2009). Longer trajectory calculation requires statistical approaches to identifying a source or origin location. As only three trajectories at different levels are considered, the result is quite subjective and uncertain.

We have rewritten the description of our moisture source estimate and hope it is clearer now for the readers.We do not define the end points of the 5-day trajectories as moisture source. We have added more information and our reasons for using this type of trajectory calculation in the manuscript.

We would like to avoid embarking on a discussion about the relative value of different methods of trajectory calculations/moisture source diagnostics in the present paper since that would strongly distract the reader from the main topic. 5-day-backward trajectories have been used by various authors (e.g. Reijmer, Scarchilli, Suzuki) to investigate moisture sources for Antarctic drilling sites. There is no "correct" number of days necessary to determine the moisture source for back-trajectory calculation.This is not possible, when only the air mass is followed. Sometimes even a shorter trajectory gives a clearer picture, e.g. at coastal stations where a 5-day backward trajectory calculation might yield a combination of katabatic flow and flow related to fast moving cyclones (Schlosser et al. , 2004).We added information about this in the paper and hope we have made it clear now how our estimate, not determination of the moisture source was done.

The time step we used was 600s. For simplicity's sake, RIP does not define a threshold for convergence, but simply does two iterations for each time step, which turned out to be exact enough in the praxis for our purposes. The resolution of the input data corresponds to the resolution of AMPS/WRF during the respective time period. The data are linearly interpolated in time and space. Taking into account the large uncertainties in trajectory calculations, for this case a main moisture source at approximately 40 °S was estimated. Note, that the moisture source is not defined as the location of the trajectory five days previous to the precipitation. Instead, for this estimate, the combined information of the trajectories and the 500hPa geopotential height fields is used. Different from the approach of Sodemann and Stohl (2009) and Sodemann et al. (2008), who calculated 20-day back-trajectories, for a 5-day trajectory it is possible to comprehend the dynamics of the synoptic situation that causes the precipitation. That way the trajectory results can be cross-checked with the geopotential height fields. Even though the trajectory not explicitely deals with moistuer, it gives information about the origin of the moist air mass. The northernmost "point" of the trough that causes the northerly flow to Dome C is supposed to be the northern limit of the potential moisture source since no substantial meridional flow is observed north of this limit. (The 500hPa trajectory seems to have some inconsistencies (e.g. kinks) on the 5th day, which should not be over-interpreted). Whereas it is not possible to exactly determine the moisture source (under the simplifying assumption of a single moisture source) with this simple method, the information is sufficient to distinguish between a source in the Southern Ocean and one at middle latitudes, which is most important for ice core interpretation and for simple isotope modeling.

The authors cite another manuscript in preparation which contains the study of more events, but as a reviewer it is not possible to evaluate what is done in that other paper. This section needs to be heavily reworked or even dropped altogether.

The reviewers of the new paper will be able to evaluate what is done in that paper.
We do not think that it is essential to assess this in the present paper.

3. Dependence/relation to manuscripts in preparation. The isotope data set used in the study is to be described in a companion paper, which is however only in preparation at this point. This is a potentially serious issue. What if that companion paper never gets published? As a consequence, the data section must contain enough information on the isotope data set to stand on its own.

We would like to refer to our general comment again. As clarified, this paper is not about stable isotopes, they only serve as motivation for our study. Whereas for mass balance studies it is not so important where the moisture comes from (the total precipitation amount counts) for isotope studies it is of high importance. The information about the isotopes given in the present study does not mean to

be complete. And we would like to note that several isotope papers are to be published about Dome C in any case.
The data section gives information about the sampling procedure and stable isotope analysis, and this is sufficient here. Our reference to this paper is a consequence of the data restriction policy, which we are dealing with.

4. Stable isotope results. The paper is intended and starts out with the role of atmospheric conditions for stable isotope fractionation, but in the end it is only one short section of the results that presents the data from a two-year period. The analysis is restricted to the correspondence of low/high values for the warm and cold year. It is not clear what to take away from this analysis other than the very obvious finding that fractionation is stronger under colder conditions. For example, further quantitative investigation of the stable isotope data for this period could strengthen the analysis. I suggest to merge Fig.10 and Fig. 3 (remove panels b and c) and present the findings on temperature and stable isotope differences right away, before going into further analysis of the circulation differences for the two years.

We would like to refer to our general comment here. We have re-written the introduction making clear that the paper does no taim to focus on stable isotopes.

5. Presentation quality. Several of the figures have a visual appearance that could be improved.

Yes, we fully agree that some of the figures do not look great the way they were published in the landscape format by ACPD. However, in the final version in ACP the figures will have the full width of one or two columns and will indeed be greatly imporved. We are glad that the format of the discussion papers will be different from 2016 on.

Detailed comments:

P. 30474, L24: "The most important positive": are there other positive components to the mass balance?

Yes, there are: deposition (= negative sublimation), wind redistribution and freezing at the bottom of ice shelves.

p. 30475, L29: "The amount of this fractionation…" citing Sodemann et al., 2008 at the end of this sentence would fit.

Since this is not a result of Sodemann et al.'s study we prefer to cite J. Jouzel (2003; 2014) here, who was one of the early pioneers in ice core studies. We believe that the older references should be preferred in such cases to give credit to the original research.

The amount of this fractionation depends on the difference between the condensation temperature close to the initial moisture source and that at the final deposition site (Jouzel et al., 2003; 2014).

Could rephrase to "initial condensation" because condensation not necessarily starts at the moisture source. "at the final deposition site": fractionation is related to the final condensation temperature, which may be different than the site temperature due to a surface inversion.

We agree and have changed this. We gave this information for the readers of ACP since we don't believe that all of them are familiar with stable isotopes. However, for more detailed information we have to refer to the literature, since, as we mentioned above, this paper is not a stable isotope paper.

The amount of this fractionation depends on the difference between the condensation temperature close to the initial moisture source and that at the final deposition site (Jouzel et al., 2003; 2014).

Very few references in general in this paragraph.

OK. We have added some. Basically, this is all summarized in Jouzel (2014).

p. 30476, L1: "winter/glacial": I understand the general intention of such a parallel interpretation, but it would be good to substantiate this more, e.g. by an appropriate reference.

This is basic textbook knowledge meanwhile. Unfortunately we did not find this explicitely formulated in J. Jouzel's chapter, but we would be grateful for a reference here.

p. 30476, L5: "This spatially derived linear…": transition from previous paragraph not clear. Consider citing Sime et al. here.

We inserted the "spatial" at the beginning of the previous paragraph to make this clear. It is not clear to us, though, why Sime et al. should be quoted her as this was found much earlier than the Sime paper. We would like to refer to our earlier comment about original work here. Sime's findings will be very interesting for a paper that focusses on the stable isotopes.

This spatially derived linear relationship has been found not to hold temporally,

p. 30476, L7: consider adding Sodemann et al (2008) here which show the importance of these factors in relation to one another. Sodemann and Stohl (2009) provide a detailed moisture source analysis for all of Antarctica and several ice core sites which adresses these issues. Also consider citing the study of Wang et al (2013) for Dome A.

Again, we would like to refer to our earlier comment about original work here.

p. 30477, L1: Dome Fuji had a similar sampling programme for one year, published by Fujita and Abe (2006). So the Dome C series can not be the first one? I don't think it is important to make the claim here, the data are anyhow worthwhile publishing. There is also a huge body of work done on firn sampling, which gives a spatial but not a temporal picture - may be worth mentioning here.

At Dome F, the measurements cover only 1 year. We only state that Dome C has the first multi-year series of such measurements. Firn sampling is very different, we are talking about precipitation here.

p. 30478, L11: Should add citation of Gorodetskaja et al. (2014) here.

We quoted this paper in the discussion. However, we have added Gorodetskaya et al. (2013) here, which seemed more suitable at this point and that we had missed when writing the paper.

p. 30478, L18: Should add citation of Sodemann and Stohl (2009) here.

We could not find anything about orographic lifting of air masses and corresponding precipitation formation in this paper.

p. 30478, L25: Explain more what you mean by "humidity inversions".

We have added some information here.

This is a very simplified view that is, however, widely used in ice core studies. It assumes that there are basically no multiple temperature inversions and that humidity is only dependent on temperature through the Clausius-Clapeyron equation, which describes the temperature dependence of vapour pressure. This would mean that humidity and temperature inversions would always have a similar profile. However, more recent studies have shown that humidity inversions are parallel to the temperature inversion only in 50% of the cases, and often multiple humidity (and temperature) inversions occur (Nygard et al., 2013).

p. 30479, L1: Connection of this paragraph to the previous not clear.

This is the beginning of a new section (3.2.), and thus it is intended to break from the preceding one.

p. 30479, L15: This section is missing some important references and discussion. In particular, it is important to distinguish between backward trajectories which by themselves do not allow to infer moisture sources or origin, but rather airmass origin, and methods to identify moisture origin from trajectories which consider for example specific humidity changes along trajectories and their vertical position. Please include a discussion of these aspects and cite the work by Sodemann et al. (2008) and Sodemann and Stohl (2009).

We agree, but would like to refer to our earlier comments here. As we have tried to convey by revising the paper, this study is not about moisture source diagnostics, and we do not want to distract from the main topic.

In particular, the study of Sodemann and Stohl showed that moisture sources are further south than anticipated from previous studies, and cluster near the SH storm track.

This is in good agreement with the results of Reijmer et al. (2002), who used 5-day back trajectories.

These authors also report an spatial gradient of moisture origin from coast to inland, placing the deep-drilling sites in a different regime than coastal sites.

Sodemann and Stohl determined mean moisture sources, whereas we are doing case studies, which changes the results considerably. Also, the deep drilling sites may not have all similar moisture sources, e.g. conditions at Kohnen and Dome A (Wang et al.) are different from Dome C and Dome Fuji.

The study by Dittmann et al. (2015) is referred to as "in preparation" and should thus not be citeable.

Dittmann et al. was submitted to ACP on Dec. 13th, but unfortuntately ACP was not able to find an editor for it. We found an editor ourselves and the paper was accepted for ACPD and went online on Feb. 1st. We have changed the reference accordingly.

Dittmann, A., Schlosser, E., Masson-Delmotte, V., Powers, J. G., Manning, K. W., Werner, M., and Fujita, K.: Precipitation regime and stable isotopes at Dome Fuji, East Antarctica, Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2015-1012, in review, 2016.

p. 30479, L25: see comment above on Dome F data.

Here we meant the first fresh snow samples at Dome C. added “at this site” in the text to make this clear.

Dome C is a deep ice core drilling site. However, the measurements presented here are the first derived from fresh snow samples at this site.

p. 30480, L6: Not clear what the focus of this section is, as the discussion changes from stable isotopes to snow type and to AWS data.

To clarify the connection between temperature and isotopes in this section, we added the influence of the fact that the precipitation temperature is higher than on average on the stable isotope ratios.

The precipitation-weighted temperature was significantly higher than the mean annual surface temperature because the precipitation events were related to warm-air advection, which leads to a warm bias in the δ^{18}O record.

See comment above on the study by Dittmann et al (2015).

Our comment above addresses this.

As this section is in the "Previous work" chapter, I would have expected more information on previous stable isotope measurements done at Dome C either in snow or firn to provide context for the data reported later on.

Once again, we would like to refer to our general comment here.(that this is not a stable isotope paper, but that the stable isotopes are the motivation for the investigation of atmospheric conditions. We state this explicitly in the introduction now.)

P. 30480: More details on the sampling and analysis procedure are required. What bags have been used, how have samples been stored, when have they been melted? Have you made checks for data quality of some kind, e.g. by transferring standard water in the same containers from the sampling site to the lab? This is important to add here since the Stenni et al (2015) reference is cited as "in prep".

See comments above, please.The Stenni et al. paper , as noted above, is now in the publication pipeline and these details on sampling and analysis are described there.

P. 30482, L. 17: This section may be shortened.

Since our analysis is based on AMPS output we think it is important to give this information to readers here.

P. 30483, L. 9: Please explain more what you mean by "coreless winter". What is the importance of cloud cover seasonality for this feature?

The "coreless winter" is a clearly defined term well-known in Antarctic meteorology and atmospheric physics. We explain it in the text and added some information following the advice of Reviewer #1. Cloud cover seasonality itself does not play a role here. (Changes in cloud cover during warm air intrusions support the warming by increasing incoming LW radiation.)

The mean annual cycle exhibits the typical coreless winter (van Loon, 1967) with a distinct temperature maximum in summer (December/January), which has no counterpart in winter, where the months May to August show relatively similar values. This is due to a combination of the local surface radiation balance and warm air intrusions. During the first part of the polar night, with the lack of short-wave radiation, anequilibrium of downwelling and upwelling longwave radiation is reached; advection of relatively warm air from lower latitudes further reduces the possibility for cooling. Thus the temperature does not decrease significantly after May (King and Turner, 1997; Schwerdtfeger 1984).

P. 30483, L. 19: "ever observed": for the period 1996-2014?

Yes

P. 30483, L. 21: correct to -54.9°C

Done

P. 30484, L. 1: "barely exceed": rephrase to "reach below" for clarity

We changed that to "are rarely lower than" as suggested by Reviewer #1.

Minimum temperatures are rarely lower than -70 °C

P. 30483, L. 11: "Most likely a mixture": Why most likely, are the data not available?

The crystal analysis was carried out using photos of the samples at the Avalanche Institute in Arabba. It was not always possible to clearly define one crystal type for the entire sample. We added some information about this in the text.

P. 30483, L. 16: add "(not shown)" after "moist"

It is shown in Fig. 3 and Fig. 10. Moist does not refer to humidity, but means high precipitation amounts in general meteorological terms. In German we would also say “niederschlagsreich”, but this term does not exist in English.

P. 30485, L. 13: please provide a table listing these events, e.g. in the supplement

A detailed study including a “climatology” of all events for the entire observation periods will be published in one of the next papers.

P. 30485, L. 16: what distance would suffice for considering an event to be in the vicinity?

There is no absolutely defined distance here. It depends on the strength of the event. Usually, these were cases where AMPS clearly showed a case of strong southward moisture transport from lower latitudes that did not quite reach Dome C, though. So even though an exact verification of precip amounts at Dome C is not seen, the model basically did represent the synoptic situation correctly.

P. 30486, L. 24: it is not clear how the source at 40°S is obtained. How large is the uncertainty, can this be quantified? I think it is difficult to justify using 500hPa fields to infer information about moisture sources, which is a surface process. Did you take into account the vertical position of the trajectories? As Sodemann and Stohl (2009) pointed out, 5 days will in general not be long enough to obtain a reliable moisture source information from trajectories in that region. The uncertainty is typically taken into account in trajectory studies by considering many (hundreds) of trajectories at slightly offset time and space to obtain a statistical information about the possible origin locations. This is a severe limitation of the analysis done here.

We have rewritten this section of the manuscript to clarify things here. And yes, we did look at the vertical position of the trajectories, the 500hPa more often showed an end point close to the ocean surface than the 300hPa. We have explained our method and the reasons for using it in more detail now, including our request on the accuracy of the moisture source estimate.

Note, that the moisture source is not defined as the location of the trajectory five days previous to the precipitation. Instead, for this estimate, the combined information of the trajectories and the 500hPa geopotential height fields is used. Different from the approach of Sodemann and Stohl (2009) and Sodemann et al. (2008), who calculated 20-day back-trajectories, for a 5-day trajectory it is possible to comprehend the dynamics of the synoptic situation that causes the precipitation. That way the trajectory results can be cross-checked with the geopotential height fields. Even though the trajectory not explicitely deals with moistuer, it gives information about the origin of the moist air mass. The northernmost “point” of the trough that causes the northerly flow to Dome C is supposed to be the northern limit of the potential moisture source since no substantial meridional flow is observed north of this limit. (The 500hPa trajectory seems to have some inconsistencies (e.g. kinks) on the 5th day, which should not be over-interpreted). Whereas it is not possible to exactly determine the moisture source (under the simplifying assumption of a single moisture source) with this simple method, the information is sufficient to distinguish between a source in the Southern Ocean and one at middle latitudes, which is most important for ice core interpretation and for simple isotope modeling.

P. 30487, L. 6: I agree with these arguments as a hypothesis but not as a result from this analysis. Please clarify.

We simply give an example about a precipitation event with a relatively northern moisture source and state that this can lead to a bias in the temperature derived from stable isotopes We do not know yet whether there was an increase in the number of such situations in a different climate. This has to be studied using more proxies (e.g. sea ice extent) combined with atmospheric models.

P. 30487, L. 25: It would be very insightful to add information on the variability of the Z500 field as shading to the mean fields.

We prefer not to show this in order to keep the clarity of the signal.

P. 30490, L. 1: "Since the main motivation": if that is indeed the main motivation I strongly suggest to move these results to the beginning such that the reader has the isotope data in mind when the further analysis of the atmospheric flow situation is presented. It may also be worthwhile to show a more detailed investigation of the isotope data, for example correlations with temperature for the two years.

We would like to refer to our general comment again here.

P. 30490, L. 13: "globally averaged": what do you mean here?

We removed the "globally averaged". That was just a thought while writing and came in by mistake, it actually referred to the mean value of d=10, which we did not mention.

P. 30490, L. 22: Can you provide more information on the d excess values here - what is the typical value in firn samples, for instance, and how is this parameter interpreted at Dome C ice cores? If the moisture sources really changed (I would consider that as an hypothesis at this point) then would you expect to see a change in the d-excess as well (see Pfahl and Sodemann, 2014, and references therein).

This also falls into the area of our general comment and the revised description of the foucs.The d-excess is not the topic of this paper.

P. 30493, L. 6: Consider discussing the recent work by Steen-Larsen et al. (2014) on the exchange between atmospheric water vapor, air in the snow pack and the ice crystals which may be able to change the isotope composition of the snow after deposition.

We have given this reference in the discussion.

Apart from the factors influencing precipitation itself, it has become clear recently that post-depositional processes between snowfall events are more important than previously thought because additionally to processes within the snowpack the interaction between the uppermost parts of the snowpack and the atmosphere is very intense (Steen-Larsen et al., 2013). Parallel measurements of stable isotope ratios of water vapour and surface now, combined with meteorological data will give more insight into these processes in Antarctica.

Figure 1 and 2: Consolidate into one figure. I don't think it is necessary to show the AMPS domains in this study.

We would prefer to have the figure to make it clear what AMPS has covered. We think the consolidation into one figure is a matter of taste.

Figure 3 and 10: Consolidate into one figure by removing panels 3b and 3c. Maybe add accumulated precipitation to Fig. 3a.

We think this is a matter of taste.

Figure 4: Remove legend from three panels. I recommend to not use 3D pie diagrams as the areal representation of the numbers is distorted by the oval shapes.

As in the precedeing comment, we think that this is a matter of taste and that the figure as it is suits our purpose .

Figure 5: Figure is cluttered - use same domain and panel size, arranged horizontally.

See comment above. We fully agree that some of the figures have a bad appearance in the ACPD version. This is due to the old landscape format of ACPD. In the final paper the figure will have the width of a full column and thus will be well readable. Unfortunately, this is the case for several of the *figures. ACPD layout has been changed for papers submitted after Dec 2015 and the authors now have more influence on the size of the figures by creating the pdf themselves. Thus this problem should not appear anymore in the future.*

Arranged horizontally the figure would look poor in the final version.

Figure 6: use same domain and size and arrange horizontally. Could use white instead of blue for regions below 0.2 mm/day.

See comment above, please.

Figure 7: use square map, consider adding variability of Z500 as shading.

This is the AMPS domain. It is not square. Rest see above

Figure 9: transpose panels to horizontal alignment

Please, see comment above.

As we mentioned before, this is a problem of the ACPD format, which will disappear in ACP.

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Precipitation regime and stable oxygen isotopes at Dome C, East Antarctica – a comparison of two extreme years 2009 and 2010

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Abstract

At the East Antarctic deep ice core drilling site Dome C, daily precipitation measurements have been initiated in 2006 and are being continued until today. The amounts and stable isotope ratios of the precipitation samples as well as crystal types are determined. Within the measuring period, the two years 2009 and 2010 showed striking contrasting temperature and precipitation anomalies, particularly in the winter seasons. The reasons for these anomalies ~~and their relation to stable isotope ratios~~ are analysed using data from the mesoscale atmospheric model WRF (Weather Research and Forecasting Model) run under the Antarctic Mesoscale Prediction System (AMPS). 2009 was relatively warm and moist due to frequent warm air intrusions connected to amplification of Rossby waves in the circumpolar westerlies, whereas the winter of 2010 was extremely dry and cold. It is shown that while in 2010 a strong zonal atmospheric flow was dominant, in 2009 an enhanced meridional flow prevailed, which increased the meridional transport of heat and moisture onto the East Antarctic plateau and led to a number of high-precipitation/warming events at Dome C. This was also evident in a positive (negative) SAM (Southern Annular Mode) index and a negative (positive) ZW3 (Zonal Wave number three) index during the winter months of 2010 (2009). Changes in the frequency or seasonality of such event-type precipitation can lead to a strong bias in the air temperature derived from stable water isotopes in ice cores.

1 Introduction

Although Antarctic precipitation has been studied for approximately half a century (see e.g. Bromwich, 1988), a number of open questions remain. There are two key motivations for studying Antarctic precipitation. The first is that precipitation/snowfall is the most important positive component of the mass balance of Antarctica. This is receiving increasing attention in discussions of climate change since the mass balance response to global warming can considerably influence sea level change. A possible increase of precipitation in a future climate due to higher air temperatures and therefore increased saturation vapour pressure would mean storage of larger amounts of water in the Antarctic ice sheet, thus mitigating sea level rise (Church et al., 2013). So far, the expected increase in precipitation has not been found in the measurements (e.g. Monaghan et al., 2006). However, in one projection derived from a combination of various models and ice core data, Frieler et al. (2015) state a possible increase in Antarctic accumulation on the continental scale of approximately 5% K^{-1}. In some parts of Antarctica, higher accumulation would lead to increased ice flow and thus dynamical ice loss, which would reduce the total mass gain (Harig and Simons, 2015; Winkelmann et al., 2012). Thus, for calculation of the Antarctic mass balance, precipitation amounts and precipitation regimes have to be known as exactly as possible.

A second driver for studying Antarctic precipitation is that the ice of Antarctica is an unparalleled climate archive: ice cores up to 800.000 years old yield crucial information about palaeotemperatures and the past constitution of the atmosphere (e.g. EPICA community members, 2004). To derive former air temperatures from ice cores, the stable-isotope ratios of water are used primarily. A linear spatial relationship has been found between mean annual stable isotope ratios in Antarctic precipitation and annual mean air temperature at the deposition site although the isotope ratios depend in a complex way on mass-dependent fractionation processes during moisture transport and precipitation formation (Dansgaard, 1964). Since the heavier isotopes have a lower saturation vapour pressure than the lighter ones, they condense more easily and evaporate less rapidly. The molecular diffusivity is smaller for the heavier isotope, ^{18}O, than for ^{16}O as well. This is equally valid for hydrogen and its heavier stable isotope deuterium (D). Therefore, the isotope ratio changes during evaporation and condensation processes. When an air mass is cooled (on the transport south to Antarctica or in ascent to higher elevations) it gets increasingly depleted in the heavier isotopes (^{18}O and D) because they preferably fall out as precipitation. The amount of this fractionation depends on the difference between the condensation temperature ~~a~~close to ~~t~~ the initial moisture source and that at the final deposition site (Jouzel et al., 2003; 2014). Since the annual temperature amplitude is larger on the continent than in the maritime climate of the Southern Ocean, the ^{18}O values are lower during cold periods (winter/glacial) than during warm periods (summer/interglacial), which leads to clear seasonal variations and likewise large differences between glacial and interglacial periods in the stable isotope ratios measured in the ice core.

This spatially derived linear relationship has been found not to hold temporally, however (Jouzel et al., 2003). Apart from air temperature, several other factors influence the stable isotope ratio, such as seasonality of precipitation, location of and conditions at the moisture sources and conditions along moisture transport paths (e.g. Sodemann and Stohl, 2009; Sodemann et al., 2008, Jouzel et al., 2003; Noone et al., 1999; Schlosser, 1999). Thus, for a correct interpretation of the ice core data a thorough understanding of the atmospheric processes responsible for the precipitation is needed, as it was the precipitation that ultimately formed the glacier ice investigated in the cores. In particular, information about moisture sources, moisture transport paths, and atmospheric conditions at the final deposition site is required.

Measuring Antarctic precipitation is a challenge, not only due to the remoteness and extreme climate of the continent, but also due to difficulties in distinguishing between drifting/blowing snow and falling precipitation. The latter is due to the high wind speeds that typically accompany precipitation events in coastal areas. In the interior of the continent, while wind speeds are lower than at the coast, the threshold for drifting snow is often lower due to lower snow densities as well. Measurements are also complicated by the extremely small amounts of precipitation produced in the cold and dry air. Precipitation measurements with optical devices may hold some hope for improved data in the future, but these instruments are currently in the testing phase in Antarctica (Colwell, pers. comm.). In light of the lack of observations, atmospheric models have become increasingly useful tools to investigate Antarctic precipitation (Bromwich et al., 2004; ~~Noone et al., 1999;~~ Schlosser et al.,~~ 2008;~~ 2010a; 2010b; 2008; Noone and Simmons, 2002; Noone et al., 1999; Noone and Simmons, 1998).

~~In this study, observational precipitation and stable isotope data from the deep-drilling site Dome C, East Antarctica, combined with data from a mesoscale atmospheric model are used to investigate the precipitation regime and its relation to stable isotope ratios of the precipitation.~~

This study focusses on the differences in the precipitation regime of two contrasting years within the short measuring period, motivated by the consequences different precipitation/flow regimes have on stable isotope interpretation. The stable istopes themselves are only discussed as additional information about the local conditions in the respective years and will be topic of a different study. ~~The Dome C precipitation series is the first and so far only multi-year precipitation/stable isotope series at an Antarctic deep ice core drilling site.~~

The present~~is~~ investigation concentrates on the years 2009 and 2010. These years were chosen because they showed striking contrasting temperature and precipitation anomalies, particularly in the winter seasons. Fogt (2010) reports that temperatures in the Antarctic were persistently above average in the mid-to-lower troposphere during the winter of 2009. The positive surface temperature anomalies were most marked in East Antarctica. In 2010, the picture was very different from 2009, with generally below-average temperatures on the East Antarctic plateau in winter and spring (Fogt, 2011).

2 Study site

Dome C (75.106 °S, 123.346 °E, elevation 3233m) is one of the major domes on the East Antarctic ice sheet. Its mean annual temperature is -54.5 °C, and the mean annual accumulation derived from ice cores amounts to 25 mm water equivalent (w.e)./yr. Several deep ice cores have been retrieved at Dome C, the first one in 1977/78, reaching a depth of 906 m, corresponding to an age of approximately 32,000 yr. The thermally drilled core was retrieved during the International Antarctic Glaciological Project (Lorius, 1979).

The oldest ice to date has been obtained at Dome C through the European deep drilling project EPICA (European Project for Ice Coring in Antarctica). The drilling was completed in January 2006; at the base of the 2774.15 m long ice core the age of the ice was estimated to be 800.000 yr, thus covering eight glacial cycles (EPICA community members, 2004). To support the EPICA drilling operation, the French-Italian Antarctic wintering base Dome Concordia became operational in 2005.

3 Previous work

3.1 Large-scale circulation patterns~~Synoptics~~ and precipitation

Precipitation conditions in the interior of Antarctica are very different from those in coastal areas. Whereas precipitation at the coast is usually caused by frontal systems of passing cyclones that form in the circumpolar trough (e.g. Simmonds et al., 2002), in the interior different precipitation mechanisms are at play. On the majority of days, only diamond dust, also called clear-sky precipitation, is observed. It forms due to radiative cooling in a nearly saturated air mass. Although diamond dust is predominant temporally, it does not necessarily account for the largest fraction of the total yearly precipitation. It has been shown that a few snowfall events per year can bring up to 50% of the total annual precipitation (Braaten et al., 2000; Reijmer and van den Broeke, 2003; Fujita and Abe, 2006; Schlosser et al., 2010a; Gorodetskaya et al., 2013~~ Fujita and Abe, 2006~~). Those events are due to amplification of Rossby waves in the circumpolar westerlies, which increases the meridional transport of heat and moisture polewards. In extreme cases this can even mean a transport from the Atlantic sector across the continent to the Pacific side (Sinclair, 1981; Schlosser et al., 2015b) The relatively moist and warm air is orographically lifted over the ice sheet, followed by cloud formation and/or precipitation (Noone et al, 1999; Massom et al., 2004; Birnbaum et al., 2006; Schlosser et al., 2010). Except for the study by Fujita and Abe (2006), all of these investigations were based on model and AWS data, rather than daily precipitation measurements.

For a long time it was believed in ice core studies that precipitation represented in Antarctic ice cores is formed close to the upper boundary of the temperature inversion layer assuming that the largest moisture amounts are found where the air temperature is highest (Jouzel and Merlivat, 1984). This is a very simplified view that is, however, widely used in ice core studies. It assumes that there are basically no multiple temperature inversions and that humidity is only dependent on temperature through the Clausius-Clapeyron equation, which describes the temperature dependence of vapour pressure. This would mean that humidity and temperature inversions would always have a similar profile. However, more recent studies have shown that humidity inversions are parallel to the temperature inversion only in 50% of the cases, and often multiple humidity (and temperature) inversions occur (Nygard et al., 2013). In particular, the local cycle of sublimation and re-sublimation (deposition) is poorly known, but it is important for both mass balance and isotope fractionation studies.

At Dome Fuji, at an elevation of 3810m, the air can be so dry that, in spite of the advection of warm and moist air related to amplified Rossby waves, no precipitation is observed at the site. However, this synoptic situation can cause a strong warming in the lower boundary layer (particularly during blocking situations) due to a combination of warm air advection and removal of the temperature inversion layer by increased wind speed that induces mixing and cloud formation, which in turn increases downwelling longwave radiation (Enomoto et al, 1998; Hirasawa et al., 2000). Increased precipitation amounts can also be observed after a snowfall event when the warm air advection has ended, but increased levels of moisture prevail, which can lead to extraordinarily high amounts of diamond dust precipitation (Hirasawa et al., 2013). In West Antarctica, intrusions of warm, marine air can lead to increased cloudiness, ~~accumulation~~precipitation and air temperature. A change in the frequency or intensity of such warm air intrusions could have a large effect on West Antarctic climate if the mean general circulation changed (Nicolas and Bromwich, 2011).

Moisture origin has been investigated in various studies using back-trajectory calculations employing different models and methods (Scarcilli et al., 2010; Sodemann and Stohl, 2009; Sodemann et al. 2008; Suzuki et al., 2008; Reijmer et al., 2002). In a recent study by Dittmann et al. (2015), who investigated precipitation and moisture sources at Dome F for precipitation events in 2003, it was ~~found~~ estimated that the origin of the moisture was farther south (on average at 50°S) and the transport occurred lower in the atmosphere (approximately at the 500-hPa level) than previously assumed in ice core studies. Since the humidity calculated along the 300hPa-trajectory was already comparatively low (absolute humidity a factor 10 lower at 300hPa than at 500hPa) we assume the 500hPa level as representative for the main moisture flow, which is, of course, not restricted to the 500hPa level, but occurs in a thicker layer that includes the 500hPa level. ~~Origins at higher atmospheric levels were found to be not plausible because of the low amounts of moisture available there.~~

3.2 Stable isotopes

Dome C is a deep ice core drilling site. However, the measurements presented here are the first derived from fresh snow samples at this site. A similar study, if only for a period of approximately one year, was carried out by Fujita and Abe (2006) at Dome Fuji (see Fig. 1), another deep-drilling site in East Antarctica. They investigated daily precipitation data together with measurements of stable isotope ratios of the precipitation samples. Temporal variations of δ^{18}O were highly correlated with air temperature. The lowest δ^{18}O value measured was –81.9 ‰, which is the isotopically lightest water ever collected on the Earth's surface. Half of the annual precipitation resulted from only 11 events (18 days), without showing any seasonality. The other half was due to diamond dust. Similar results were found in studies by Schlosser et al. (2010a), at Kohnen Station (see Fig. 1) and by Reijmer and Van den Broeke (2003), who used data from automatic weather stations in Dronning Maud Land. The precipitation-weighted temperature was significantly higher than the mean annual surface temperature because the precipitation events were related to warm-air advection, which leads to a warm bias in the δ^{18}O record.~~,~~ Recently, Dittmann et al. (2015) investigated the stable isotope data obtained by Fujita and Abe (2006) at Dome Fuji for all days with dynamically caused snowfall in a combined approach of synoptic analysis and isotope modelling. They found that, for single events, the relationship between deuterium excess and atmospheric conditions at the moisture source used in ice core studies was not existent.

Formatiert: Schriftart: Symbol

Formatiert: Hochgestellt

4 Data and methods

4.1 Precipitation and isotopes

Daily precipitation measurements were initiated at Dome C in 2006, and have, with some interruptions, been continued until today. Daily precipitation amounts are measured using a wooden platform set up at a distance of 800 m from the main station, at a height of 1 m above the snow surface to avoid contributions from low drifting snow. For the same reason, the platform is surrounded by a rail of approximately 8 cm height. The measurements include precipitation sampling and analysis of stable water isotopes (δ^{18}O, δD) of the samples. Additionally the crystal structure of the precipitation is analysed in order to distinguish between diamond dust, snowfall, and drift snow. Diamond dust consists of extremely fine ice needles whereas synoptic snowfall shows various types of regular snow crystals, which tend to be broken in case of drifting/blowing snow. The snow crystal type depends on air temperature during formation in the cloud. Samples of mixed crystal types can also occur.

While errors of the precipitation measurements cannot be quantified, it is understood that they can exceed 100% given the extremely small precipitation amounts.

The snow samples were sent to the Geochemistry Laboratory of the University of Trieste, where they were melted and stored in freezers at approximately -20 °C until, provided the precipitation amount was sufficient, they were analysed using a mass spectrometer (Thermo-Fisher Delta Plus XP). Very small samples were analysed using a Picarro I1102-I cavityringdown spectroscopy (CRDS) analyser. The precision of the Picarro I1102-I is 0.1 ‰ for $\delta^{18}O$ and 0.5 ‰ for δD (Stenni et al., 2015). Details of the measurements and an extensive discussion of the full data set can be found in Stenni et al. (2015)

The Dome C precipitation series is the first and so far only multi-year precipitation/stable isotope series at an Antarctic deep ice core drilling site.

4.2 AWS data

The Antarctic Meteorological Research Center (AMRC) and Automatic Weather Station (AWS) Program are sister projects of the University of Wisconsin-Madison funded under the United States Antarctic Program (USAP) that focus on data for Antarctic research support, providing real-time and archived weather observations and satellite measurements and supporting a network of automatic weather stations across Antarctica.

The current AWS at Dome C was set up by the AMRC, in December 1995. The station measures the standard meteorological variables of air temperature, pressure, wind speed, wind direction, and humidity. Data can be obtained from http://amrc.ssec.wisc.edu. Note that an initial AWS (named Dome C) had been set up in 1985, however, at a distance of about 70 km from the current site. Thus, only data from the new station (Dome C II) are used in the present study.

4.3 WRF Model Output from the AMPS Archive

In addition to the observations described above, this study uses numerical weather prediction (NWP) model output for analysis of the synoptic environments of the target years, of precipitation processes, and of events. The output is from forecasts of the Weather Research and Forecasting (WRF) Model (Skamarock et al., 2008) run under the Antarctic Mesoscale Prediction System (AMPS) (Powers et al., 2003; 2012), a real-time NWP capability that supports the weather forecasting for the United States Antarctic Program (USAP). The (U.S.) National Center for Atmospheric Research (NCAR) has run AMPS since 2000 to produce twice-daily forecasts covering Antarctica with model grids of varying resolutions. The AMPS WRF forecasts have been stored in the AMPS Archive and used extensively in studies (e.g. Monaghan et al., 2005; Seefeldt and Cassano, 2008; Schlosser et al., 2008; Seefeldt and

Cassano, 2012). For 2009 and 2010, the WRF output over the Dome C region reflects a forecast domain with a horizontal grid spacing of 15 km, employing 44 vertical levels between the surface and 10 hPa. This 15-km grid was nested within a 45-km grid covering the Southern Ocean, and Fig. 2 shows these domains.

Model output from AMPS has been verified through various means over the years. Multi-year AMPS forecast evaluations have been conducted (Bromwich et al., 2005), and WRF's ability for the Antarctic in particular has been confirmed (Bromwich et al., 2013). AMPS's and WRF's Antarctic performance has also been documented in a number of case and process studies (e.g. Bromwich et al., 2013; Nigro et al., 2011; 2012; Powers, 2007~~; Nigro et al., 2011; 2012~~). For model development within AMPS, verification for both warm and cold season periods is performed prior to changes in model versions or configurations (Powers et al., 2012). The reliability of AMPS WRF forecasts is also reflected in their demand from international Antarctic operations and field campaign forecasting efforts (see e.g. Powers et al., 2012). Lastly, similarly to how it is used here, AMPS output has been a key tool in previous published studies of Antarctic precipitation related to ice core analyses (Schlosser et al., 2008; 2010a; 2010b).

In this study the WRF output from the AMPS archive is used to study both the synoptic patterns and the local conditions related to the precipitation regimes and events in the years compared. The WRF forecasts provide reliable depictions of conditions and their evolution, and are used for trajectories and estimates of precipitation source and type. This includes information on temperatures (in both source and deposition areas) and precipitation.

5 Results

5.1 Temperature and precipitation

Figure 3a shows the mean monthly air temperature observed at the Dome C AWS for 2009 and 2010 as well as the mean of 1996-2014. The mean annual ~~course~~cycle exhibits the typical coreless winter (van Loon, 1967) with a distinct temperature maximum in summer

(December/January), which has no counterpart in winter, where the months May to August show relatively similar values. This is due to a combination of the local surface radiation balance and warm air intrusions. ~~the fact that d~~During the first part of the polar night, with the lack of short-wave radiation, a~~nn~~ equilibrium of downwelling and upwelling longwave radiation is reached; advection of relatively warm air from lower latitudes further reduces the possibility for cooling. Thus ~~thereafter~~ the temperature does not ~~further~~ decrease significantly after May (King and Turner, 1997; Schwerdtfeger 1984).

Whereas during the summer months little difference is seen between 2009 and 2010 the winter months are strikingly different. The lowest mean July temperature of the station record occurs in 2010 with a value of -69.7 °C. This is the lowest monthly mean ever observed at Dome C, 5.9 °C lower than the average 1996-2014, corresponding to a deviation of 1.7σ, σ being the standard deviation. In contrast, the highest July mean temperature is found in 2009; with a value of -54.9 °C, it was 8.9 °C higher (corresponding to 2.5σ) than the long-term July mean and the only July mean that exceeded -60 °C. In Figure 3b, observed daily mean temperatures and daily precipitation sums for the years 2009 and 2010 are displayed. Again, the differences between the two years are most striking in winter. In 2009, the temperature variability is very high, and several warming events with temperatures up to almost -30 °C can be seen. Minimum temperatures ~~barely exceed~~are rarely lower than -70 °C whereas in 2010, minima are close to -80 °C. The highest temperature in the winter of 2010 was only slightly above -50 °C. The winter 2009 thus was not only a “coreless winter”, but had a “warm” core due to the high number of warm air intrusions.

A very high value precipitation value of 1.36 mm on 9 February 2010, followed by 0.67 mm on 10 February, both classified as diamond dust from the photographic crystal analysis, stems from only one event around 9 February. These values should be considered with care given the high error possibilities of the measurements. Considering the extremely low density of diamond dust, a diamond dust amount of more than 1mm/day seems to be unlikely. However, the model data do show a precipitation event connected to warm air advection from the north (see below) for this day, which would indicate the occurrence of snowfall rather than diamond dust. Most likely a mixture of crystal types was found during this event with the diamond dust on top of the snow crystals, which possibly led to the classification of the event as diamond dust. (Note that the crystal classification was carried out purely from photographs by an expert at the Avalanche Institute in Italy and that snow crystals are also comparatively small at the temperatures prevailing at Dome C). The precipitation totals for May to

September are 12.0 mm w.e. for 2009 and 4.3 mm w.e. for 2010. Daily sums exceed 0.25 mm only three times in 2010, but 16 times in 2009. Usually, high daily precipitation amounts are associated with relative maxima in air temperature. In general, the winter of 2010 was cold and dry, whereas 2009 was relatively warm and moist compared to the long-term average.

Figure 4a shows monthly precipitation amounts for 2009 and 2010, distinguishing between diamond dust, hoar frost, and snowfall; Figure 4b gives the relative frequencies of the three different observed types of precipitation for both years. Again, large differences between 2009 and 2010 are found. While approximately half of the precipitation fell as snow in 2009, less than a quarter of the total precipitation stemmed from snowfall in 2010, when mostly diamond dust was observed. As seen before, the winter months of May to September exhibit the largest differences. In particular, the extremely “warm” July of 2009 brought high amounts of snowfall. The lowest amounts of precipitation are seen in austral summer 2009/2010, with no precipitation observed in November and only very small amounts in December and January.

The total amount of precipitation measured on the raised platform is 16.5 mm w.e. for 2009 and 13.4 mm w.e. for 2010, compared to the mean annual accumulation of 25 mm w.e. derived from firn core and stake measurements (Frezzotti et al., 2005). From the ~~given~~available data it cannot be determined whether the difference is due to snow removed from the measuring platform by wind or sublimation or snow added to the snow surface by wind (blowing or drifting snow) or deposition (re-sublimation).

5.2 Atmospheric flow conditions

5.2.1 Synoptic analyses with AMPS archive data

The synoptic situations that caused precipitation at Dome C were analysed using WRF output data from the AMPS archive. In particular, fields of 500hpa geopotential height and 24-h precipitation were used. For the 500hPa geopotential height information the 12-h forecast was utilized. For 24-h precipitation, the 12-36h forecast sums of precipitation (rather than 0-24h) were used to allow for model spin up of clouds and microphysical fields. This is considered long enough for moist process spin-up, but avoids error growth reflected in longer forecast times (Bromwich et al., 2005).

For all precipitation events with observed daily sums exceeding 0.2mm, the synoptic situations that caused the precipitation were investigated. In total, 29 events were studied, 20 in 2009 and 9 in 2010. For 2009 (2010), the model showed precipitation at Dome C in 44% (50%) of the studied cases and precipitation in the vicinity in 33 (25) % of the cases; no precipitation was shown in the model in 22 (25) % of the cases. In total, approximately half of the precipitation events were represented well by the model, one quarter showed synoptic events that did not bring precipitation exactly at the location and time of the measurements, and one quarter of the cases were not forecast by the model at all. An exact quantitative analyis of the model skill using the entire data series starting in 2006 is ongoing and the results will be more meaningful than those of only two, not very typical, years.

Generally, snowfall events were found to be associated with an amplification of the Rossby waves in the circumpolar westerlies, which causes a northerly flow across the Dome C region between a trough to the west and an upper-level ridge to the east of Dome C. This northerly flow brings relatively warm and moist air from as far as 35 °S - 40 °S to the East Antarctic plateau, leading to orographic precipitation when it is forced to ascende on the way from the coast to the high-altitude interior. Variations of this general situation are due to the duration of the flow pattern (e.g. whether there is a blocking anticyclone or not) and the strength of the upper-level ridge, which determines how far north the main moisture origin is situated. Figure 5 shows an example of this synoptic situation typical for snowfall events. In the 500hPa geopotential height field (Fig. 5a) for 13 September 2009 the amplified ridge that leads to a northerly flow towards Dome C can be seen slightly east of Dome C, with an axis tilted in a NE-SW direction. Figure 5b displays the 24-h precipitation caused by the N-NE flow onto the continent. Dome C is situated at the southeastern edge of the precipitation area.

Using the WRF output, three-dimensional 5-day back-trajectories were calculated for for arrival levels of 300hPa, 500hPa, and 600hPa (Fig. 5c) for this event. These levels were chosen as 600 hPa is close to the surface of Dome C (note that surface pressure can be lower than 600hPa at times, too), while 500hPa and 300hPa yield information about the large-scale atmospheric flow. The trajectories were calculated with the graphics software RIP. RIP stands for “**R**ead/**I**nterpolate/**P**lot” and is a Fortran program that invokes NCAR Graphics routines for the purpose of visualizing output from gridded meteorological data sets, which includes trajectory calculations (Stoelinga, 2009). The three-dimensional displacement of an air parcel during a time step Δt is calculated using an iterative scheme:

$$X_{n+1} = X_0 + \Delta t/2\ [v(X_{0,t}) + v\ (X_{n,t} + \Delta t)], \qquad \text{(Eq. 1)}$$

where Δt is the iteration time step, X_0 the position vector of the parcel at time t, X_n the nth iterative approximation of the position vector at time t + Δt and v(X,t) the wind vector at position X and time t. The time step we used was 600s. For simplicity's sake, RIP does not define a threshold for convergence, but simply does two iterations for each time step, which turned out to be exact enough in the praxis for our purposes. The resolution of the input data corresponds to the resolution of AMPS/WRF during the respective time period. The data are linearly interpolated in time and space. Taking into account the large uncertainties in trajectory calculations, for this case a main moisture source at approximately 40 °S was estimated. Note, that the moisture source is not defined as the location of the trajectory five days previous to the precipitation. Instead, f~~F~~or this estimate, the combined information of the trajectories and the 500hPa geopotential height fields is used. Different from the approach of Sodemann and Stohl (2009) and Sodemann et al. (2008), who calculated 20-day back-trajectories, for a 5-day trajectory it is possible to comprehend the dynamics of the synoptic situation that causes the precipitation. That way the trajectory results can be cross-checked with the geopotential height fields. Even though the trajectory not explicitely deals with moistuer, it gives information about the origin of the moist air mass. The northernmost "point" of the trough that causes the northerly flow to Dome C is supposed to be the northern limit of the potential moisture source since no substantial meridional flow is observed north of this limit. (The 500hPa trajectory seems to have some inconsistencies (e.g. kinks) on the 5th day, which should not be over-interpreted). Whereas it is not possible to exactly determine the moisture source (under the simplifying assumption of a single moisture source) with this simple method, the information is sufficient to distinguish between a source in the Southern Ocean and one at middle latitudes, which is most important for ice core interpretation and for simple isotope modeling.

A frequent occurrence of the synoptic situation described (as it was the case in 2009) means a more northern mean moisture source than on average, which has to be taken into account for deriving air temperature from stable isotopes. (A detailed study using trajectory calculations for all observed precipitation events at Dome C is ongoing.) It was also found to be typical for precipitation events at Dome C that the main westerly flow is split into a~~ meandering branch and a~~ northern branch that remains zonal, whereas the southern branch starts meandering with a strong meriodional component.~~.~~ This is observed more often at Dome C than at Dome F (Dittmann et al., 2015) or at Kohnen Station (Schlosser et al., 2010a).

Figure 6 presents an~~n~~ example for a case with no precipitation in the model, but relatively large observed precipitation amounts. The 500hPa geopotential height field (Fig. 6a) shows a cutoff-high west of Dome C on the day after the precipitation event shown in Figure 5. The remaining atmospheric moisture is not sufficient to produce precipitation in the model (Fig. 6b), but it does lead to remarkably high amounts of diamond dust and/or hoar frost (0.7 mm observed during this event). This synoptic situation was also found by Hirasawa et al. (2013) in a detailed study of the synoptic~~s~~ conditions and precipitation during and after a blocking event at Dome Fuji. (Note that neither diamond dust nor hoar frost formation is specifically parameterized in the model.) In 2010, the flow was mainly zonal and the synoptic situations described above were much less frequent than in 2009 and not as strongly developed.

Using the WRF output, monthly composite fields of 500hPa-geopotential height were calculated to compare the general flow conditions in 2009 and 2010. Figure 7 shows the composite mean 500-hPa geopotential height for July 2009 and 2010, respectively. Even in the monthly mean, the distinct upper-level ridge in 2009 that projects onto the East Antarctic plateau and leads to warm air advection and increased precipitation at Dome C is clearly seen.

In 2010, in the monthly average, the flow was mainly zonal, which reduced the meridional exchange of heat and moisture, thus leading to lower temperatures and less precipitation in the interior of the Antarctic continent.

5.2.2 Southern Annular Mode

The occurrence of high-precipitation events on the Antarctic plateau due to amplification of Rossby waves is often connected to a strongly positive phase of the Southern Annular Mode (SAM). The SAM is the dominant mode of atmospheric variability in the extratropical Southern Hemisphere. It is revealed as the leading empirical orthogonal function in many atmospheric fields (e.g. Thompson and Wallace, 2000), such as surface pressure, geopotential height, surface temperature, and zonal wind (Marshall, 2003). Since pressure fields from global reanalyses commonly used to study the SAM are known to have relatively large errors in the polar regions, Marshall (2003) defined a~~n~~ SAM index based on surface observations. He calculated the pressure differences between 40 °S and 65 °S using data from six mid-latitude stations and six Antarctic coastal stations to calculate the corresponding zonal means. A large (small) meridional pressure gradient corresponds to a positive (negative) SAM index ~~and vice versa~~. The positive index means strong, mostly zonal westerlies and comparatively little exchange of moisture and energy between middle and high latitudes, which leads to a general cooling of Antarctica, except for the Antarctic Peninsula that projects into the westerlies. A negative SAM index is associated with weaker westerlies and a larger meridional flow component.

Figure 8 shows the monthly mean SAM index for 2009 and 2010 (data can be found at http://www.nerc-bas.ac.uk/icd/gjma/sam.html). Whereas in the winter months (May to September) of 2009 the SAM index was generally negative (with the exception of a weakly positive value in June), 2010 has positive indices from April to August, with strongly positive values in June and July, and only a weakly negative index in September. This is consistent with the pattern of a strong zonal flow with few precipitation events at Dome C due to amplified ridges in the winter of 2010, with the opposite situation holding in 2009. The highest SAM index is found in November 2010; however, in austral summer the relationship between the SAM index and precipitation seems to be less straightforward. The differences between 2009 and 2010 are not extraordinarily high compared to other years (e.g. 2001/2002 as seen at http://www.nerc-bas.ac.uk/public/icd/gjma/newsam.spr.pdf), however, qualitatively they are in agreement with the observed flow pattern. Furthermore, it should be kept in mind that SAM explains only about one third of the atmospheric variability in the Southern Hemisphere (Marshall, 2007) and that the SAM index alone gives no information about the location of respective ridges and troughs in a highly meridional flow pattern..

5.2.3 Zonal wave number 3

Another method to investigate the general atmospheric flow conditions is to analyse spatial and temporal variations of the quasi-stationary zonal waves in the Southern Hemisphere. In this study zonal wave number 3 (ZW3) is used. While the atmospheric circulation in the Southern Hemisphere appears strongly zonal (or symmetric), there is a significant non-zonal (asymmetric) component and ZW3 represents a significant proportion of this asymmetry. It is a dominant feature of the circulation on a number of different time scales (e.g. Karoly, 1989), is responsible for 8% of the spatial variance in the field (van Loon and Jenne, 1972), and contributes significantly to monthly and interannual circulation variability (e.g. Trenberth, 1990; Trenberth and Mo, 1985). The asymmetry is revealed when the zonal mean is subtracted from the geopotential height field thereby creating a coherent pattern of zonal anomalies, with the flow associated with these patterns becoming apparent. ZW3 has preferred regions of meridional flow, which influence the meridional transport of heat and moisture into and out of the Antarctic. Raphael (2004) defined an index of ZW3 based on its amplitude (effectively the size of the zonal anomaly) at 50^{o}S showing that ZW3 has identifiable positive and negative phases associated with the meridionality of the flow. A positive value for this index indicates more meridional flow (large zonal anomaly) and a negative value more zonal flow (small zonal anomaly). Note that the ZW3 index used here does not fully capture the shift in phase of the wave. However, Raphael (2004) found that the net effect is a small reduction in the amplitude of the wave, but the sign of the index is not influenced. A new approach for identifying Southern Hemisphere quasi-stationary planetary wave activity that allows variations of both wave phase and amplitutde is described in a recent study by Irving and Simmonds (2015).

Figure 9a shows the monthly mean ZW3 index for the period 2009–2010. From June to September 2009 the ZW3 index was largely positive except for a comparatively small negative excursion in July. On the contrary, from June to September 2010 it was negative. The asymmetry in the circulation suggested by the index is shown in Figure 9b (July 20090 and 9c (July 2010). These figures were created by subtracting the long-term zonal mean at each latitude, from the mean 500-hPa geopotential height field in July 2009 and 2010, respectively. The flow onto Dome C suggested by the alternating negative and positive anomalies is northerly in July 2009, but has a strong zonal component in July 2010. This information given by the ZW3 index and the patterns of zonal anomalies is consistent with that suggested by the SAM.

5.3 Stable Isotopes

Since the main motivation of the presented precipitation study is the improvement of the climatic interpretation of stable isotope data, in Figure 10 the daily mean temperature and the measured stable isotope ratios of the precipitation samples, namely δ^{18}O and the second-order parameter deuterium excess d (d= δD-8 δ^{18}O~~, globally averaged~~), are displayed for 2009 and 2010. As expected, δ^{18}O and air temperature exhibit a similar annual cycle, with high values in summer and the lowest values in the winter months. Consistent with the unusually “warm” winter of 2009, also the δ^{18}O reaches higher values in winter 2009 than in winter 2010. Because of the more meridional flow and thus more northerly (and warmer) oceanic moisture source, the initial δ^{18}O is already higher than on average and the condensation temperature at

Dome C is above-average during the precipitation events as well. In addition to the warm-air advection, the existing near-surface temperature inversion layer is often removed because of increased wind speed and increased cloud cover, the latter causing a change in the radiation balance, namely increased down-welling long-wave radiation. In contrast to $\delta^{18}O$, the deuterium excess shows maxima in winter and minima in summer. In winter 2010, the deuterium excess is clearly higher than in 2009; the difference between the maxima in 2009 and 2010 amounts to 20 **‰**. A comprehensive analysis of the full stable isotope data set of Dome C can be found in a companion paper by Stenni et al. (2015).

6 Discussion and Conclusion

In the present study that was motivated by stable water isotope studies, atmospheric conditions~~Precipitation and stable water isotope data from~~of the two contrasting years 2009 and 2010 at the Antarctic deep-drilling site Dome C, on the East Antarctic Plateau were investigated using observational precipitation and temperature data and data from a mesoscale atmospheric model~~in the present study~~. The observations from Dome C ~~are~~represent the first and only multi-year series of daily precipitation/stable isotope measurements at a deep-drilling site, even though “multi” means only nine years in this case. The differences between the two years 2009 and 2010 were most striking in winter. Whereas 2009 was relatively warm and moist due to frequent warm air intrusions connected to amplification of Rossby waves in the circumpolar westerlies, the winter of 2010 was extremely cold and dry, with the lowest monthly mean July temperature observed since the beginning of the AWS measurements in 1996. This can be explained by the prevailing strong zonal flow in the winter of 2010, related to a strongly positive SAM index and a negative ZW3 index. Also, the frequency distribution of the various precipitation types was largely different in 2009 and 2010, with snowfall prevailing in 2009 whereas diamond dust was dominant in 2010.

Similarly striking differences in weather conditions of 2009 and 2010 were seen in other parts of East Antarctica. Gorodetskaya et al. (2013) found that accumulation in 2009 was eight times higher than in 2010 at the Belgian year-round station “Princess Elisabeth”. At this loca~~ta~~tion, the temperature was also higher in 2009 than in 2010, particularly in fall/early winter. The findings are supported by Boening et al. (2012), who used observations from GRACE (Gravity Recovery And Climate Experiment) and found an abrupt mass increase on the East Antarctic ice sheet in the period 2009-2011. Similarly, Lenaerts et al. (2013) investigated snowfall anomalies in Dronning Maud Land, East Antarctica. They state that the large positive anomalies of accumulation found in 2009 and 2011 stand out in the past approximately 60 years although comparable anomalies are found further back in time.

Distinguishing between the different forms of precipitation, namely diamond dust, hoar frost and dynamically caused snowfall, is important for both mass balance and ice core interpretation. For mass balance, the different precipitation types do not have to be known if the surface mass balance is determined as an annual value from snow pits, firn/ice cores or stake arrays. For temporally higher resolved precipitation measurements, however, a fraction of both hoar frost and diamond dust might be just a part of the local cycle of sublimation and deposition (re-sublimation), thus representing no total mass gain. More detailed measurements are thus necessary to allow a better understanding of the processes involved. This also applies to isotopic fractionation during this cycle; continuous measurements of water vapour stable isotope ratios (e.g. Steen-Larsen et al., 2013) should be included here.

For ice core interpretation, the problem generally becomes more complex. Diamond dust is observed during the entire year without a distinct seasonality. Therefore a signal from an ice core property measured in the ice (in contrast to measured in the air bubbles) will have contributions from diamond dust that stem nearly equally from all seasons. Although snowfall events are not very frequent at deep ice core drilling sites, they can account for a large percentage of the total annual precipitation/accumulation at those locations. If these events have a seasonality that has changed between glacials and interglacials, a large bias will be found in the temperature derived from the stable isotopes in ice cores. Today, the frequency of such snowfall events shows a high inter-annual variability, but both frequency and seasonality of the events might be different in a different climate due to changes in the general atmospheric circulation and in sea ice extent (e.g. Godfred-Spenning and Simmonds, 1996). Since it was found that snowfall events are connected to the synoptic activity in the circumpolar trough, it is plausible that the seasonality of such events was different during glacial times because the sea ice edge and the mean position of the westerlies were considerably farther north than today. This influences the zone of the largest meridional temperature gradient, thus the largest baroclinicity and consequently cyclogenesis. A larger sea ice extent might reduce the number of snowfall events in the Antarctic interior in winter by pushing the zone of largest baroclinicity northwards. However, it is not possible to assess such hypotheses using observational data since the instrumental period, with few exceptions, started in Antarctica with the IGY (International Geopyhysical Year) 1957/58. However, modelling studies can be supported by studies of the physical processes in the atmosphere using recent data, and, in particular, cases of extreme situations can be helpful here. Even if the full amplitude of the change between glacial and interglacial climates is not observed, extrema can give insight into the sign and kind of the reaction of the system to a change in one or several atmospheric variables.

Another implication for ice core interpretation derived from the present study is that a more northern moisture source does not necessarily mean larger isotopic fractionation (which is usually assumed in ice core studies (e.g. Stenni et al., 2001; 2010). Even though the temperature at the main moisture source is higher than on average for a northern moisture source, the depletion in heavy isotopes is comparatively small because the temperature at the deposition site is also clearly higher than on average due to the warm air advection, which reduces the temperature difference between the moisture source region and the deposition site, thus the amount of isotopic fractionation.

Looking towards future work, the results here indicate that a combination of process studies using recent data and modelling of the atmospheric flow conditions on larger time scales will lead to a better quantitative interpretation of ice core data. Apart from the factors influencing precipitation itself, it has become clear recently that post-depositional processes between snowfall events are more important than previously thought because, additionally to processes within the snowpack, the interaction between the uppermost parts of the snowpack and the atmosphere is very intense (Steen-Larsen et al., 2013). Parallel measurements of stable isotope ratios of water vapour and surface now, combined with meteorological data will give more insight into these processes in Antarctica.

Altogether, this means that the relationship between air temperature and stable isotopes of Antarctic precipitation/ice is anything else but straightforward, since the isotope ratio measured in an ice core (or in the snow) is the result of a complex precipitation history that is strongly influenced by the synoptics and general atmospheric flow conditions, followed by post-depositional processes. Without thorough knowledge of all the processes involved a quantitatively correct derivation of paleo temperatures from ice core stable water isotopes is thus not possible.

Author contribution

BS is responsible for the precipitation measurements and stable isotope analysis, MV and AC for the crystal analysis. MR did the ZW3 study. MD and KW assisted with software ~~depelopment~~development. ES prepared the manuscript with contributions from JP, KW, MR, and BS.

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Figure Captions

Fig. 1

Map of Antarctica indicating Dome C and other important deep-drilling sites in Antarctica

Fig. 2

AMPS domains used for model output analysis in this study

Fig. 3

a) Mean monthly temperatures for 2009 and 2010 at Dome C AWS

b) Daily precipitation and daily mean temperature at Dome C for 2009 and 2010

Fig. 4

Monthly precipitation at Dome C a) 2009 and b) 2010, distinguishing three different types of precipitation: diamond dust, hoar frost, and snowfall

Relative frequency of diamond dust, hoar frost, and snowfall for c) 2009 and d) 2010

The types were determined from photos of the crystals on the platforms by the Avalanche Research Institute, Arabba, Italy.

Fig. 5

a) 500hPa geopotential height from AMPS archive data (Domain 1) 13.9.2009 00Z

(The axis of the upper-level ridge mentioned in the text is marked by a bold black line.)

b) 24h-precipitation from AMPS 13.9. 2009 00GMT to 24 GMT

c) 5-day back-trajectories for parcels arriving at Dome C at 0000UTC 12.9.2009. Trajectories for three arrival levels are shown: 1. 600hPa, 2. 500hPa, 3. 300hPa

Fig. 6

Example for synoptic situation, during which precipitation is observed at Dome C, but not forecast by WRF in AMPS.

a) 500 hPa geopotential height, Domain 2.

b) 24h-precipitation total (mm) from AMPS

Fig. 7

Mean July- 500hPa geopotential height based on AMPS archive model output for 2009 and 2010.

Fig. 8

Mean monthly SAM index for 2009 and 2010 (after Marshall, 2003).

Fig. 9

a) Monthly mean Zonal Wave Number 3 (ZW3) index for 2009-2010

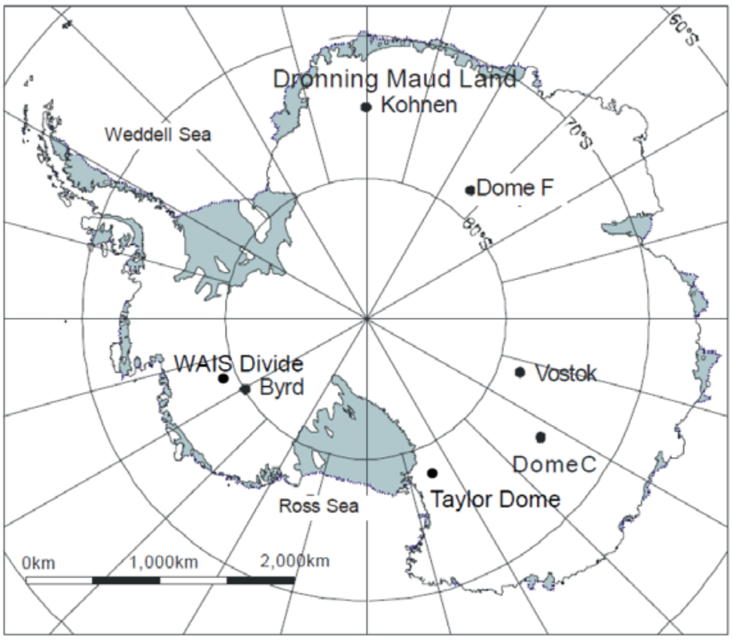
b) July 2009 500hPa geopotential height anomaly: Mean July 2009 height minus long-term zonal mean height

c) July 2010 500hPa geopotential height anomaly: Mean July 2009 height minus long-term zonal mean height

Fig. 10

Daily mean air temperatures at Dome C 2009 and 2010 from AWS and stable isotopes (δ^{18}O and deuterium excess) of corresponding precipitation samples

Fig. 1


60°S
Dronning Maud Land
Kohnen
Weddell Sea
70°S
Dome F
80°S
Vostok
WAIS Divide
Byrd
DomeC
Taylor Dome
Ross Sea
0km
1,000km
2,000km

~~Fig. 2~~

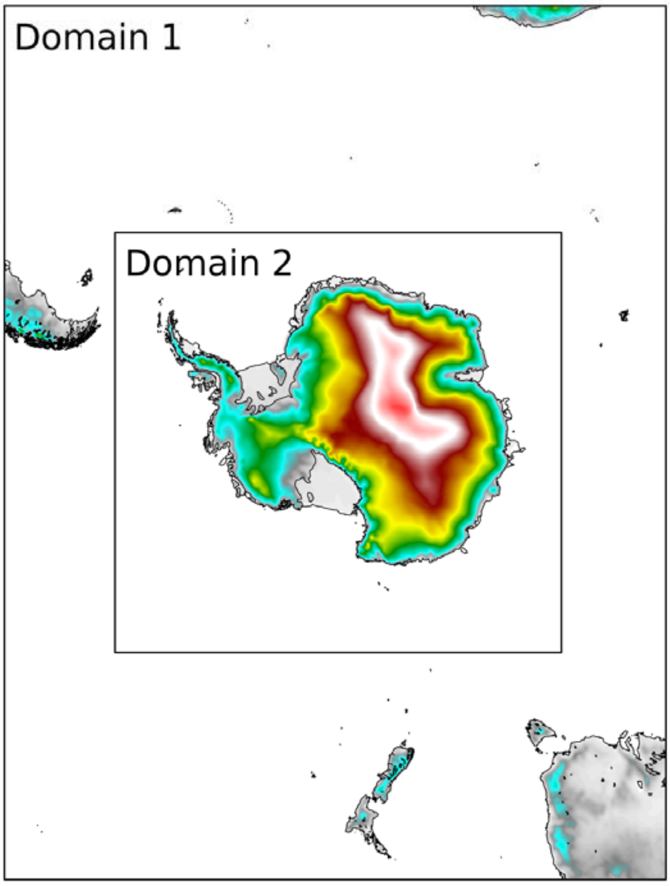
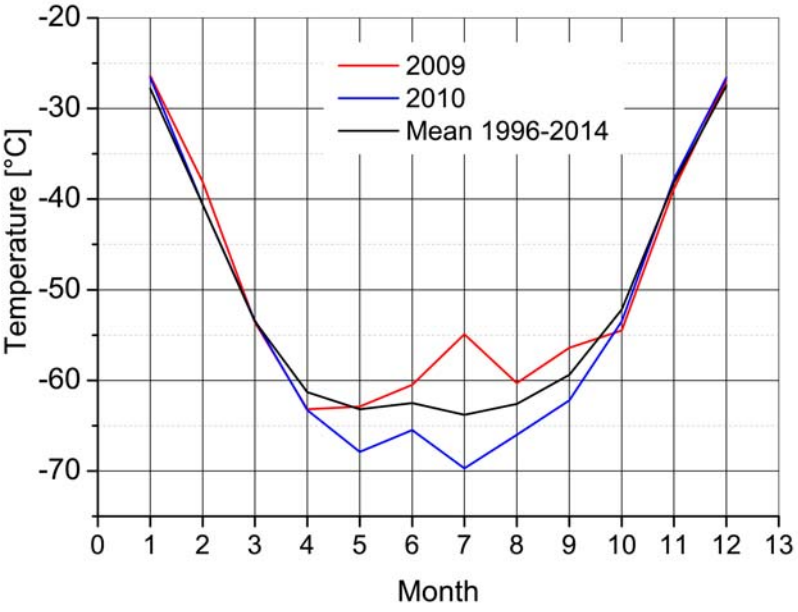


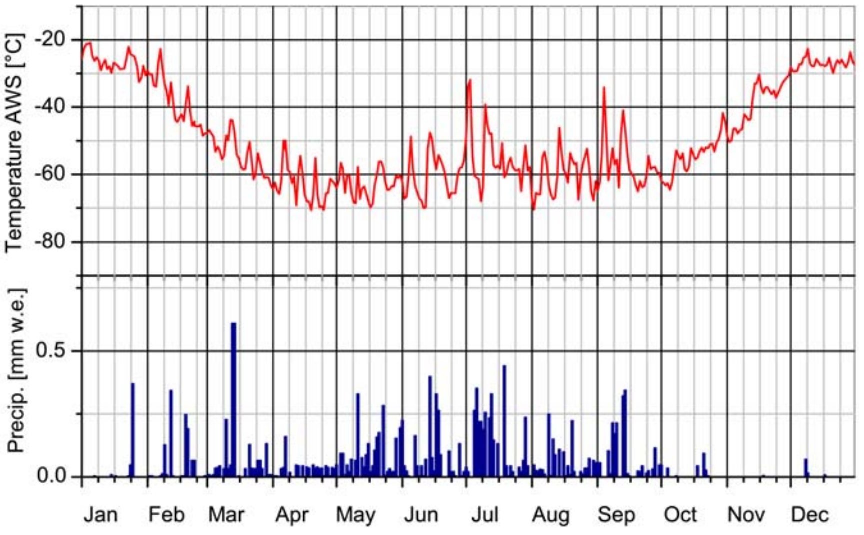
Fig. 3

a)


2009
2010
Mean 1996-2014
Temperature [°C]
-20
-30
-40
-50
-60
-70
0
1
2
3
4
5
6
7
8
9
10
11
12
13
Month

b)

2009


Temperature AWS [°C]
-20
-40
-60
-80
Precip. [mm w.e.]
0.5
0.0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

2010

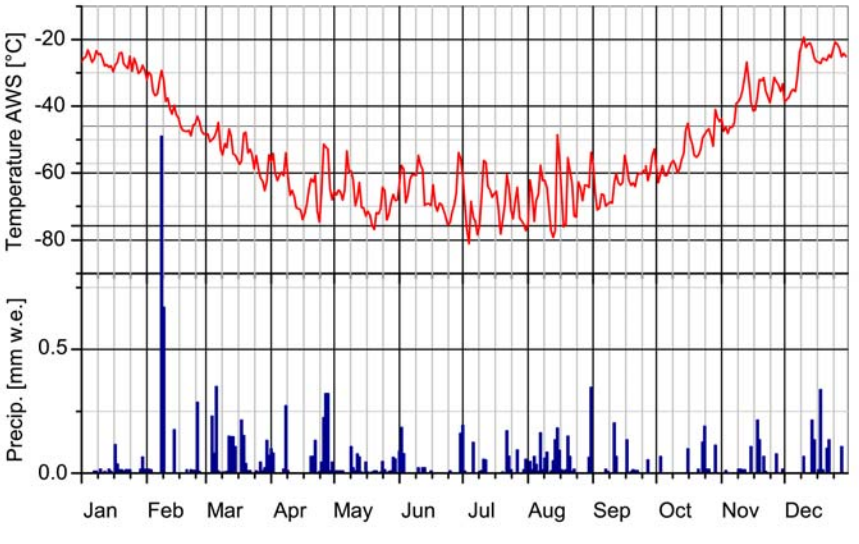
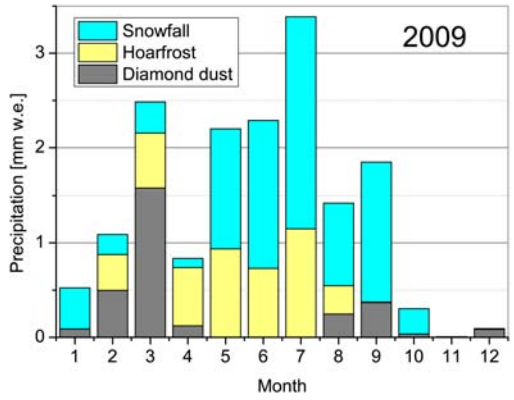
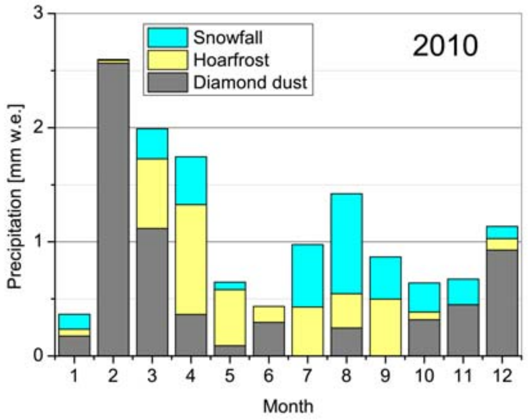

Temperature AWS [°C]
-20
-40
-60
-80
Precip. [mm w.e.]
0.5
0.0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

Fig. 4

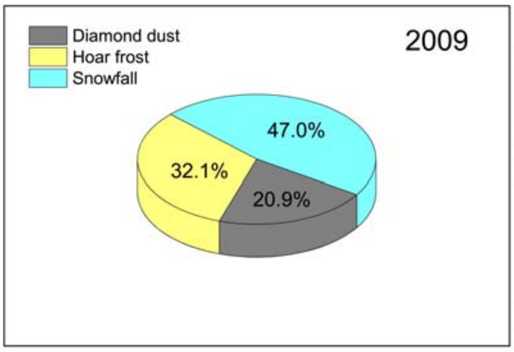
a) b)


Snowfall
Hoarfrost
Diamond dust
2009
Precipitation [mm w.e.]
0
1
2
3
1
2
3
4
5
6
7
8
9
10
11
12
Month


Snowfall
Hoarfrost
Diamond dust
2010
Precipitation [mm w.e.]
0
1
2
3
1
2
3
4
5
6
7
8
9
10
11
12
Month

c)

d)


Diamond dust
Hoar frost
Snowfall
2009
47.0%
32.1%
20.9%

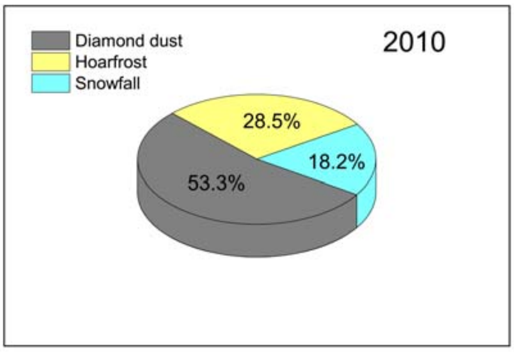
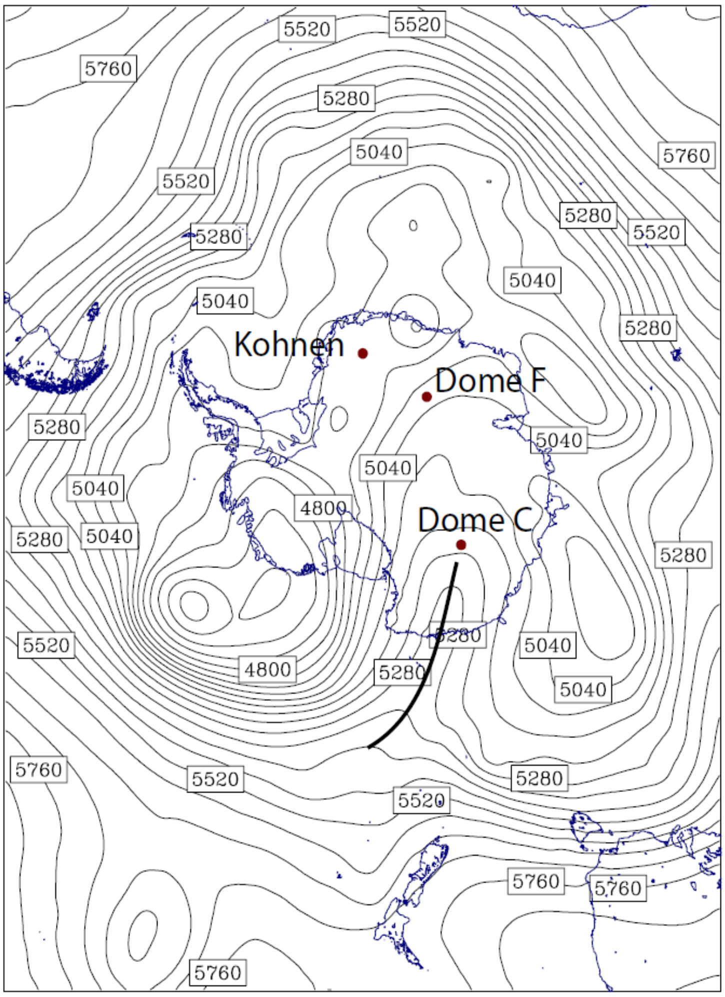
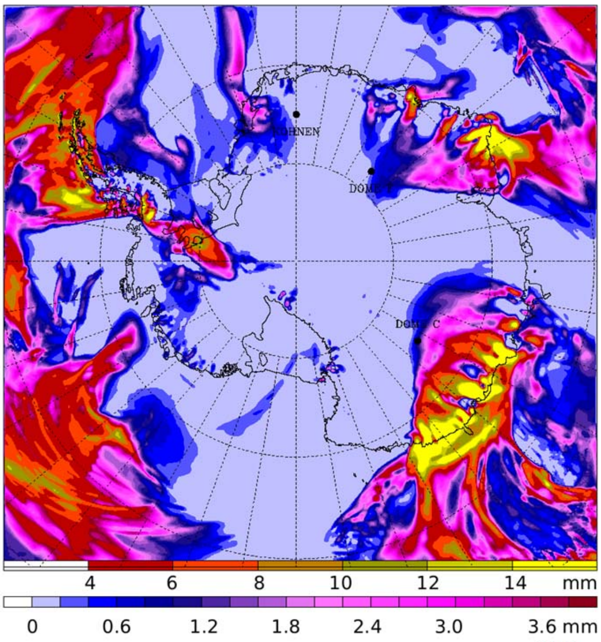

Diamond dust
Hoarfrost
Snowfall
2010
28.5%
18.2%
53.3%

Fig. 5

a)


5520
5520
5760
5280
5040
5760
5520
5280
5280
5520
5040
5040
Kohnen
5280
Dome F
5280
5040
5040
5040
4800
Dome C
5280
5040
5280
5280
5520
5040
4800
5280
5040
5760
5520
5280
5520
5760
5760
5760

b)


KOHNEN
DOME C
DOME C
4
6
8
10
12
14
mm
0
0.6
1.2
1.8
2.4
3.0
3.6 mm

c)

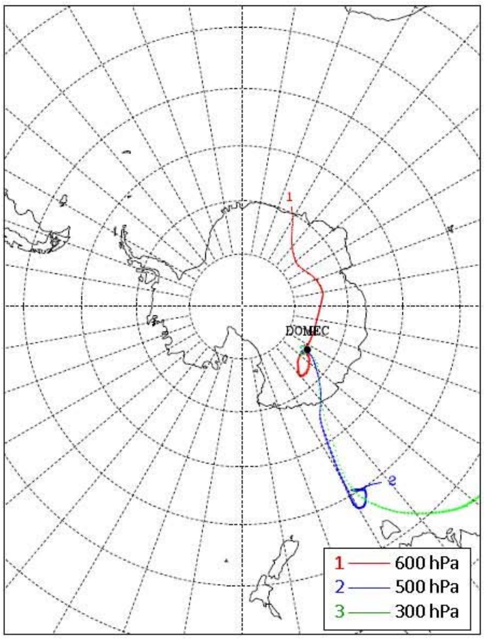
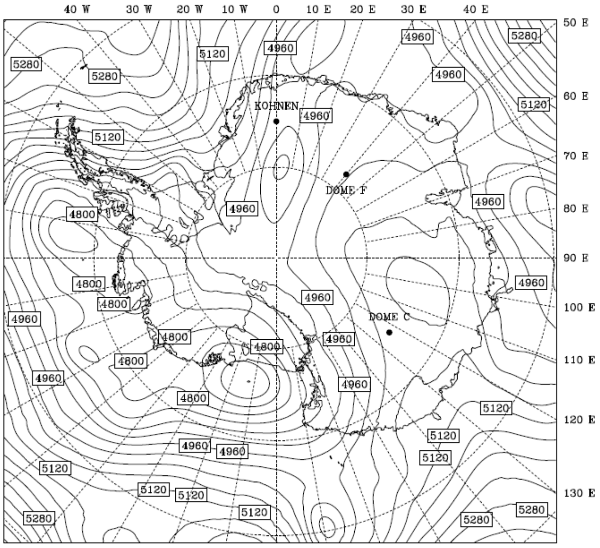

1
DOMEC
2
1 600 hPa
2 500 hPa
3 300 hPa

Fig. 6

a)


40 W
30 W
20 W
10 W
0
10 E
20 E
30 E
40 E
50 E
60 E
70 E
80 E
90 E
100 E
110 E
120 E
130 E
KOHNEN
DOME F
DOME C
4800
4960
5120
5280

b)

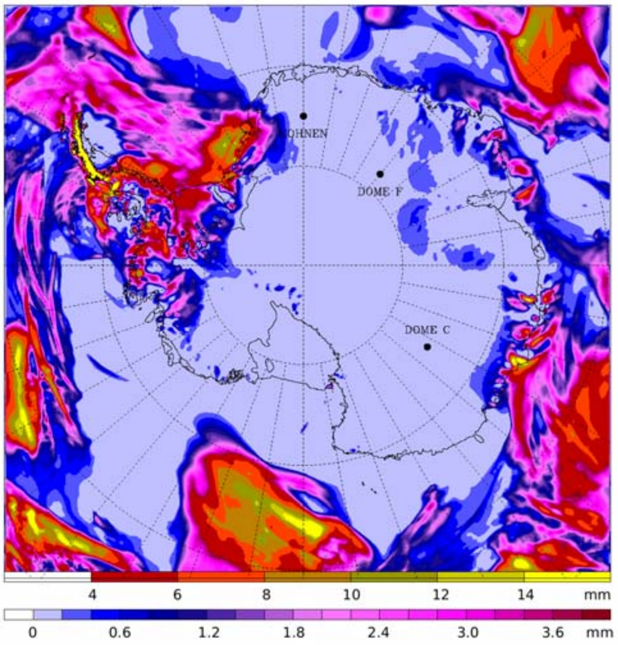
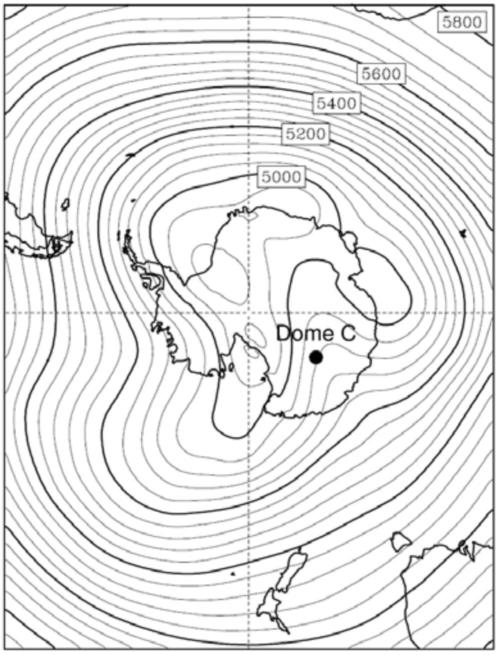

KOHNEN
DOME F
DOME C
4
6
8
10
12
14
mm
0
0.6
1.2
1.8
2.4
3.0
3.6
mm

Fig. 7

a) July 2009



b) July 2010

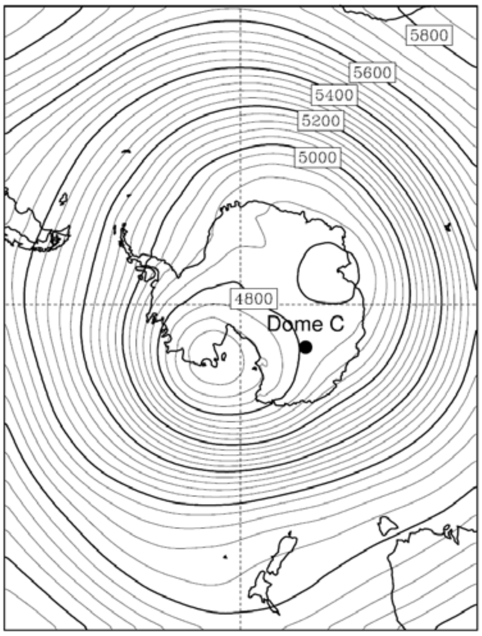


Fig. 8

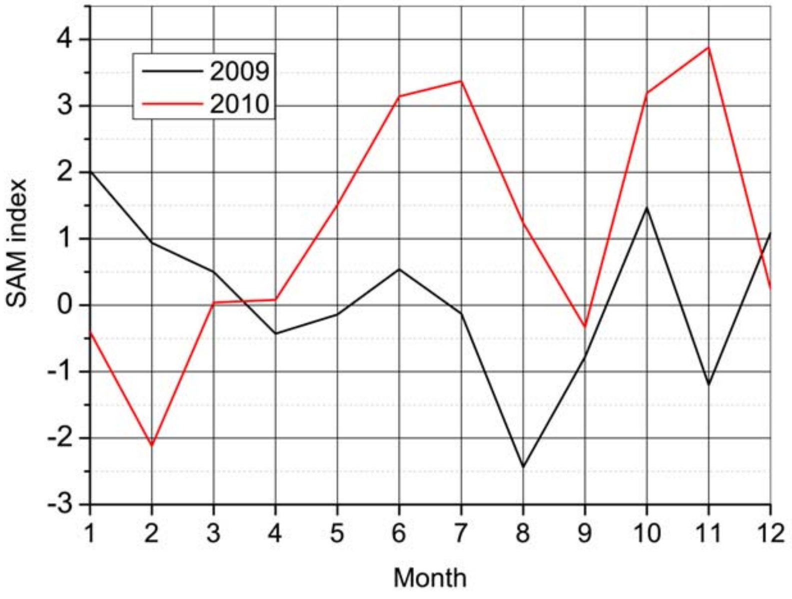
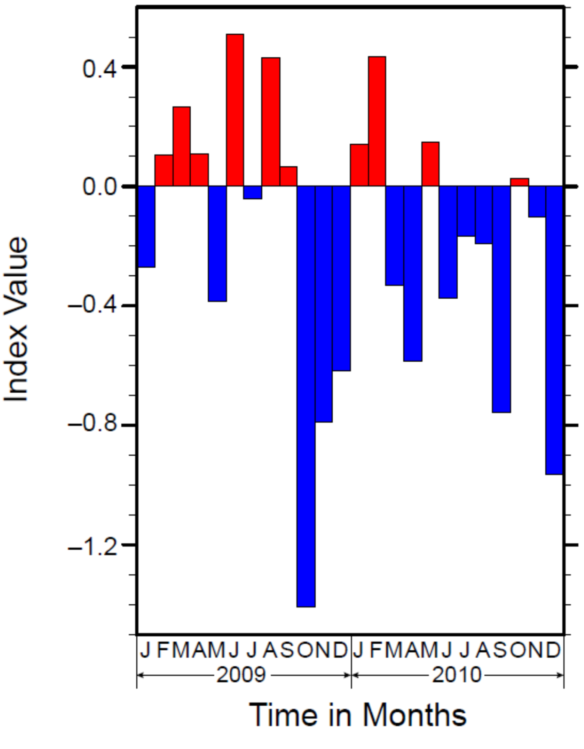
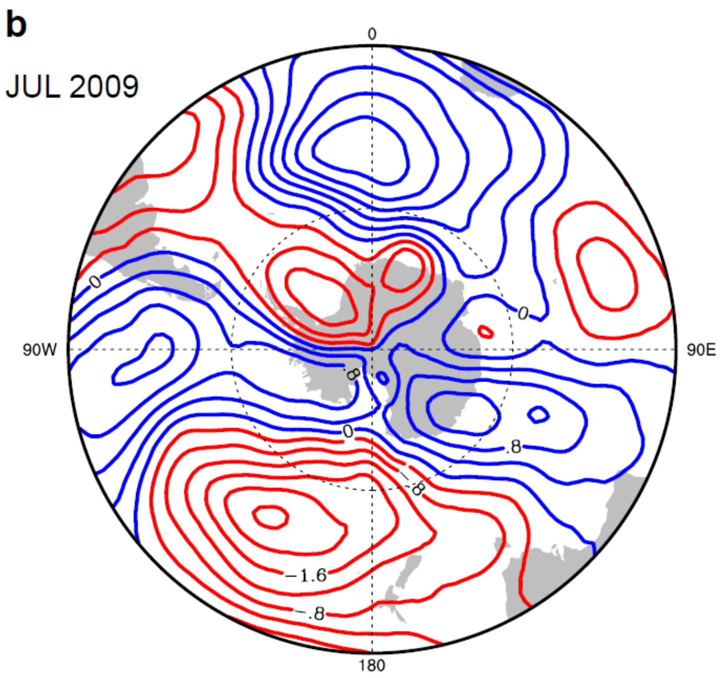


Fig. 9

a)


Index Value
0.4
0.0
−0.4
−0.8
−1.2
J F M A M J J A S O N D J F M A M J J A S O N D
2009
2010
Time in Months

b) 500hPa geopotential height: mean July 2009 minus long-term zonal mean



9 c) 500hPa geopotential height: mean July 2010 minus long-term zonal mean

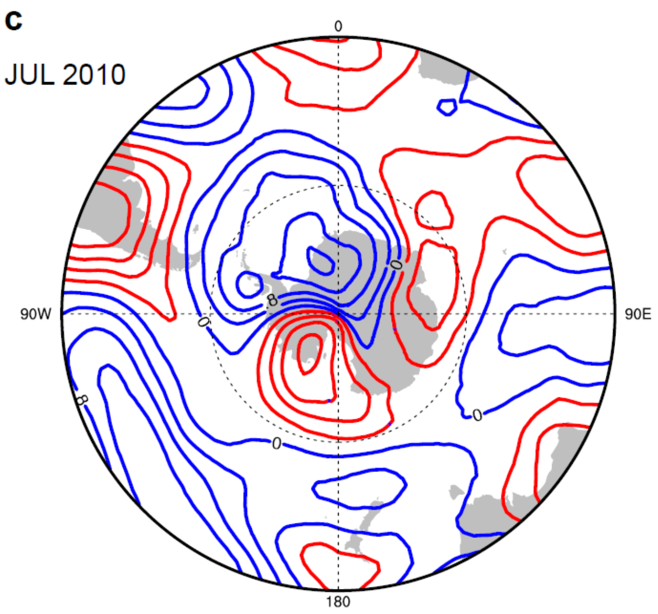
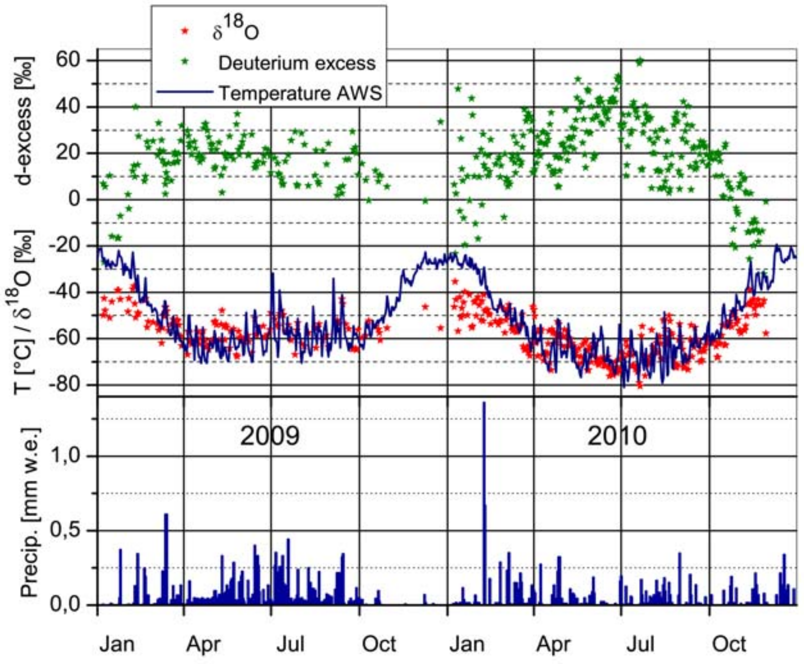


Fig. 10



Remark: for d-excess we prefer not to use a capital letter in the axis title because commonly "d" is defined as deuterium excess whereas "D" means deuterium.