

Below we provide point-to-point answers to the comments of the two reviewers and to the short comment by Eric Wolff. We thank the reviewers and Eric Wolff for their insightful comments that have helped to improve the manuscript. Reviewer comments are in black and our responses are in red.

Review by F. Parrenin (Referee)

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This manuscript presents an analysis of annual layers in a 5 m thick section of the Dome Fuji ice core during the Early Holocene period, as well as a synchronization of this section to the EDML and NGRIP ice cores by the mean of three common volcanic events.

The main conclusions are that:

- 1) it is possible to count annual layers in this section with a typical uncertainty of $\pm 10\%$
- 2) there are three common volcanic spikes with the EDML and NGRIP ice cores in the age interval
- 3) the results of the layer counting are compatible with the EDML and NGRIP layer counted chronologies
- 4) among the three volcanic spikes, 2 have corresponding high dust concentrations (tephra layers)
- 5) there is a so-called 'peculiar event' in the bottom part of the section, where the variations of the various proxies are very small. This event is suggested to be due either to snow redeposition by wind (sastrugi) or to a high precipitation event (blocking event).
- 6) the accumulation rate (3.0 ± 0.3) is slightly higher than what can be deduced from ice isotopes

This manuscript is useful for two reasons. First, it informs us on the snow accumulation process in central East Antarctica. In my opinion this is the most important aspect of the manuscript but it is not emphasized in the abstract. Second, it opens an interesting perspective on the annual counting of the Eemian section of the Dome Fuji ice core, a period for which we currently don't know the duration better than a few kyr. For the second point, I have a question that the authors might want to discuss in the manuscript.

What is the best location in Antarctica for counting the Eemian? There is a compromise to be found between a high accumulation rate and a high thinning factor, so this question is not completely trivial. Is Dome Fuji really among the best locations?

Based on the present study alone, we cannot judge which Antarctic ice core would be most suited for resolving the Eemian in annual resolution, but we can of course list the approximate thickness of the Eemian section in the Antarctic ice cores:

EDC: Eem covers ca 250m depth interval (1510-1760m)

DF: Eem covers ca 200m depth interval (1610-1810m)

Vostok: Eem covers ca 300m depth interval (1600-1900m)

This information is now given at the end of the manuscript.

The manuscript is clear and concise so I have very few technical comments.

- abstract: the conclusions regarding the accumulation process at DF should be emphasized here.

Included.

- p. 812, l. 9: Note that Parrenin et al. (CP, 2007) also found that the accumulation at DC during the Early Holocene period was larger than what can be inferred from the ice isotopes. I therefore suggest to add to this sentence: '..., in agreement with what was inferred at EPICA Dome C (Parrenin et al., 2007)."

Included.

- p. 815, l. 2: the 'peculiar event' is now called 'P3 tail event'. Please use a consistent denomination.

Changed.

- p. 815, l. 3-13: I suggest to start this paragraph with 'Another possible explanation for the event is related to unusual meteorological conditions'. Then, the fact that it might be related to the volcanic event is only a sub-hypothesis inside this 'meteorological' hypothesis.

Changed.

- p. 815, l. 19-21: remove this sentence this the 'peculiar event' is already described in the following paragraph.

Removed.

- figure 1: there are strange grey lines in this figure that are not described in the legend.

The grey lines are now described as traverse tracks.

Short comment by EW Wolff

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This is a valuable paper, showing the kinds of features that can be resolved, even at low accumulation rate sites. It indeed shows that features of an annual nature may be resolved. I do not propose to carry out a full review but would like to make two comments.

The first comment concerns the "peculiar event". This is indeed strange. My first thought was that the high concentrations in the adjacent volcanic peak had induced movement of chemistry out of the sides of the peak. There are several documented examples of acidic anions such as nitrate and fluoride being "pushed out" of volcanic peaks, leaving a "hole" under the volcanic peak, and higher concentrations on the shoulders. Presumably this occurs in firn. By analogy, one might imagine ammonium being "sucked" into the acidic volcanic peak, causing a depletion on the side, and a peak (as observed) under the volcanic peak. However, this would not explain the situation for Na, the absence of any effect on the deep side of the volcano, nor the lack of effect in other such events. I therefore do not believe this is the explanation, but present it here just for completeness. The authors toy with the idea that the homogeneity is the result of a large sastrugi being formed: however the flat section is 20 cm thick, which would require a 50 cm surface feature, much larger than the sastrugi typically observed at sites on the plateau.

I therefore cannot explain the event, but I think the authors need to absolutely establish that it is real before they publish it. It has something of the look of an analytical issue, with sensors losing sensitivity for what would be about 10 minutes, after the acidic melt has passed. I am sure the authors would think this very unlikely but it can easily be checked. The authors must have core sections remaining. They could simply cut 20 samples at 1 cm resolution across this section and analyse them by ion chromatography.

If the resulting depth profile is still flat (as I hope), they have proven that the event is real. I would strongly recommend such a check before putting such a mystery into the literature for us all to worry about.

Indeed, this is a strange event and we admit to not being able of giving a satisfactory explanation for it. We have, however, considered some of the possibilities mentioned above:

- The core was melted and analyzed from top to bottom. Therefore, the peculiar event was analyzed before the large acidity peak (P3) was melted. Furthermore, there is a bag separation just above the P3 peak (at 306.40m depth), so the peculiar event has been physically separated from the acidity peak during measurement.

- The DEP curve shown in Figure 2 and now also in Figure 4 was performed in Japan after the CFA analysis on a parallel section of the core. Across the peculiar event, the DEP curve has a very similar shape to that of the meltwater conductivity. We take this as a sign (but not a proof) that the chemistry records are those of the ice and not an analytical artefact.

- Unfortunately, there is not sufficient ice core sample left in the granted ice core section to perform high resolution IC analyses. It is questionable that we would learn much more from such IC analysis than what we already see in the DEP profile. Neither of these techniques are able to resolve the high frequency (annual) variability.

My second comment concerns the implications of seeing some annual signals. I agree that some annual features can be seen, and in this sense, annual layers (perhaps even in the Eemian) may be resolved. However, the paper takes the extra step, in its very last sentence, of suggesting that a "counted time scale can be established" at Dome F.

I think this is wildly optimistic, and perhaps points to some questions we should revisit about the philosophy of annual layer counting. In this case, it is accepted that a significant number of annual layers are missing. In addition, Figs 3 and 4 make it obvious that layer counting in the traditional sense has not been achieved throughout the sequence.

Taking for example the section from 304.2-304.4 m, I would count maybe 3 peaks, while the figure shows 7 certain and one uncertain. Like the authors, I would know already that the accumulation rate is about 3 cm, so I would insert extra year marks to achieve about the right spacing. However this is not layer counting - it is assigning of year dividers in a section where we think we already know the number of years. The authors assign "certain" years to sections with no chemical indication of a year, and thus end up with a 10% uncertainty, which seems unrealistically low if based only on the chemistry.

It has only been achieved because the prior assumption of layer thickness leads to a tight condition on the allowable gap between counted layer marks. To me, this becomes circular, and it is not clear if the counting itself improves the chronology that would already be estimated based on the presumed layer thickness.

I don't want to give the wrong impression. I think that layer counting is an ideal way to establish a chronology when the layers are sufficiently clear and generally present.

This is the case for example in most of the counted GICC05 age model, and in the counted section of the WAIS Divide core. However as soon as that is not the case layer counting becomes layer marking, and I do not expect it to improve our chronological uncertainty. I think this issue, even if the authors disagree, needs to be acknowledged.

I would personally recommend removing that last sentence from the paper, as I think it raises false expectations, perhaps even for the authors themselves.

Maybe we have been too much on the optimistic side concerning the establishment of a counted time scale for the Eemian section of Dome F. We now modified the last sentence to 'The present study suggests that annual layer counting in the Antarctic Eemian period may help to constrain the chronology of that section, if annual layers are preserved'. Bearing in mind that the duration of the Eemian section of the Antarctic ice cores currently is fairly poorly constrained.

On the other hand, some of the not-so-young authors of the present manuscript remember when we published the GICC05 time scale about a decade ago. At the time, we were given many warnings that annual layer counting in glacial ice in Greenland would not produce a useable time scale. Given the success of the GICC05 time scale, we may keep part of the optimism concerning layer counting in the Antarctic Eemian at least in our minds.

Review by R Mulvaney (Referee)

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In this paper, the authors use a continuous flow analysis (CFA) system to measure dust, ammonium, sodium and liquid conductivity on an early Holocene section of the Dome Fuji, and demonstrate seasonal cycles in the core which allow them to count annual layers and deduce a mean accumulation rate for this section.

The paper is an important contribution to the field because, although annual layers have been clearly demonstrated deep in for example relatively high accumulation Greenland ice cores, and in high accumulation West Antarctic ice cores, it is perhaps the first convincing attempt at layer counting in relatively low accumulation rate East Antarctic cores – Dome Fuji has an accumulation rate of around 27 mm water per annum.

While diffusion has a tendency to quickly smear out the seasonal signal in stable water isotopes making them unsuitable for layer counting purposes, it is generally held view that if the flux of chemistry to a site has a clear seasonal signal at the surface then, for some species at least, this seasonal signal is likely to be maintained to considerable depth. Post depositional migration (methane sulphonic acid is a good example) may affect some species, while grain growth might sweep some species to grain boundaries. However, it has been demonstrated that for many analytes in ice cores, the seasonal cycle is maintained –this paper demonstrates the case for dust, sodium and ammonium.

Thus, recovering the seasonal cycles and layer thickness at depth becomes only a matter of sample resolution, and the CFA technique has amply demonstrated that it can recover seasonal cycles in the ice, and at an acceptable analytical speed.

But, I'm not sure that they really achieve 'a counted time scale' as the final line of the conclusions claim (P816, L10). Was not the eye guided by an existing knowledge of the number of years between each of the three volcanic peaks already established in the NGRIP and EDML cores? There are many uncertain layers, and I think other observers might have produced quite different 'time scales' over this period had they not had the guidance of how many layers ought to lie between volcanic peaks.

The final line of the manuscript has been modified as follows: 'The present study suggests that annual layer counting in the Antarctic Eemian period may help to constrain the chronology of that section, if annual layers are preserved.'

There are many uncertain layers because the annual signal is not very prominent due to the low accumulation. Most likely, not two persons would pick layers in exactly the same way, but the many uncertain layers increase the chance that different layer counting attempts agree within error estimates. If the layer counting results in a 'time scale' is of course a matter of debate. Maybe 'event duration estimate' would be a better phrase.

In focussing on 'a counted time scale', I think the authors miss commenting on another significant benefit to their technique. Most deep ice cores use a model time scale rather than a layer counted time scale (though a layer counted time scale has been developed for Greenland ice to in excess of 60 kys). The models tend to use the stable water isotopes to infer temperature and from that

accumulation rate, which is then integrated over the ice column, corrected for thinning, and trained on occasional reference horizons, to give the final time scale. Independent observation of the annual layer thickness at various depths through the ice column, particularly during periods of rapid climate change, would be extremely valuable in verifying the model time scale. Perhaps this is just a subtlety of wording, and perhaps it is implicit in the paper, but I feel the power of the high-resolution analytical technique in testing ice core time-scales has been missed and could be brought to the fore by the authors.

Even if the seasonal cycle in chemistry and dust is preserved at depth (and this does seem likely in the early Holocene ice here from a low accumulation site, and to at least 60 kyr at high accumulation site in Greenland), then the CFA technique is perhaps only marginally capable of recovering the seasonal cycle from the ice where the layer thickness is small. The continuous melting technique generates some mixing of the melt-water directly at the melthead, while there is further dispersion in the tubing and reaction columns between the melthead and the detectors. This inevitably results in a more diffuse seasonal signal than might have been present in the ice, and likely limits the annual layer thickness that can be resolved to perhaps something around 10 mm or perhaps a little better. Other high resolution techniques have been developed that do not suffer this analytical dispersion of the original signal. Thomas (2008, doi:10.3189/172756408784700590) described mm-scale sub-sampling of ice sticks using a microtome for subsequent discrete analysis - laborious but effective in eliminating signal dispersion. Several groups have been developing laser ablation mass spectrometry (LA-ICP-MS) for in-situ and mostly non-destructive highly resolved analysis of ice (Reinhardt, 2001, doi:10.1007/s002160100853; Müller, 2011, doi: 10.1039/c1ja10242g; Sneed, 2014, doi: 10.3189/2015JoG14J139). Given the power to test age-scale model accumulation, and layer counting at depth, I would have liked to see the author's comment that other high-resolution techniques might be valuable and complementary to CFA.

With an annual layer thickness close to 3 cm in the present study, we are not close to the resolution limit of the CFA technique, but, indeed, it is relevant to mention other high-resolution techniques and we now refer to those techniques in the introduction.

I'm unsure about the interpretation of the 'peculiar event', and feel it has been given too much weight in the paper. A first impression was that we had observed something similar deep in the Dome C core where volcanic spikes were wider in depth (and therefore time) than was likely for a single eruption, and had clearly displaced other species such as nitrate to shoulders either side of the main sulphate peak, indicating that dispersion of the original volcanic peak had taken place, and that other acidic species had been excluded from the central event and migrated in the ice. For example, Barnes (2003, doi:10.1029/2002JD002538) described peak broadening of volcanic sulphate peaks at 350m in the Dome C core, though does not allude to the displacement of other species, and unfortunately I can't now remember if and where this was published. However, this doesn't appear to be the case in the DF results since the peculiar event is only present on the one (younger) side of the volcanic peak, and only occurs in one of the three events recorded in this section. My second thought was analytical error, and I'd really like to see this excluded as a possibility before this section is accepted in the literature. Is there any chance of re-analysis of a parallel section?

Unfortunately, we are not able to obtain sufficient ice for a high-resolution re-analysis of the peculiar event. The DEP curve shown in Figures 2 and 4 is, however, obtained independently from the chemistry profiles on a parallel ice core section.

P816, L2: for sure you have shown layers exist for the early Holocene, but extending this to the Eemian as you do here is speculative. The additional grain growth over >100kys might have disturbed the clear seasonal cycle in chemistry; while even with higher accumulation, thinning might mean that the layers are just too thin for your CFA technique (though maybe not for the even higher resolution techniques mentioned here).

The thickness of the Eemian section in the EDC, DF, and Vostok ice cores is about 250 m, 200 m, and 300 m, respectively. This may provide sufficient depth resolution to resolve annual layers by CFA. Other high-resolution techniques will also be able to resolve such layers, but they may not cover the entire Eemian depth intervals.

Annual layers have been detected in 100 kyr old ice in Greenland, where the ice is much warmer and grain growth is much more active than in Antarctica (Svensson et al., 2011). Annual layers may therefore also be identified in Antarctic Eemian ice. We now mention this at the end of the manuscript.

The manuscript is well-written, in excellent English and is laid out well and logical. I have no minor technical points of note.

Reference:

Svensson, A., Bigler, M., Kettner, E., Dahl-Jensen, D., Johnsen, S., Kipfstuhl, S., Nielsen, M., and Steffensen, J. P.: Annual layering in the NGRIP ice core during the Eemian, *Clim. Past.*, 7, 1427-1437, 2011.

Marked up manuscript. Revised text is marked red.

On the occurrence of annual layers in Dome Fuji ice core early Holocene ice

A. Svensson¹, S. Fujita^{2,3}, M. Bigler⁴, M. Braun¹, R. Dallmayr², V. Gkinis¹, K. Goto-Azuma^{2,3}, M. Hirabayashi², K. Kawamura^{2,3}, S. Kipfstuhl⁵, H.A. Kjær¹, T. Popp¹, M. Simonsen¹, J.P. Steffensen¹, P. Vallelonga¹, and B.M. Vinther¹

¹Centre for Ice and Climate, Niels Bohr Institute, University of Copenhagen, Denmark

²National Institute of Polar Research, Research Organization of Information and Systems, Tokyo, Japan

³Department of Polar Science, SOKENDAI (The Graduate University for Advanced Studies), Tokyo, Japan

⁴Climate and Environmental Physics, Physics Institute & Oeschger Centre for Climate Change Research, University of Bern, Switzerland

⁵Stiftung Alfred-Wegener-Institut für Polar- und Meeresforschung, Bremerhaven, Germany

ABSTRACT

Whereas ice cores from high accumulation sites in coastal Antarctica clearly demonstrate annual layering, it is debated whether a seasonal signal is also preserved in ice cores from lower accumulation sites further inland and particularly on the East Antarctic Plateau. In this study, we examine five metres of early Holocene ice from the Dome Fuji (DF) ice core in high temporal resolution by continuous flow analysis. The ice was continuously analyzed for concentrations of dust, sodium, ammonium, liquid conductivity, and water isotopic composition. Furthermore, a dielectric profiling was performed on the solid ice. In most of the analyzed ice, the multi-parameter impurity dataset appears to resolve the seasonal variability although the identification of annual layers is not always unambiguous. **The study thus provides information on the snow accumulation process in central East Antarctica.** A layer counting based on the same principles as those previously applied to the Greenland NGRIP and the Antarctic EPICA Dronning Maud Land (EDML) ice cores leads to a mean annual layer thickness for the DF ice of 3.0 ± 0.3 cm that compares well to existing estimates. The measured DF section is linked to the EDML ice core through a characteristic pattern of three significant acidity peaks that are present in both cores. The corresponding section of the EDML ice core has recently been dated by annual layer counting and the number of years identified independently in the two cores agree within error estimates. We therefore conclude that, to first order, the annual signal is preserved in this section of the DF core. This case study demonstrates the feasibility of determining annually deposited strata on the central Eastern Antarctic Plateau. It also opens the possibility of resolving annual layers in the Eemian section of **Antarctic ice cores** where the accumulation is estimated to have been greater than in the Holocene.

1. INTRODUCTION

Detection of annual layers has long been the method of preference for obtaining high-precision ice-core chronologies (Alley et al., 1997; Hammer et al., 1978). Annual layer detection in ice cores was originally based mostly on the water isotopic composition of the ice but has evolved to also include the seasonal variation of ice core impurities, such as dust and ionic species (Rasmussen et al., 2006; Sommer et al., 2000). Ice core dating based on annual layer counting is limited by the temporal resolution of the ice but it is feasible for annual layers thicknesses down to about one centimeter **by application of Continuous Flow Analysis** (Vallelonga et al., 2012). **Other high-resolution techniques are available that can resolve thin annual layers, such a discrete millimetre-scale sampling (Thomas et al., 2008) and laser ablation mass**

spectrometry (LA-ICP-MS) for in-situ and mostly non-destructive analysis of ice (Della Lunga et al., 2014; Reinhardt et al., 2001; Sneed et al., 2015). In Greenland, ice cores have been dated continuously by annual layer counting back to 60 kyr (Svensson et al., 2008) and in Antarctica the younger section of ice cores at high-accumulation sites have been dated by layer counting (Fudge et al., 2013; Plummer et al., 2012; Sommer et al., 2000).

Large volcanic eruptions can spread sulphate and ash across large parts of the globe, thus producing acid and tephra strata that can be used to synchronize ice cores globally (Gao et al., 2008; Sigl et al., 2012). Historical volcanic eruptions furthermore provide important constraints on the accuracy of layer counting techniques for the past two millennia. Through bipolar synchronization of ice cores the Greenland ice core chronologies have been transferred to Antarctic ice cores back to 60 kyr, but beyond that limit the accuracy and the precision of ice core chronologies generally decreases (Bazin et al., 2013; Veres et al., 2013). Annual layer counting in older parts of both Greenland and Antarctic ice cores could potentially improve this situation.

Until now, the identification of annual layers in ice cores from the East Antarctic Plateau (EAP) has been very limited. At the EAP the present day annual accumulation is typically a few centimeters of ice equivalent and therefore dating by annual layer counting is generally challenging and during colder climatic periods of low accumulation annual layer identification is probably impossible. On the other hand, only ice cores from the EAP appear to continuously cover the last interglacial period in Antarctica, so if this period should be dated by layer counting it will have to be in a core from that region.

Dome Fuji is the summit of the EAP Dronning Maud Land located at 77°19'S, 39°42'E (Figure 1) (Watanabe et al., 1999). The Dome Fuji elevation is 3800 m, and the ice thickness is 3028 (± 15) m (Fujita et al., 1999). The glaciological conditions at Dome Fuji, such as the surface mass balance and subglacial conditions have been investigated (Fujita and Abe, 2006; Fujita et al., 2011; Fujita et al., 2012). The Dome Fuji deep ice cores 1 (DF1) and 2 (DF2) were retrieved by the Japanese Antarctic Research Expeditions (JARE) in 1992-98 and 2004-07, respectively (Motoyama, 2007; Watanabe et al., 1999). DF1 covers the upper 2503 m of the ice sheet, whereas the DF2 core is 3035 m long and reaches almost to bedrock. At Dome Fuji the present day (1995 - 2006) annual accumulation is 2.73 ± 0.15 cm water equivalent (Kameda et al., 2008). The DF cores have mainly been dated by orbital tuning using O_2/N_2 age markers (Kawamura et al., 2007) and by glaciological modelling based on a set of age markers (Parrenin et al., 2007). A recent study is concerned with transfer of the EDML ice core time scale to the DF cores for the last two millennia (Motizuki et al., 2014). In addition, the Dome Fuji deep ice cores have recently been synchronized to the EPICA Dome C (EDC) ice core (EPICA community members, 2004) using a total of 1401 volcanic tie points over the past 216 kyr (Fujita et al., 2015). Using the established EDC/EDML volcanic synchronization (Ruth et al., 2007), the DF ice cores are thus indirectly synchronized with the EDML ice core.

Several studies have considered the occurrence of annual layers in the Dome Fuji ice cores. A case study of high-resolution discrete chemistry records discuss the preservation of annual layering in ice from Marine Isotope Stage (MIS) 2 (Iizuka et al., 2004). Based on counting of seasonal cycles in sodium and non-sea-salt (nss) sulphate the authors conclude that high-resolution stratigraphic dating at Dome Fuji may be feasible. During the last glacial period, the annual layers are, however, likely to be of the order of 1 cm thick (Kawamura et al., 2007) and the layer identification is very challenging and uncertain. The volcanic synchronization between the Dome Fuji and the EDC ice cores revealed periods where no reliable tie points could be identified in MIS 2, 4, 5b, and 6 (Fujita et al., 2015). In those cold periods, there are frequent losses or disturbances of volcanic signals due to the low accumulation rate and possible accumulation hiatus. Thus, the preservation of annual layers in these cold periods should be very carefully assessed. A

study of the ice core visual stratigraphy investigated the preservation of annual layers in various sections of the ice core (Takata et al., 2004). Although the conclusion concerning the existence of annual layers in the ice core stratigraphy is positive the investigated sections were restricted to the deeper part of the ice core in MIS 2, 5c, and 6, where annual layers are very thin.

A detailed stake measurement survey of the surface mass balance was carried out at the Dome Fuji site for the period 1995-2006 (Kameda et al., 2008). Accumulation at 36 stakes was measured at least annually and whereas the average accumulation agrees with the average DF ice core accumulation of the last millennium, a negative or zero accumulation was measured for 8.6 % of the annual stake measurements. This result suggests that post-depositional processes influence the local mass balance, and that today not all annual layers are preserved at the DF site.

Recently, Hoshina et al. (2014) measured the major ion concentrations of a 4 m pit at the Dome Fuji site that covers the past 50 years. By counting seasonal cycles in profiles of chemistry and crust layers the authors find that the frequency distribution of the annual accumulation rates agree well with the stake study mentioned above (Kameda et al., 2008). The agreement of the two independent accumulation estimates suggest that annual layers can be counted with some probabilistic limitations in the present Holocene layering.

In this work, we present high resolution chemistry and dust data from a 5.0 m section of early Holocene ice from the Dome Fuji 1 ice core. Based on this dataset we attempt to date the DF ice by annual layer counting and we discuss issues related to layer counting at low accumulation sites. We apply prominent acidity spikes to synchronize the measured section of DF ice to the EDML ice core (Barbante et al., 2006) from the Atlantic Antarctic sector (Figure 1). The EDML ice core has thicker annual layers in the early Holocene due to its more coastal location and higher accumulation. The EDML ice core has, in turn, been synchronized to the Greenland NGRIP by bipolar volcanic matching. The synchronization of the three cores allows for a comparison of their respective time scales over the time interval of synchronization allowing for an evaluation of the DF layer counting.

2. ANALYSES AND RESULTS

For this study, 5.0 m of high quality ice from the Dome Fuji 1 (DF1) ice core were selected. The samples cover the interval 301.90-306.90 m depth and are in sticks of 0.5 m length with a cross-section of 3.4 x 3.4 cm². The ice is Holocene and has an age close to 9.8 ka BP. The samples were analysed in January 2012 at the Niels Bohr Institute in Copenhagen using a Continuous Flow Analysis (CFA) system optimized to provide the highest possible depth resolution (Bigler et al., 2011). The samples are melted continuously and the melt water is separated into an inner part (sample) and an outer part (waste) to avoid contamination. The continuous sample water flow is distributed into several detection systems measuring concentrations of ammonium (NH₄), sodium (Na) and mineral dust particles, the electrolytic conductivity of the melt water, and the water isotopic composition, respectively. A low ice melt rate of approximately 1.5 cm per minute allows for obtaining records of very high depth resolution that can resolve annual layers and other features of less than a centimetre thickness (Bigler et al., 2011; Vallelonga et al., 2012). In addition, a Dielectric Profile (DEP) of the solid ice has been obtained at the National Institute of Polar Research (NIPR), Tokyo, using a parallel set of samples.

Dual water isotopic measurements ($\delta^{18}\text{O}$ and δD , Figure S6) were performed online using a cavity ring down spectrometer (Picarro 1102-i) and a continuous vaporization system (Gkinis et al., 2011). Measurements are set on the VSMOW scale using a 2-point calibration with local standard waters. In order to account for

diffusion imposed by the CFA system a Wiener deconvolution filter was applied. The precision of the analysis is in the order of 0.06 ‰ ($\delta^{18}\text{O}$) and 0.5 ‰ (δD).

An overview of the Dome Fuji profiles obtained for this study is presented in Figure 2. The CFA profiles cover the full 5 m interval continuously except for short core breaks every 0.5 m and a less than 10 cm data gap at around 305.45 m depth. The average $\delta^{18}\text{O}$ values and the impurity levels over the entire interval are in good accordance with the long-term Dome Fuji profiles of the early Holocene (Watanabe et al., 2003).

The DEP and electrolytic conductivity records show three major acidity spikes at around 303.51, 304.70, and 306.44 m depth that are denoted P1, P2, and P3, respectively (Figure 2). Events P1 and P2 are associated with the most prominent dust peaks observed in the 5 m profiles. Those peaks are discussed in section 3.3.

Just above P3, in the depth interval 306.25-306.40 m, the four CFA profiles and the DEP profile express a characteristic smooth shape that is not observed anywhere else in the dataset. There were no irregularities in the melting system or measurement equipment which could lead to such anomalous results, hence we interpret this event to result from anomalous snow deposition and/or remobilization. The event is discussed in detail in section 3.4.

3. DISCUSSION

3.1 Layer counting

The entire CFA chemistry dataset presented in Figure 2 is shown in high depth resolution in Figures 3 and 4 and in supplementary Figures S1-S5. In high depth resolution, the chemistry and dust records show clear evidence of a periodic signal that we interpret as seasonal variability in impurity fluxes to the ice. Using this dataset we count the annual layers of the measured section following the same principles as applied for the glacial section of the Greenland NGRIP ice core (Rasmussen et al., 2006) and for deeper sections of the Antarctic EDML ice core (Svensson et al., 2013). In the DF1 dataset the annual layers are found to be of more than two centimetres thickness on average, which are reliably resolved by the CFA system used (Bigler et al., 2011). The annual signal in DF1 is generally quite pronounced in the sodium, ammonium, and dust records. When data are missing over a short interval the layer marks are interpolated based on adjacent intervals. In case of an ambiguity, layers are indicated as 'uncertain'. The 'uncertain' layers are counted as $(\frac{1}{2} \pm \frac{1}{2})$ year (that is, either the year is present, $\frac{1}{2} + \frac{1}{2}$, or the year is not present, $\frac{1}{2} - \frac{1}{2}$) and the uncertainties are added up to provide a cumulative uncertainty of the layer counting.

For the entire 5 m section we obtain 165 ± 17 years corresponding to a mean annual layer thickness of approximately 3.0 ± 0.3 cm ice. The counting uncertainty of around 10% is greater than that of other deep ice cores with similar layer thicknesses (Svensson et al., 2008) in part due to the occurrence of the event discussed in section 3.4. The mean annual layer thickness for this early Holocene period is slightly greater than the modelled layer thickness of 2.6 cm ice based on surface mass balance estimated from water isotopes, **in agreement with what was inferred at EPICA Dome C** (Parrenin et al., 2007). The determined mean annual layer thickness is comparable to the present day accumulation of 2.98 ± 0.16 cm ice (Kameda et al., 2008) and greater than the 2.7 cm ice mean accumulation of the last eight millennia (Fujita et al., 2011). The result is thus in accordance with the existence of a widespread Antarctic early Holocene optimum occurring between 11.5 and 9 ka BP (Masson et al., 2000).

3.2 Synchronizing DF to EDML and NGRIP

The three characteristic acidity peaks P1, P2, and P3 are also recognized in the EDML ice core in the corresponding age interval (Figure 5). Based on those and other significant acidity peaks in adjacent ice the two ice cores are synchronized over the investigated interval within a few years of uncertainty (Fujita et al., 2015; Ruth et al., 2007). The EDML Holocene ice has thicker annual layers than DF and the early Holocene part of EDML has been dated by both layer counting (Vinther et al., 2012) and modelling (Ruth et al., 2007; Veres et al., 2013). The EDML-DF matching allows for a comparison of the dating of the two cores between the acidity spikes (Tables 1 and 2). The comparison shows an agreement of the layer-counted interval durations within the error estimates generated by the assignment of 'uncertain' annual layer counts. The depth matching of the volcanic synchronization between the EDML and DF ice cores adds a few years of uncertainty to the interval duration comparison.

In the Holocene the EDML ice core is matched to the Greenland NGRIP ice core (Andersen et al., 2004) by identification of bipolar volcanic markers (Veres et al., 2013). The DF and EDML acidity spikes have Greenland counterparts that allows for a time scale comparison to the layer counted Greenland ice core chronology GICC05 (Vinther et al., 2006) between the spikes (Tables 1 and 2). Within uncertainties, the DF layer counting is in agreement with the Greenland time scale, but in this case, the bipolar matching may add more importantly to the uncertainty of the interval durations.

3.3 Dust peaks

The DF1 dust profile obtained in this study was measured with an Abakus instrument that also provide approximate dust size distributions in the 1-15 micrometre range (Ruth et al., 2003). In Figure 6 the background dust volume distribution of the present study is compared to those related to the three prominent acidity spikes P1, P2, and P3 (Figure 2). The background dust size distribution is centred around 3 micrometre and is similar to that determined for other sections of the Dome Fuji core. The dust peaks associated with P1 and P2 - in particular - are seen to hold significant fractions of large particles, whereas the dust size distribution associated with the P3 acidity peak is very comparable to that of the background dust. A recent study of dust particles from the WAIS (West Antarctic Ice Sheet) Divide ice core suggests that dust peaks associated with acidity peaks may be of volcanic origin although the argument is based solely on dust size distributions and not on geochemical analyses (Koffman et al., 2013). Based on Figure 3 we suggest that the large fraction particles related to P1 and P2 are tephra particles, whereas no tephra appears to be related to P3. Future geochemical analyses of the dust peaks, as it was done for 26 visible Dome Fuji tephra layers by Kohno et al. (2004), will allow a definitive evaluation of the presence of tephra in the dust peaks.

3.4 A peculiar event

In the DF depth interval 306.25-306.40 m, at the tail of the major acidity spike P3, the impurity records show an unusual behavior (Figure 4). In contrast to the rest of the analyzed depth interval, where all impurities show clear evidence of an annual cycle, the chemical and dust profiles all show an unusually smooth pattern in a 15 cm long interval corresponding to the accumulation of 5-6 years in adjacent ice. We refer to this depth interval as 'the peculiar event'. The event occurs immediately after the largest volcanic signal in the analyzed section.

The peculiar event cannot be attributed to the melting or measurement process. The ice-core melt speed was typical and constant and the analytical systems were operating normally. Furthermore, the DEP profile that is obtained on the solid ice shows a very comparable pattern across the event. The ice was melted down-core (i.e., from 306.10 m to 306.40 m depth) and the section of interest occurs toward the end of an ice core section terminating at 306.40 m depth. The large P3 acidity spike peaking at around 306.44 m

depth was analyzed in the following ice core section and was physically separate from the event during measurement.

The event is unique for the analyzed section of DF ice and nothing comparable is seen in the proximity of the other major acidity spikes in the analyzed DF ice. A similar event is not appearing in the corresponding section of the EDML ice core (Figure 5). To our knowledge, similar smooth profiles have not been observed following other large acidity spikes in Antarctic and Greenland ice cores.

We do not know the cause of this event, but, possibly, it may be related to sastrugi formation at the surface. Sastrugi are local snow dunes caused by post-depositional redistribution of surface snow. We note that the subsequent annual layers are thinner than the average (Figure 4), which would be expected from deposition on top of an elevated surface. It is surprising, however, that the event is unique in the 165 year long timeseries presented here. The recent snow stake study at DF (Kameda et al., 2008), where 8% of the observed stake sites experienced zero or negative accumulation, does support the possibility of local snow remobilization at DF, although on a much smaller scale than suggested by the **peculiar** event.

Another possible explanation for the event is related to unusual meteorological conditions. It is possible that the sulphate flux from a large volcanic eruption could have contributed to unusual meteorological conditions and hence unusually high accumulation at the DF site. Such a scenario is highly unlikely because we do not see a similar event in the matched record from the EDML ice core. Nonetheless, high snow precipitation events have been recorded for East Antarctica, often due to rare meteorological situations such as atmospheric rivers (Gorodetskaya et al., 2014) and blocking anticyclonic systems (Hirasawa et al., 2000; Schlosser et al., 2010). Enomoto et al. (1998) observed such a blocking high in June 1994, when temperatures at DF increased by 40°C in two days. Of particular interest is that heat was transported to DF from the Northeast, the opposite direction to EDML.

4. CONCLUSIONS

The high-resolution impurity profiles obtained from the early Holocene section of the Dome Fuji ice core demonstrate the feasibility of determining annually deposited strata on the central Eastern Antarctic plateau during warm climates. For the most part of the analyzed section annual layer counting was feasible and the average annual layer thickness is found to be 3.0 ± 0.3 cm. **The preservation of annual layers at this low accumulation site may have implications for the understanding of the air enclosure process and for the determination of gas age-ice age differences (Landais et al., 2006).**

Synchronization of the analyzed Dome Fuji section to corresponding sections of the EDML and NGRIP ice cores allows for a comparison of the independent layer counted time intervals. Within the error estimates of the layer counting and taking into account the uncertainty related to the matching of the cores, the dating of the DF core agrees with the EDML and NGRIP chronologies.

Our results show that annual layers can be resolved in the interior of Antarctica **in the early Holocene**. Over longer time intervals, a low percentage of individual annual layers may be missing, due to remobilisation of surface snow. Additionally, we observe one 'peculiar event' in the 165-year record in which 5-6 years' accumulation appears to have been deposited in one year. The event occurs immediately after a large volcanic eruption, and may have resulted from surface sastrugi or anomalously high accumulation following a blocking high. Despite these disturbances, our study suggests that the original deposition at Dome Fuji is often preserved and that a counted time scale can be established from high-resolution ice-core impurity profiles.

During the Eemian period (MIS 5e) the accumulation is known to have been higher than in the Holocene. The present study suggests that annual layer counting in the Antarctic Eemian period may help to constrain the chronology of that section, if annual layers are preserved. In Greenland, Eemian annual layers are preserved at least in some sections of the NGRIP ice core (Svensson et al., 2011). The Antarctic cores of interest for layer counting in the Eemian are Vostok, where the Eemian covers a 300 m depth interval (1600-1900m), EPICA Dome C, where the Eemian covers a 250 m depth interval (1510-1760m), and Dome Fuji, where the Eemian covers a 200 m depth interval (1610-1810m).

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FIGURES

Figure 1:

The Atlantic sector of the East Antarctic Ice Sheet with the positions of Dome Fuji (DF) and the EPICA Dronning Maud Land (EDML) drilling sites. Black lines are elevation curves in metres, blue curves indicate major ice flow lines, and the grey lines are traverse tracks. Satellite image from MODIS (Haran et al., 2005, updated 2006).

Figure 2:

Overview of the high-resolution records obtained from the five metres of early Holocene Dome Fuji ice. From top, the $\delta^{18}\text{O}$ is obtained continuously on a cavity ring down spectrometer and the Dielectric Profiling (DEP) is made on the solid ice. The electrolytic (liquid) conductivity, the Ammonium, the Sodium, and the dust concentrations were obtained on the Copenhagen CFA analytical system. Data gaps are due to core breaks or failure of the analytical systems. The three major acidity spikes P1, P2, and P3 centred at 303.51, 304.70, and 306.44 m depth, respectively, are indicated.

Figure 3.

Example of high-resolution profiles of electrolytic conductivity, Ammonium, Sodium, and dust concentrations. Thin curves show the records in 1 mm depth resolution and thicker curves are 1 cm averages. 'Certain' and 'uncertain' annual layer marks are indicated with full and dashed vertical lines, respectively. The entire dataset is shown in the supplementary material Figures S1-S5.

Figure 4.

Same records as shown in Figure 3 plus the DEP record for the section containing the major acidity peak P3 centred around 306.44 m depth and the 'peculiar event' with unusually smooth profiles 306.25-306.40 m depth. Thin curves show the records in 1 mm depth resolution and thicker curves are 1 cm averages. 'Certain' and 'uncertain' annual layer marks are indicated with full and dashed vertical lines, respectively. For the interval 306.25-306.40 the layer indication is tentative.

Figure 5.

Volcanic matching of the Dome Fuji and EPICA Dronning Maud Land (EDML) ice cores based on the three characteristic acidity peaks P1, P2, and P3 here shown in the electrolytic conductivity signal. Due to the different shapes of the acidity peaks the matching of the cores has an uncertainty of a few years.

Figure 6.

Dust volume distributions of average background dust and across the three prominent volcanic peaks, P1, P2, and P3 (see Figure 2). The size distributions are obtained by an Abakus instrument that covers the particle size interval 1-15 μm (spherical equivalent diameter). The Abakus is known not to measure dust sizes as accurately as a Coulter counter instrument (Ruth et al., 2003) and the shape of the dust size distribution may be somewhat biased. The relative sample differences in dust sizes are, however, robust and significant.

Depth intervals			
Interval	Dome Fuji (m)	EDML (m)	NGRIP (m)
P1 → P2	303.51 → 304.70	593.30 → 595.34	1368.35 → 1371.54
P2 → P3	304.70 → 306.44	595.34 → 598.32	1371.54 → 1376.59
P1 → P3	303.51 → 306.44	593.30 → 598.32	1368.35 → 1376.59
Full interval	301.90 → 306.90		

Table 1. The depth intervals defined by the characteristic acidity spikes P1, P2, and P3 in the ice cores (see Figures 2 and 5).

Ice Core	Time scale	Number of years				P3 age (yr BP)	Reference
		P1 → P2	P2 → P3	P1 → P3	Full interval		
Dome Fuji	Layer count	43±3	59±9	102±12	165±17		This work
EDML	AICC2012	46	67	113		9,852	Veres et al., 2013
EDML	Layer count	45±3	61±5	106±8			Vinther et al., 2012
NGRIP	GICC05	39±1	64±1	103±2		9,849	Vinther et al., 2006

Table 2. The number of years between the characteristic acidity spikes P1, P2, and P3 (see Table 1).

REFERENCES

- Alley, R. B., Shuman, C. A., Meese, D. A., Gow, A. J., Taylor, K. C., Cuffey, K. M., Fitzpatrick, J. J., Grootes, P. M., Zielinski, G. A., Ram, M., Spinelli, G., and Elder, B.: Visual-stratigraphic dating of the GISP2 ice core: Basic, reproducibility, and application, *Journal of Geophysical Research*, 102, 26367-26382, 1997.
- Andersen, K. K., Azuma, N., Barnola, J. M., Bigler, M., Biscaye, P., Caillon, N., Chappellaz, J., Clausen, H. B., Dahl-Jensen, D., Fischer, H., Fluckiger, J., Fritzsche, D., Fujii, Y., Goto-Azuma, K., Gronvold, K., Gundestrup, N. S., Hansson, M., Huber, C., Hvidberg, C. S., Johnsen, S. J., Jonsell, U., Jouzel, J., Kipfstuhl, S., Landais, A., Leuenberger, M., Lorrain, R., Masson-Delmotte, V., Miller, H., Motoyama, H., Narita, H., Popp, T., Rasmussen, S. O., Raynaud, D., Rothlisberger, R., Ruth, U., Samyn, D., Schwander, J., Shoji, H., Siggard-Andersen, M. L., Steffensen, J. P., Stocker, T., Sveinbjornsdottir, A. E., Svensson, A., Takata, M., Tison, J. L., Thorsteinsson, T., Watanabe, O., Wilhelms, F., White, J. W. C., and Project, N. G. I. C.: High-resolution record of Northern Hemisphere climate extending into the last interglacial period, *Nature*, 431, 147-151, 2004.
- Barbante, C., Barnola, J. M., Becagli, S., Beer, J., Bigler, M., Boutron, C., Blunier, T., Castellano, E., Cattani, O., Chappellaz, J., Dahl-Jensen, D., Debret, M., Delmonte, B., Dick, D., Falourd, S., Faria, S., Federer, U., Fischer, H., Freitag, J., Frenzel, A., Fritzsche, D., Fundel, F., Gabrielli, P., Gaspari, V., Gersonde, R., Graf, W., Grigoriev, D., Hamann, I., Hansson, M., Hoffmann, G., Hutterli, M. A., Huybrechts, P., Isaksson, E., Johnsen, S., Jouzel, J., Kaczmarek, M., Karlin, T., Kaufmann, P., Kipfstuhl, S., Kohno, M., Lambert, F., Lambrecht, A., Landais, A., Lawer, G., Leuenberger, M., Littot, G., Loulergue, L., Luthi, D., Maggi, V., Marino, F., Masson-Delmotte, V., Meyer, H., Miller, H., Mulvaney, R., Narcisi, B., Oerlemans, J., Oerter, H., Parrenin, F., Petit, J. R., Raisbeck, G., Raynaud, D., Rothlisberger, R., Ruth, U., Rybak, O., Severi, M., Schmitt, J., Schwander, J., Siegenthaler, U., Siggard-Andersen, M. L., Spahni, R., Steffensen, J. P., Stenni, B., Stocker, T. F., Tison, J. L., Traversi, R., Udisti, R., Valero-Delgado, F., van den Broeke, M. R., van de Wal, R. S. W., Wagenbach, D., Wegner, A., Weiler, K., Wilhelms, F., Winther, J. G., Wolff, E., and Members, E. C.: One-to-one coupling of glacial climate variability in Greenland and Antarctica, *Nature*, 444, 195-198, 2006.
- Bazin, L., Landais, A., Lemieux-Dudon, B., Toyé Mahamadou Kele, H., Veres, D., Parrenin, F., Martinerie, P., Ritz, C., Capron, E., Lipenkov, V., Loutre, M. F., Raynaud, D., Vinther, B., Svensson, A., Rasmussen, S. O., Severi, M., Blunier, T., Leuenberger, M., Fischer, H., Masson-Delmotte, V., Chappellaz, J., and Wolff, E.: An optimized multi-proxy, multi-site Antarctic ice and gas orbital chronology (AICC2012): 120-800 ka, *Clim. Past.*, 9, 1715-1731, 2013.
- Bigler, M., Svensson, A., Kettner, E., Vallelonga, P., Nielsen, M. E., and Steffensen, J. P.: Optimization of High-Resolution Continuous Flow Analysis for Transient Climate Signals in Ice Cores, *Environmental Science and Technology*, 45, 4483-4489, 2011.
- Della Lunga, D., Muller, W., Rasmussen, S. O., and Svensson, A.: Location of cation impurities in NGRIP deep ice revealed by cryo-cell UV-laser-ablation ICPMS, *J. Glaciol.*, 60, 970-988, 2014.
- Enomoto, H., Motoyama, H., Shiraiwa, T., Saito, T., Kameda, T., Furukawa, T., Takahashi, S., Kodama, Y., and Watanabe, O.: Winter warming over Dome Fuji, East Antarctica and semiannual oscillation in the atmospheric circulation, *Journal of Geophysical Research-Atmospheres*, 103, 23103-23111, 1998.
- EPICA community members: Eight glacial cycles from an Antarctic ice core, *Nature*, 429, 623-628, 2004.
- Fudge, T. J., Steig, E. J., Markle, B. R., Schoenemann, S. W., Ding, Q., Taylor, K. C., McConnell, J. R., Brook, E. J., Sowers, T., White, J. W. C., Alley, R. B., Cheng, H., Clow, G. D., Cole-Dai, J., Conway, H., Cuffey, K. M., Edwards, J. S., Lawrence Edwards, R., Edwards, R., Fegyveresi, J. M., Ferris, D., Fitzpatrick, J. J., Johnson, J., Hargreaves, G., Lee, J. E., Maselli, O. J., Mason, W., McGwire, K. C., Mitchell, L. E., Mortensen, N., Neff, P., Orsi, A. J., Popp, T. J., Schauer, A. J., Severinghaus, J. P., Sigl, M., Spencer, M. K., Vaughn, B. H., Voigt, D. E., Waddington, E. D., Wang, X., and Wong, G. J.: Onset of deglacial warming in West Antarctica driven by local orbital forcing, *Nature*, 500, 440-444, 2013.

- Fujita, K. and Abe, O.: Stable isotopes in Daily precipitation at Dome Fuji, East Antarctica, *Geophysical Research Letters*, 33, 2006.
- Fujita, S., Holmlund, P., Andersson, I., Brown, I., Enomoto, H., Fujii, Y., Fujita, K., Fukui, K., Furukawa, T., Hansson, M., Hara, K., Hoshina, Y., Igarashi, M., Iizuka, Y., Imura, S., Ingvander, S., Karlin, T., Motoyama, H., Nakazawa, F., Oerter, H., Sjöberg, L. E., Sugiyama, S., Surdyk, S., Ström, J., Uemura, R., and Wilhelms, F.: Spatial and temporal variability of snow accumulation rate on the East Antarctic ice divide between Dome Fuji and EPICA DML, *Cryosphere*, 5, 1057-1081, 2011.
- Fujita, S., Holmlund, P., Matsuoka, K., Enomoto, H., Fukui, K., Nakazawa, F., Sugiyama, S., and Surdyk, S.: Radar diagnosis of the subglacial conditions in Dronning Maud Land, East Antarctica, *The Cryosphere Discuss.*, 6, 1781-1837, 2012.
- Fujita, S., Maero, H., Uratsuka, S., Furukawa, T., Mae, S., Fujii, Y., and Watanabe, O.: Nature of radio echo layering in the Antarctic ice sheet detected by a two-frequency experiment, *Journal of Geophysical Research*, 104, 13013-13024, 1999.
- Fujita, S., Parrenin, F., Severi, M., Motoyama, H., and Wolff, E.: Volcanic synchronization of Dome Fuji and Dome C Antarctic deep ice cores over the past 216 kyr, *Climate of the Past Discussions*, 11, 407-445, 2015.
- Gao, C. C., Robock, A., and Ammann, C.: Volcanic forcing of climate over the past 1500 years: An improved ice core-based index for climate models, *Journal of Geophysical Research-Atmospheres*, 113, 2008.
- Gkinis, V., Popp, T. J., Blunier, T., Bigler, M., Schüpbach, S., Kettner, E., and Johnsen, S. J.: Water isotopic ratios from a continuously melted ice core sample, *Atmospheric Measurement Techniques*, 4, 2531-2542, 2011.
- Gorodetskaya, I. V., Tsukernik, M., Claes, K., Ralph, M. F., Neff, W. D., and Van Lipzig, N. P. M.: The role of atmospheric rivers in anomalous snow accumulation in East Antarctica, *Geophysical Research Letters*, 41, 6199-6206, 2014.
- Hammer, C. U., Clausen, H. B., Dansgaard, W., Gundestrup, N., Johnsen, S. J., and Reeh, N.: Dating of Greenland ice cores by flow models, isotopes, volcanic debris, and continental dust, *J. Glaciol.*, 20, 3-26, 1978.
- Haran, T., Bohlander, J., Scambos, T., Painter, T., and Fahnestock, M.: MODIS mosaic of Antarctica (MOA) image map. In: National Snow and Ice Data Center, Digital media, Boulder, Colorado, USA, 2005, updated 2006.
- Hirasawa, N., Nakamura, H., and Yamanouchi, T.: Abrupt changes in meteorological conditions observed at an inland Antarctic station in association with wintertime blocking, *Geophysical Research Letters*, 27, 1911-1914, 2000.
- Hoshina, Y., Fujita, K., Nakazawa, F., Iizuka, Y., Miyake, T., Hirabayashi, M., Kuramoto, T., Fujita, S., and Motoyama, H.: Effect of accumulation rate on water stable isotopes of near-surface snow in inland Antarctica, *Journal of Geophysical Research: Atmospheres*, 119, 274-283, 2014.
- Iizuka, Y., Takata, M., Hondoh, T., and Fujii, Y.: High-time-resolution profiles of soluble ions in the last glacial period of a Dome Fuji (Antarctica) deep ice core, *Annals of Glaciology*, 39, 452-456, 2004.
- Kameda, T., Motoyama, H., Fujita, S., and Takahashi, S.: Temporal and spatial variability of surface mass balance at Dome Fuji, East Antarctica, by the stake method from 1995 to 2006, *J. Glaciol.*, 54, 107-116, 2008.
- Kawamura, K., Parrenin, F., Lisiecki, L., Uemura, R., Vimeux, F., Severinghaus, J. P., Hutterli, M. A., Nakazawa, T., Aoki, S., Jouzel, J., Raymo, M. E., Matsumoto, K., Nakata, H., Motoyama, H., Fujita, S., Goto-Azuma, K., Fujii, Y., and Watanabe, O.: Northern Hemisphere forcing of climatic cycles in Antarctica over the past 360,000 years, *Nature*, 448, 912-U914, 2007.
- Koffman, B. G., Kreutz, K. J., Kurbatov, A. V., and Dunbar, N. W.: Impact of known local and tropical volcanic eruptions of the past millennium on the WAIS Divide microparticle record, *Geophysical Research Letters*, 40, 4712-4716, 2013.
- Kohno, M., Fujii, Y., and Hirata, T.: Chemical composition of volcanic glasses in visible tephra layers found in a 2503 m deep ice core from Dome Fuji, Antarctica, *Annals of Glaciology*, 39, 576-584, 2004.

- Landais, A., Barnola, J. M., Kawamura, K., Caillon, N., Delmotte, M., Van Ommen, T., Dreyfus, G., Jouzel, J., Masson-Delmotte, V., Minster, B., Freitag, J., Leuenberger, M., Schwander, J., Huber, C., Etheridge, D., and Morgan, V.: Firn-air $\delta^{15}\text{N}$ in modern polar sites and glacial-interglacial ice: A model-data mismatch during glacial periods in Antarctica?, *Quaternary Science Reviews*, 25, 49-62, 2006.
- Masson, V., Vimeux, F., Jouzel, J., Morgan, V., Delmotte, M., Ciais, P., Hammer, C., Johnsen, S., Lipenkov, V. Y., Mosley-Thompson, E., Petit, J.-R., Steig, E. J., Stievenard, M., and Vaikmae, R.: Holocene climate variability in Antarctica based on 11 ice-core isotopic records, *Quaternary Research*, 54, 348-358, 2000.
- Motizuki, Y., Nakai, Y., Takahashi, K., Igarashi, M., Motoyama, H., and Suzuki, K.: Dating of a Dome Fuji (Antarctica) shallow ice core by volcanic signal synchronization with B32 and EDML1 chronologies, *The Cryosphere Discussions*, 8, 769–804, 2014.
- Motoyama, H.: The second deep ice coring project at Dome Fuji, Antarctica, *Scientific Drilling*, 2007. 41-43, 2007.
- Parrenin, F., Dreyfus, G., Durand, G., Fujita, S., Gagliardini, O., Gillet, F., Jouze, J., Kawamura, K., Lhomme, N., Masson-Delmotte, V., Ritz, C., Schwander, J., Shoji, H., Uemura, R., Watanabe, O., and Yoshida, N.: 1-D-ice flow modelling at EPICA Dome C and Dome Fuji, East Antarctica, *Clim. Past.*, 3, 243-259, 2007.
- Plummer, C. T., Curran, M. A. J., Van Ommen, T. D., Rasmussen, S. O., Moy, A. D., Vance, T. R., Clausen, H. B., Vinther, B. M., and Mayewski, P. A.: An independently dated 2000-yr volcanic record from Law Dome, East Antarctica, including a new perspective on the dating of the 1450s CE eruption of Kuwae, Vanuatu, *Clim. Past.*, 8, 1929-1940, 2012.
- Rasmussen, S. O., Andersen, K. K., Svensson, A. M., Steffensen, J. P., Vinther, B. M., Clausen, H. B., Siggaard-Andersen, M.-L., Johnsen, S. J., Larsen, L. B., Dahl-Jensen, D., Bigler, M., Röthlisberger, R., Fischer, H., Goto-Azuma, K., Hansson, M. E., and Ruth, U.: A new Greenland ice core chronology for the last glacial termination, *Journal of Geophysical Research*, 111, D06102, doi:06110.01029/02005JD006079, 2006.
- Reinhardt, H., Kriews, M., Miller, H., Schrems, O., Lüdke, C., Hoffmann, E., and Skole, J.: Laser ablation inductively coupled plasma mass spectrometry: A new tool for trace element analysis in ice cores, *Fresenius' Journal of Analytical Chemistry*, 370, 629-636, 2001.
- Ruth, U., Barnola, J.-M., Beer, J., Bigler, M., Blunier, T., Castellano, E., Fischer, H., Fundel, F., Huybrechts, P., Kaufmann, P., Kipfstuhl, S., Lambrecht, A., Morganti, A., Oerter, H., Parrenin, F., Rybak, O., Severi, M., Udisti, R., Wilhelms, F., and Wolff, E.: "EDML1": a chronology for the EPICA deep ice core from Dronning Maud Land, Antarctica, over the last 150 000 years, *Clim. Past.*, 3, 475-484, 2007.
- Ruth, U., Wagenbach, D., Steffensen, J. P., and Bigler, M.: Continuous record of microparticle concentration and size distribution in the central Greenland NGRIP ice core during the last glacial period, *Journal of Geophysical Research*, 108, 4098, doi:4010.1029/2002JD002376, 2003.
- Schlosser, E., Manning, K. W., Powers, J. G., Duda, M. G., Birnbaum, G., and Fujita, K.: Characteristics of high-precipitation events in Dronning Maud Land, Antarctica, *Journal of Geophysical Research: Atmospheres*, 115, 2010.
- Sigl, M., McConnell, J. R., Layman, L., Maselli, O., McGwire, K., Pasteris, D., Dahl-Jensen, D., Steffensen, J. P., Vinther, B., Edwards, R., Mulvaney, R., and Kipfstuhl, S.: A new bipolar ice core record of volcanism from WAIS Divide and NEEM and implications for climate forcing of the last 2000 years, *Journal of Geophysical Research-Atmospheres*, In press, 2012.
- Sneed, S. B., Mayewski, P. A., Sayre, W. G., Handley, M. J., Kurbatov, A. V., Taylor, K. C., Bohleber, P., Wagenbach, D., Erhardt, T., and Spaulding, N. E.: New LA-ICP-MS cryocell and calibration technique for sub-millimeter analysis of ice cores, *J. Glaciol.*, 61, 233-242, 2015.
- Sommer, S., Appenzeller, C., Rothlisberger, R., Hutterli, M. A., Stauffer, B., Wagenbach, D., Oerter, H., Wilhelms, F., Miller, H., and Mulvaney, R.: Glacio-chemical study spanning the past 2 kyr on three ice cores from Dronning Maud Land, Antarctica. 1. Annually resolved accumulation rates, *Journal of Geophysical Research*, 105, 29411-29421, 2000.

- Svensson, A., Andersen, K. K., Bigler, M., Clausen, H. B., Dahl-Jensen, D., Davies, S. M., Johnsen, S. J., Muscheler, R., Parrenin, F., Rasmussen, S. O., Röthlisberger, R., Seierstad, I., Steffensen, J. P., and Vinther, B. M.: A 60 000 year Greenland stratigraphic ice core chronology, *Clim. Past.*, 4, 47-57, 2008.
- Svensson, A., Bigler, M., Blunier, T., Clausen, H. B., Dahl-Jensen, D., Fischer, H., Fujita, S., Goto-Azuma, K., Johnsen, S. J., Kawamura, K., Kipfstuhl, S., Kohno, M., Parrenin, F., Popp, T., Rasmussen, S. O., Schwander, J., Seierstad, I., Severi, M., Steffensen, J. P., Udisti, R., Uemura, R., Vallelonga, P., Vinther, B. M., Wegner, A., Wilhelms, F., and Winstrup, M.: Direct linking of Greenland and Antarctic ice cores at the Toba eruption (74 ka BP), *Clim. Past.*, 9, 749-766, 2013.
- Svensson, A., Bigler, M., Kettner, E., Dahl-Jensen, D., Johnsen, S., Kipfstuhl, S., Nielsen, M., and Steffensen, J. P.: Annual layering in the NGRIP ice core during the Eemian, *Clim. Past.*, 7, 1427-1437, 2011.
- Takata, M., Iizuka, Y., Hondoh, T., Fujita, S., Fujii, Y., and Shoji, H.: Stratigraphy analysis of Dome Fuji Antarctic ice core using an optical scanner, *Annals of Glaciology*, 39, 467-472, 2004.
- Thomas, R., Davis, C., Frederick, E., Krabill, W., Li, Y. H., Manizade, S., and Martin, C.: A comparison of Greenland ice-sheet volume changes derived from altimetry measurements, *J. Glaciol.*, 54, 203-212, 2008.
- Vallelonga, P., Bertagna, G., Blunier, T., Kjaer, H. A., Popp, T. J., Rasmussen, S. O., Steffensen, J. P., Stowasser, C., Svensson, A. S., Warming, E., Winstrup, M., Bigler, M., and Kipfstuhl, S.: Duration of Greenland Stadial 22 and ice-gas Delta age from counting of annual layers in Greenland NGRIP ice core, *Clim. Past.*, 8, 1839-1847, 2012.
- Veres, D., Bazin, L., Landais, A., Toyé Mahamadou Kele, H., Lemieux-Dudon, B., Parrenin, F., Martinerie, P., Blayo, E., Blunier, T., Capron, E., Chappellaz, J., Rasmussen, S. O., Severi, M., Svensson, A., Vinther, B., and Wolff, E. W.: The Antarctic ice core chronology (AICC2012): An optimized multi-parameter and multi-site dating approach for the last 120 thousand years, *Clim. Past.*, 9, 1733-1748, 2013.
- Vinther, B. M., Clausen, H. B., Johnsen, S. J., Rasmussen, S. O., Andersen, K. K., Buchardt, S. L., Dahl-Jensen, D., Seierstad, I. K., Siggaard-Andersen, M.-L., Steffensen, J. P., Svensson, A. M., Olsen, J., and Heinemeier, J.: A synchronized dating of three Greenland ice cores throughout the Holocene, *Journal of Geophysical Research*, 111, D13102, doi:10.1029/2005JD006921, 2006.
- Vinther, B. M., Clausen, H. B., Kipfstuhl, S., Fischer, H., Bigler, M., Oerter, H., Wegner, A., Wilhelms, F., Severi, M., Udisti, R., Beer, J., Steinhilber, F., Muscheler, R., Rasmussen, S. O., and Svensson, A.: An annual layer counted EDML time scale covering the past 16700 years, *Geophysical Research Abstracts*, 14, EGU2012-13043, 2012.
- Watanabe, O., Kamiyama, K., Motoyama, H., Fujii, Y., Igarashi, M., Furukawa, T., Goto-Azuma, K., Saito, T., Kanamori, S., and Kanamori, N.: General tendencies of stable isotopes and major chemical constituents of the Dome Fuji deep ice core (scientific paper), *Memoirs of National Institute of Polar Research. Special issue*, 57, 1-24, 2003.
- Watanabe, O., Kamiyama, K., Motoyama, H., Fujii, Y., Shoji, H., and Satow, K.: The palaeoclimate record in the ice core from Dome Fuji station, Antarctica, *Annals of Glaciology*, 29, 176-183, 1999.