Clim. Past Discuss., 11, 377–405, 2015
www.clim-past-discuss.net/11/377/2015/
doi:10.5194/cpd-11-377-2015

Climate of the Past
Discussions
Open Access

Climate dependent contrast in surface mass balance in East Antarctica over the past 216 kyr

F. Parrenin[1,2], **S. Fujita**[3,4], **A. Abe-Ouchi**[5,6], **K. Kawamura**[3,4],
V. Masson-Delmotte[7], **H. Motoyama**[3,4], **F. Saito**[5], **M. Severi**[8], **B. Stenni**[9],
R. Uemura[10], and **E. Wolff**[11]

[1]CNRS, LGGE, 38041 Grenoble, France
[2]Univ. Grenoble Alpes, LGGE, 38041 Grenoble, France
[3]National Institute of Polar Research, Research Organization of Information and Systems, Tokyo, Japan
[4]Department of Polar Science, The Graduate University for Advanced Studies (SOKENDAI), Tokyo, Japan
[5]Japan Agency for Marine–Earth Science and Technology, Yokohama, Japan
[6]Atmosphere and Ocean Research Institute (AORI), University of Tokyo, Chiba, Japan
[7]Laboratoire des Sciences du Climat et de l'Environnement, Institut Pierre Simon Laplace, UMR CEA-CNRS-UVSQ 8212, Gif-sur-Yvette, France
[8]Department of Chemistry, University of Florence, Florence, Italy
[9]Department of Geosciences, University of Trieste, Trieste, Italy

[10]Department Chemistry, Biology and Marine Science, Faculty of Science, University of the Ryukyus, Okinawa, Japan
[11]Department of Earth Sciences, University of Cambridge, UK

Received: 14 January 2015 – Accepted: 29 January 2015 – Published: 17 February 2015

Correspondence to: F. Parrenin (parrenin@ujf-grenoble.fr) and S. Fujita (sfujita@nipr.ac.jp)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Documenting past changes in the East Antarctic surface mass balance is important to improve ice core chronologies and to constrain the ice sheet contribution to global mean sea level. Here we reconstruct the past changes in the ratio of surface mass balance (SMB ratio) between the EPICA Dome C (EDC) and Dome Fuji (DF) East Antarctica ice core sites, based on a precise volcanic synchronisation of the two ice cores and on corrections for the vertical thinning of layers. During the past 216 000 years, this SMB ratio, denoted $\mathrm{SMB_{EDC}} / \mathrm{SMB_{DF}}$, varied between 0.7 and 1.1, decreasing during cold periods and increasing during warm periods. While past climatic changes have been depicted as homogeneous along the East Antarctic Plateau, our results reveal larger amplitudes of changes in SMB at EDC compared to DF, consistent with previous results showing larger amplitudes of changes in water stable isotopes and estimated surface temperature at EDC compared to DF. Within interglacial periods and during the last glacial inception (Marine Isotope Stages, MIS-5c and MIS-5d), the SMB ratio deviates by up to 30 % from what is expected based on differences in water stable isotope records. Moreover, the SMB ratio is constant throughout the late parts of the current and last interglacial periods, despite contrasting isotopic trends. These SMB ratio changes not closely related to isotopic changes are one of the possible causes of the observed gaps between the ice core chronologies at DF and EDC. Such changes in SMB ratio may have been caused by (i) climatic processes related to changes in air mass trajectories and local climate, (ii) glaciological processes associated with relative elevation changes, or (iii) a combination of climatic and glaciological processes, such as the interaction between changes in accumulation and in the position of the domes. Our inferred SMB ratio history has important implications for ice sheet modeling (for which SMB is a boundary condition) or atmospheric modeling (our inferred SMB ratio could serve as a test).

1 Introduction

In the context of global warming and sea level rise, changes in the mass balance of the ice sheets must be carefully monitored, understood and anticipated, as they could become the main contributor of sea-level rise in the coming centuries (Church et al., 2013). The mass balance of an ice sheet is approximately the sum of the SMB and the grounding line mass balance, both terms being uncertain in the context of global warming (Bengtsson et al., 2011; Rignot et al., 2014).

Present-day field monitoring and atmospheric reanalyses depict a year-round occurrence of rare snowfall events in central East Antarctica (e.g., Ekaykin, 2003; Fujita and Abe, 2006). Moisture back-trajectories identify ice core moisture sources located in average at 45° S today but with a larger contribution of lower latitudes for the highest elevation, most inland sites (Masson-Delmotte et al., 2008; Sodemann and Stohl, 2009). Different ice cores have different longitudinal origins of water vapour, depending on their location. For instance, Dome C receives moisture predominantly from the Indian Ocean sector, while it is mostly advected from the Atlantic Ocean towards Dome F (e.g., Reijmer et al., 2002; Sodemann and Stohl, 2009; Suzuki et al., 2008) (Fig. 1). The SMB in Antarctica is also function of the surface elevation of the ice sheet (e.g., Krinner and Genthon, 1999; Takahashi et al., 1994) and is affected by the redeposition of snow by wind (Gallée et al., 2013). It is also known that SMB differs between the windward and leeward sides of ice divides for strong-wind events and that the SMB is highly influenced by interactions between the large-scale surface topography of ice divides and the wind field of strong-wind events that are often associated with high-precipitation events (Fujita et al., 2011). In addition, local variations in the SMB are governed by the local surface topography, which is influenced by the bedrock topography (Fujita et al., 2011).

Ice sheets also form a rich paleo-climatic archive. For dating (e.g., Kawamura et al., 2007; Parrenin et al., 2007a) or interpreting the ice core records (e.g. transferring concentrations of species in ice into atmospheric fluxes, Wolff et al., 2006), an evaluation of the past SMB is needed. Indeed, the annual layer thickness along an ice core is the product of the initial SMB multiplied by the vertical thinning function. Usually, past SMB is presumed to be exponentially related to the deuterium (δD_{ice}) or oxygen-18 ($\delta^{18}O_{ice}$) isotopic content of ice. The underlying assumption is that condensation is proportional to the saturation vapor pressure of water in air, which itself is related to condensation temperature and therefore to precipitation isotopic composition (Jouzel et al., 1987; Masson-Delmotte et al., 2008; Parrenin et al., 2004, 2007b). This approach has been applied for deep ice cores after correction of water stable isotope records for variations in the isotopic composition of the ocean, and for artefacts due to changes in moisture sources, using the second order deuterium excess information (Parrenin et al., 2007b; Stenni et al., 2001; Uemura et al., 2012).

Alternatively, constrains on ice core chronologies can be used to infer relative changes in layer thickness, which, after correction for thinning, provide information on past changes in SMB. For example, an independent alternative approach to estimating past SMB of polar ice sheets is to investigate ice-equivalent thickness between accurately dated reference horizons in stratigraphy, which are often represented by volcanic eruption markers. Once the ice-equivalent thicknesses between neighboring volcanic markers are properly corrected for the ice-thinning effect after deposition, the SMB is estimated for the investigated time intervals. The thinning function is relatively straightforward to evaluate for drilling sites located on a dome, where horizontal advection is expected to be negligible (e.g. Dome Fuji, Dome C, TALDICE). This approach is widely used to estimate the SMB of relatively shallow cores or snow pits (e.g., Frezzotti et al., 2013 and references therein). However, thus far, this independent approach has not been used for the enormous number of volcanic markers found in very deep ice cores because most of the volcanic markers in such ice cores have not been dated independently.

Here, we propose a new approach to estimating the past ratio of SMB between two remote dome sites in East Antarctica, Dome Fuji (DF) and EPICA Dome C (EDC) (see Fig. 1), based on a volcanic matching of the stratigraphies. Deep ice cores drilled from the two sites were first synchronized by identifying 1401 volcanic tie points over a period covering the last 216 kyr (see the companion paper Fujita, Parrenin et al., 2015). Instead of dating these 1401 volcanic horizons independently, we derive relative changes in ice thicknesses covering the same time periods between the two cores. After correction of the mechanical thinning effects due to glacial flow, we are able to derive the SMB ratio. This new approach provides information on the SMB pattern of the East Antarctic ice sheet over glacial–interglacial cycles from the last 216 kyr. We discuss how spatially inhomogeneous changes of the SMB occurred between the two remote dome sites.

In addition, Fujita, Parrenin et al. (2015) compared the chronologies for these cores, DFO2006 (Kawamura et al., 2007) and AICC2012 (Bazin et al., 2013; Veres et al., 2013), in terms of differences in ages and event durations. The age gaps between the two chronologies are within 2 kyr, except at Marine Isotope Stage (MIS) 5. DFO2006 gives ages older than AICC2012, with two peaks of gap of 4.5 and 3.1 kyr at MIS 5d and MIS 5b, respectively. Based on cross-analyses for the age gaps between the age markers used for establishing these two chronologies and the ages of the two chronologies, Fujita, Parrenin et al. (2015) hypothesize that systematic DFO2006/AICC2012 age gaps in MIS 5 are are caused by differences in the dating approaches, either the age-markers-based dating or the glaciological dating. They further hypothesize that major sources of the gaps are systematic errors in SMB estimation, rather than errors in ice thinning estimation. We also explore this hypothesis in this study.

2 Methods

2.1 The two studied ice core drilling sites

Dome Fuji and Dome C are two ~ 2000 km distant remote dome summits in East Antarctica (Table 1, Fig. 1). Dome Fuji is located on the polar plateau facing the Atlantic and Indian Ocean sectors and is surrounded by the Dronning Maud mountains, a coastal escarpment in particular along longitude ranging from ∼ 20° W to ∼ 35° E. At Dome Fuji, prevailing wind direction is from the east (Table 1). Present Dome Fuji is located under a spatial gradient of SMB decreasing southwards (Fujita et al., 2011). High-precipitation events associated with strong winds from a NE direction have a major influence on the SMB (Fujita and Abe, 2006), but no seasonality of precipitation has been noted (Fujita and Abe, 2006; Kameda et al., 2008).

Dome C is located at one of the dome summits in East Antarctica in the Indian Ocean sector. Its elevation is lower than that of Dome Fuji by ∼ 570 m. This part of the East Antarctic ice sheet has a gentler slope from the coast to polar plateau compared with the escarpment surrounding Dome Fuji (Fig. 1). Reflecting the shape of the East Antarctic ice sheet, prevailing surface winds are from the south, that is, from continental inland; surface winds rarely occur from W-N-E directions (Aristidi et al., 2005).

In the current climatic conditions, the main moisture transport paths towards these dome sites are estimated to come from lower latitudes based on air mass trajectory calculations using atmospheric reanalyses (Reijmer et al., 2002; Scarchilli et al., 2011; Sodemann and Stohl, 2009; Suzuki et al., 2008). But there are also clear sky precipitation events as well as exchanges of water vapor between surface snow and the surrounding air which have been highlighted in Greenland (Steen-Larsen et al., 2014) and also suggested in Antarctica (Hoshina et al., 2014). Considering the exchanges of water vapor between surface snow and the surrounding air, not only high-precipitation events associated with strong winds, but also daily exposure to prevailing wind, east at DF and south at EDC, may have significant effects to SMB, water stable isotope ratios and snow properties at these dome sites.

At each of the two sites, two long ice cores have been drilled. At Dome Fuji, the first core (DF1) was drilled in 1992–1998 to a depth down to 2503 m (Watanabe et al., 2003). The second 3035 m long core (DF2) reaching nearly the ice sheet bed was drilled in 2004–2007, at a site ∼ 43 m away from the DF1 borehole (Motoyama, 2007). At Dome C, the first core (EDC96) was started in the 1996/1997 season to a depth down to 790 m. The second 3270 m long core (EDC99) reaching nearly the ice sheet bed was started during the 1999/2000 season at a site 10 m away from the EDC96 core (EPICA community members, 2004). Ice core signals from these four cores have been used here for volcanic synchronization.

Here we use as a reference chronology the DFO-2006 time scale established for the DF ice core (Kawamura et al., 2007). This age scale is only used to plot quantities vs. age, but has no impact on the reconstruction of the $\mathrm{SMB_{EDC}/SMB_{DF}}$ ratio. Comparisons between chronologies for DF and EDC cores are discussed in the companion paper Fujita, Parrenin et al. (2015) and later in this paper.

2.2 EDC-DF volcanic synchronization and synchro-based $\mathrm{SMB_{EDC}/SMB_{DF}}$ ratio

The EDC-DF volcanic matching consists of 1401 depth tie points (Fujita, Parrenin et al., 2015), down to a depth of 2184 m at DF and 2170 m at EDC, which roughly corresponds to an age of 216 kyr in the DFO-2006 chronology (Kawamura et al., 2007). In average, that makes one tie point every 154 yr, although their distribution is irregular (Fig. 2). For the periods of MIS 3, 5a and 5b–5e, large number of tie points were found, typically 10–20 points over every 1 kyr. Identifying unequivocal tie points was difficult in some cold periods such as MIS 2, 4 5b and 6. For volcanic signals, ECM, DEP and sulfate data were used for EDC, and ECM and ACECM data were used for DF. More details on the method are given in the companion paper Fujita, Parrenin et al. (2015). These tie points were then re-interpolated every kyr and the ratio of layer thickness at EDC and DF $\Delta z_{\mathrm{EDC}}/\Delta z_{\mathrm{DF}}$ could be inferred (Figs. 2 and 3). We refer to it as layer thickness ratio.

Vertical thinning due to ice flow has been estimated both for the EDC and Dome Fuji ice cores based on a 1-D ice flow model (Parrenin et al., 2007b) with prescribed ice thickness evolution based on a 3-D model of Antarctica evolution (Ritz et al., 2001). The thinning ratio between EDC and DF is 1 for present-day and increases up to about 1.5 at 200 kyr (high thinning ratios imply that EDC thins less than DF), which is mainly due to the fact that the ice thickness is larger at EDC than DF (Table 1). After correcting the layer thickness ratio $\Delta z_{\mathrm{EDC}}/\Delta z_{\mathrm{DF}}$ by the vertical thinning effects, we obtain a synchro-based $\mathrm{SMB}_{\mathrm{EDC}}/\mathrm{SMB}_{\mathrm{DF}}$ ratio (Fig. 2).

2.3 Surface temperature and mass balance at EDC and DF

Surface temperature and mass balance are evaluated from the isotopic content of the ice $\delta^{18}\mathrm{O}_{\mathrm{ice}}$ and $\delta\mathrm{D}_{\mathrm{ice}}$, first corrected for the variations in isotopic content of the ocean $\delta^{18}\mathrm{O}_{\mathrm{SW}}$ and $\delta\mathrm{D}_{\mathrm{SW}}$ (Jouzel et al., 2003):

$$\delta^{18}\mathrm{O}_{\mathrm{corr}} = \delta^{18}\mathrm{O}_{\mathrm{ice}} - \delta^{18}\mathrm{O}_{\mathrm{SW}}\frac{1+\delta^{18}\mathrm{O}_{\mathrm{ice}}}{1+\delta^{18}\mathrm{O}_{\mathrm{SW}}}, \tag{1}$$

$$\delta\mathrm{D}_{\mathrm{corr}} = \delta\mathrm{D}_{\mathrm{ice}} - \delta\mathrm{D}_{\mathrm{SW}}\frac{1+\delta\mathrm{D}_{\mathrm{ice}}}{1+\delta\mathrm{D}_{\mathrm{SW}}}. \tag{2}$$

$\delta^{18}\mathrm{O}_{\mathrm{SW}}$ is taken as reconstructed by Bintanja et al. (2005) based on the exhaustive LR04 oceanic stack (Lisiecki and Raymo, 2005). $\delta\mathrm{D}_{\mathrm{SW}}$ is calculated on the assumption that $\delta\mathrm{D}_{\mathrm{SW}} = 8\ \delta^{18}\mathrm{O}_{\mathrm{SW}}$. From this, we derive a first reconstruction of accumulation, called ocean-corrected:

$$a_{\mathrm{oc}} = A^0 \exp\left(\beta\Delta\delta\mathrm{D}_{\mathrm{corr}}\right) \tag{3}$$

with $\beta = 0.015$ and $A^0(\delta\mathrm{D}_{\mathrm{corr}} = -390.9\,‰) = 3.1\ \text{ice-cm yr}^{-1}$ for EDC and $\beta = 0.013$ and $A^0(\delta\mathrm{D}_{\mathrm{corr}} = -403.1\,‰) = 3.8\ \text{ice-cm}^{-1}$ for DF. The values of these parameters were chosen for a best fit with the published accumulation reconstructions which are compatible with the age scales of the two cores (Parrenin et al., 2007b). The ratio of these reconstructed SMB ratio is hereafter named ocean-corrected $\mathrm{SMB}_{\mathrm{EDC}}/\mathrm{SMB}_{\mathrm{DF}}$ ratio.

Site and source temperatures variations ΔT_{site} and $\Delta T_{\mathrm{source}}$ can then be deduced using a set of two linear equations (Stenni et al., 2001; Uemura et al., 2012):

$$\Delta\delta\mathrm{D}_{\mathrm{corr}} = \gamma_{\mathrm{site}}\Delta T_{\mathrm{site}} - \gamma_{\mathrm{source}}\Delta T_{\mathrm{source}}, \tag{4}$$

$$\Delta\delta d_{\mathrm{corr}} = -\beta_{\mathrm{site}}\Delta T_{\mathrm{site}} + \beta_{\mathrm{source}}\Delta T_{\mathrm{source}}, \tag{5}$$

where d_{corr}, the corrected deuterium excess, is $d_{\mathrm{corr}} = \delta\mathrm{D}_{\mathrm{corr}} - 8\delta^{18}\mathrm{O}_{\mathrm{corr}}$. The coefficients of Eqs. (4) and (5) have been inferred at both sites using a simple Rayleigh-based model, constrained with present-day surface data on the trajectories of air masses (Uemura et al., 2012). Site temperature is calculated from ΔT_{site} using the 10 m snow temperature (Table 1) as the average temperature for the 0–1 kyr BP interval. From this, we derive a second accumulation reconstruction, called source-corrected, which is not based directly on $\delta\mathrm{D}_{\mathrm{ice}}$ but on the source-corrected site temperature reconstruction:

$$a_{\mathrm{sc}} = A^0 \exp\left(\beta \gamma_{\mathrm{site}} \Delta T_{\mathrm{site}}\right) \qquad (6)$$

with $\beta = 0.016$ and $A^0(\delta\mathrm{D}_{\mathrm{corr}} = -368.1\,‰) = 3.2$ ice-cm yr^{-1} for EDC and $\beta = 0.015$ and $A^0(\delta\mathrm{D}_{\mathrm{corr}} = -376.4\,‰) = 3.7$ ice-cm yr^{-1} for DF. The values of these parameters were chosen for a best fit with the published accumulation reconstructions which are compatible with the age scales of the two cores (Parrenin et al., 2007). The ratio of these reconstructed SMB ratio is hereafter named source-corrected $\mathrm{SMB}_{\mathrm{EDC}}/\mathrm{SMB}_{\mathrm{DF}}$ ratio.

3 Results

3.1 Synchro-based $\mathrm{SMB}_{\mathrm{EDC}}/\mathrm{SMB}_{\mathrm{DF}}$ ratio and comparison with the δD records

The ratio of layer thickness $\Delta z_{\mathrm{EDC}}/\Delta z_{\mathrm{DF}}$ inferred from the volcanic synchronization (Fig. 2, green curve) varies at the glacial–interglacial scale; it is maximum during Antarctic warm interglacial phases as indicated by higher $\delta\mathrm{D}_{\mathrm{ice}}$ values. It also exhibits an increasing trend towards the past. We correct the layer thickness ratio for the vertical thinning ratio as deduced from ice flow modeling at both sites (Fig. 2, blue curve) and obtain the $\mathrm{SMB}_{\mathrm{EDC}}/\mathrm{SMB}_{\mathrm{DF}}$ ratio (Fig. 2, orange curve).

Our synchro-based $\mathrm{SMB}_{\mathrm{EDC}}/\mathrm{SMB}_{\mathrm{DF}}$ ratio depicts large variations of up to 40 %. These variations resemble the variations of the $\delta\mathrm{D}_{\mathrm{ice}}$ profiles. Figure 4 suggests a correlation for minor troughs and peaks, as indicated by the thin red vertical dashed lines, although the correlation is not systematic. For example, during the early optimum occurring at about 128 kyr on the DFO-2006 age scale, our method reconstructs EDC SMB to be 10 % higher than DF SMB. However, there are also periods when no relationship between SMB_{EDC}/SMB_{DF} and δD_{ice} is observed. This is the case during the glacial inception cooling (MIS 5d and 5c). Indeed, the lowest values of the synchro-based SMB_{EDC}/SMB_{DF} ratio (0.7) are reached for MIS 5d and 5c, while the lowest values of the δD_{ice} profiles are reached at the Last Glacial Maximum (LGM).

We now focus on the present and last interglacial periods. We first observe that the synchro-based SMB_{EDC}/SMB_{DF} is stable during the late part of the interglacial periods (125–118 kyr b1950 and 8–0 kyr b1950), despite different δD trends (a long-term decrease at DF vs. stable levels at EDC). Second, we note very similar levels in the synchro-based SMB_{EDC}/SMB_{DF} during the present and last interglacial periods, despite more enriched (warmer) mean isotopic ratios during the last interglacial period.

3.2 Comparison of the synchro-based and isotope-based SMB_{EDC}/SMB_{DF} ratios

The synchro-based and isotope-based (ocean-corrected and source-corrected) SMB_{EDC}/SMB_{DF} ratios are compared in Fig. 4. The large scale variations of all SMB ratios display glacial–interglacial variations. The source correction has only a minor effect when compared to the ocean-corrected SMB_{EDC}/SMB_{DF}, with differences generally less than 10 %. The differences are larger between the synchro-based and isotope-based SMB_{EDC}/SMB_{DF} ratios. In particular during MIS 5d and 5c, the difference reaches 20 %, the synchro-based SMB_{EDC}/SMB_{DF} ratio being less than what can be inferred based on water isotopes. The difference also reaches 10 % for periods at 60 and 90 kyr BP. Another noticeable difference is that the synchro-based SMB_{EDC}/SMB_{DF} ratio displays peaks at the beginning of the Holocene and Eemian periods while the isotope-based SMB_{EDC}/SMB_{DF} ratios do not.

4 Discussions

4.1 Present day conditions at EDC and DF

It should first be noted that at present, DF is higher by 600 m, slightly colder, and has 30 ‰ more depleted surface snow δD (Table 1 and Fig. 2). The EDC-DF isotopic differences cannot be explained by differences in surface temperature or relationships with accumulation, based on Rayleigh distillation relationships. Possible hypotheses for this surface isotopic difference, equivalent to about 6 °C when using the classical isotopic paleothermoter (Jouzel and Merlivat, 1984) are linked with the origin of precipitation (Masson-Delmotte et al., 2011), with differences in condensation temperature, with precipitation seasonality and/or intermittency (Masson-Delmotte et al., 2011) or with surface snow–vapor interactions (Hoshina et al., 2014; Steen-Larsen et al., 2014). The more depleted modern value of $\delta \mathrm{D}_{\mathrm{ice}}$ at DF may for instance be explained by a higher proportion of precipitation occurring during winter at this site compared to EDC (but we have no observational evidences to confirm this hypothesis at the moment) or by a more remote moisture source, as expected from the wider winter expansion of sea ice in the Atlantic compared to the Indian Ocean sector (Gersonde et al., 2005).

4.2 Reliability of the thinning corrections

A first argument for the reliability of the thinning evaluation comes from the fact that the $\mathrm{SMB}_{\mathrm{EDC}}/\mathrm{SMB}_{\mathrm{DF}}$ curve, after the thinning correction, has a negligible decreasing trend toward the past. The part of the $\Delta z_{\mathrm{EDC}}/\Delta z_{\mathrm{DF}}$ curve which varies at the glacial–interglacial scale could also be due in part to the vertical thinning, with glacial layers relatively more thinned at EDC, and not correctly accounted for in our ice flow modeling exercise. However, this hypothesis seems unlikely for two reasons. First, by mass conservation, a thinner layer at some place can only be explained if this layer is thicker at a neighboring place, but no irregularity is observed in the isochronal layers observed by ice sounding radars at DF and EDC (Fujita et al., 1999; Tabacco et al., 1998). Second, if glacial ice is softer, the relative difference in cumulated vertical thinning with interglacial ice should increase with the age of the ice layers, as is shown by mechanical simulations (Durand et al., 2007), but no such effect is observed in the $\Delta z_{\mathrm{EDC}}/\Delta z_{\mathrm{DF}}$ curve. We therefore conclude that our vertical thinning evaluation at both sites is robust.

4.3 Relative change of SMB and relative change of local temperature

Glacial climatic conditions coincide with a reduced synchro-based $\mathrm{SMB}_{\mathrm{EDC}}/\mathrm{SMB}_{\mathrm{DF}}$ ratio. At the LGM, we note that the 20 % lower accumulation at EDC than at DF roughly corresponds to 1/5 of the full magnitude of the Holocene-LGM accumulation variations (see Fig. 4). How would this difference in SMB translate into temperature differences, assuming a constant accumulation–temperature relationship? It would correspond to a 2 °C temperature anomaly, scaled to a 10 °C Holocene-LGM contrast of surface temperature (Parrenin et al., 2013). This is consistent with a recent estimate of 2.5 °C for the difference in LGM-present precipitation-weighted temperature change at both sites, with a larger amplitude estimated at EDC than at DF (Uemura et al., 2012). We therefore conclude that our inferred synchro-based SMB ratio change may be a consequence of a change of precipitation-weighted temperature difference between both sites.

4.4 Relative change of SMB and relative change of δD, implications for ice core dating

The differences between the variations of $\mathrm{SMB}_{\mathrm{EDC}}/\mathrm{SMB}_{\mathrm{DF}}$ ratio and the δD variations described in Sect. 3.1 as well as the differences between the synchro-based and isotope based SMB ratios described in Sect. 3.2 challenge the assumption of close relationships between water stable isotope and accumulation anomalies, especially during past interglacial periods.This feature has already been suggested from Holocene data (Parrenin et al., 2007b; Sigl et al., 2014) and from climate simulations of the last interglacial (Sime et al., 2009). Our study also indicates that this decoupling is location dependent. During the late part of the Holocene and the Eemian, our synchro-based SMB_{EDC}/SMB_{DF} ratio is more constant than what is inferred from δD variations.

Clearly, the isotope-based SMB at either EDC or DF or both are associated with relative uncertainties of the order of 10 % at minimum, possibly more with correlated errors which cannot be detected using our synchronization method. This was also suggested in the companion paper Fujita, Parrenin et al. (2015) based on the same volcanic synchronization. They hypothesize that a cause of the systematic DFO2006/AICC2012 age gaps in MIS 5 are associated with differences in the dating approaches, either the age-markers-based dating or the glaciological dating. They further hypothesize that major sources of the gaps are systematic errors in SMB estimation.

Inaccurate estimates of SMB based on water stable isotope records can cause important errors for chemical fluxes reconstructions and ice core chronologies but also for firn (Goujon et al., 2003) and ice sheet (Ritz et al., 2001) modeling.

4.5 Possible implications on relative elevation changes

We now investigate the possible impacts of our estimated changes in the SMB_{EDC}/SMB_{DF} ratio for the relative elevation at both sites. Parrenin et al. (2007b) calculated a LGM-present elevation change of ~ 120 m at both sites, mainly due to an accumulation change of ~ 50 %, those accumulation changes having been deduced from the ice isotopes. Therefore, a deviation of the accumulation reconstruction of ~ 20 % as is observed at ~ 110 kyr b1950 could correspond to a difference in elevation change of ~ 50 m at the glacial–interglacial scale. Taking into account a vertical gradient of temperature of 1 °C/100 m, such ice sheet thinning would lead to an underestimation of the magnitude of temperature decrease “at fixed elevation” by approximately 0.5 °C.

4.6 Atmospheric process, dome movement or elevation change artifact?

In the following, we will discuss three different hypotheses to explain the changes in the SMB_{EDC}/SMB_{DF} ratio: regional differences in climate (at constant geometry of the ice sheet), changes of dome position affecting snow redeposition by wind, or differences in elevation changes.

Different atmospheric processes may explain the variations in the $\mathrm{SMB_{EDC}/SMB_{DF}}$ ratio: (1) effects related to moisture sources and distillation along transport paths, (2) different glacial sea ice expansions in the Atlantic and Indian ocean sectors (Gersonde et al., 2005), enhancing accumulation and temperature changes at EDC compared with those at DF, (3) effects associated with precipitation intermittency and/or seasonality (e.g., Suzuki et al., 2013), (4) less frequent blocking events at EDC (Massom et al., 2004) than at DF (Hirasawa et al., 2000) during glacial periods, these warm events being responsible of a large proportion of the total annual accumulation (Hirasawa et al., 2000) and (5) differences in surface snow–vapor exchanges which can alter the snowfall signal in-between snowfall events (Hoshina et al., 2014; Steen-Larsen et al., 2014).

We now explore the dome movement hypothesis. Today, we observe a spatial gradient of accumulation at Dome C (Urbini et al., 2008) and Dome Fuji (Fujita et al., 2011), due to orographic precipitation or to snow redeposition by winds linked with surface curvature. Under a spatial gradient of accumulation rate and glacial/interglacial climatic changes, it seems natural that the ice divides locations migrate. In addition, SMB is affected by local features of the bedrock topography (Fujita et al., 2011). A movement of the domes (see Saito, 2002 for the movement of DF during the past) could therefore create an apparent change of accumulation in the ice core records. In this case, we would not expect any constant relationship between water stable isotopes and accumulation rate, except if the dome movement is itself correlated to processes affecting the isotopic composition of water vapor and precipitation (e.g. via sea level changes and grounding line migration).

Concerning the elevation hypothesis, it is not impossible that EDC and DF experienced different changes in elevation, since the ice flow at those two sites should not react in the same way to sea level changes (Saito and Abe-Ouchi, 2010). On one hand, DF is relatively insensitive to sea level changes since it is well protected by the Dronning Maud Mountains. On the other hand, EDC is very sensitive to sea level changes since grounding lines in Wilkes Lands can advance and retreat far away (Mengel and Levermann, 2014). Therefore, it is expected that elevation change should be different at EDC and DF. Quantitatively, if inter-site temperature differences would only be driven by ice thickness changes and using a vertical temperature gradient of 1 °C/100 m (Krinner and Genthon, 1999), then 2 °C colder glacial conditions at EDC would translate into a 200 m relative elevation difference at the LGM between EDC and DF. This is quite large compared to the current estimates of the central East Antarctic ice sheet LGM topography, as ice sheet simulations suggest an overall lowering of surface elevation by about 120 m (Ritz et al., 2001), driven by the lower glacial accumulation. We however stress that these ice sheet simulations were driven by a homogenous scenario of accumulation changes (a hypothesis challenged by our findings), and that they have intrinsic limitations in the representation of dynamical effects associated with grounding line migration (Pattyn et al., 2012).

5 Conclusions

Our study suggests that the vertical thinning functions evaluated by ice flow models at EDC and DF are valid for the depth range covered here (the last 216 kyr). We produce a new paleoclimatic record, the $\mathrm{SMB_{EDC}/SMB_{DF}}$ ratio, which varies at the glacial–interglacial scale. Regional differences in climate are identified, with EDC characterized by an enhanced (+20 %) amplitude of glacial cooling and drying, compared to DF. The data evidence that interglacial changes in $\mathrm{SMB_{EDC}/SMB_{DF}}$ ratio do not scale with those of water stable isotopes, challenging classical hypotheses used for ice core chronologies and for ice sheet modeling. The SMB ratio reduces strongly in MIS 5d and c, 30 % lower than what would be deduced from the isotopes. Moreover, the SMB ratio is almost constant during the late parts of the current and last interglacial periods, in contradiction with contrasting isotopic trends at EDC and DF. Changes in the $\mathrm{SMB_{EDC}/SMB_{DF}}$ ratio may be due to regional climate differences at both sites, or to

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◄| |►
◄ ►
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

an artifact of dome movement influencing snow redistribution by wind, or to a different change of elevation at both sites. Further studies are necessary to discriminate between these three hypotheses. Expanding this approach towards other sites will also give more regional information on the past SMB pattern. We also identified plausible cause of the gaps between the ice core chronologies at DF and at EDC. The overall results of the DF/EDC volcanic synchronization will be used when establishing the next synchronized and optimized age scale. The inferred regional differences in SMB variations should also be taken into account in glacial–interglacial Antarctic ice sheet modelling.

Author contributions. The writing of this paper was lead by the two first authors: F. Parrenin and S. Fujita. They contributed equally and shared the responsibilities for this paper. They carried out the synchronization work, lead discussions, and oversaw the writing of this paper. E. Wolff and M. Severi provided the EDC electrical profile data and EDC sulphate data, respectively. S. Fujita and H. Motoyama provided the entire electrical profile data of the DF core. All authors joined in the scientific discussions.

Acknowledgements. We thank Gerhard Krinner, Catherine Ritz, Kazue Suzuki and Jean Jouzel for helpful discussions. We wish to also thank all participants to the field seasons at Dome C. The main logistic support was provided by IPEV and PNRA at Dome C. This work is a contribution to the European Project for Ice Coring in Antarctica (EPICA), a joint European Science Foundation/European Commission scientific program, funded by the EU and by national contributions from Belgium, Denmark, France, Germany, Italy, the Netherlands, Norway, Sweden, Switzerland and the United Kingdom. This is EPICA publication nb XX.

We also thank all the Dome Fuji Deep Ice Core Project members who contributed to obtaining the ice core samples, either through logistics, drilling or core processing. The main logistics support was provided by the Japanese Antarctic Research Expedition (JARE), managed by the Ministry of Education, Culture, Sports, Science and Technology (MEXT). This study was supported in part by a Grant-in-Aid for Scientific Research (A) (20241007) and a Grant-in-Aid for Young Scientists (S) (21671001) from the Japan Society for the Promotion of Science (JSPS). The manuscript was prepared with the support of an National Institute of Polar Research (NIPR) publication subsidy.

References

Aristidi, E., Agabi, K., Azouit, M., Fossat, E., Vernin, J., Travouillon, T., Lawrence, J. S., Meyer, C., Storey, J. W. V, Halter, B., Roth, W. L., and Walden, V.: An analysis of temperatures and wind speeds above Dome C, Antarctica, Astron. Astrophys., 430, 739–746, 2005.

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, doi:10.5194/cp-9-1715-2013, 2013.

Bengtsson, L., Koumoutsaris, S., and Hodges, K.: Large-scale surface mass balance of ice sheets from a comprehensive atmospheric model, Surv. Geophys., 32, 459–474, 2011.

Bintanja, R., de Wal, R. S. W., and Oerlemans, J.: Modelled atmospheric temperatures and global sea levels over the past million years, Nature, 437, 125–128, 2005.

Church, J. A., Clark, P. U., Cazenave, A., Gregory, J. M., Jevrejeva, S., Levermann, A., Merrifield, M. A., Milne, G. A., Nerem, R. S., Nunn, P. D., Payne, A. J., Pfeffer, W. T., Stammer, D., and Unnikrishnan, A. S.: Sea Level Change, in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge, UK and New York, NY, USA, 2013.

Durand, G., Gillet-Chaulet, F., Svensson, A., Gagliardini, O., Kipfstuhl, S., Meyssonnier, J., Parrenin, F., Duval, P., and Dahl-Jensen, D.: Change in ice rheology during climate variations – implications for ice flow modelling and dating of the EPICA Dome C core, Clim. Past, 3, 155–167, doi:10.5194/cp-3-155-2007, 2007.

Ekaykin, A.: Régime météorologique de l’Antarctique central et son rôle dans la composition isotopique de la neige, Faculté de géographie de Saint Pétersbourg, 23 October, available at: http://tel.archives-ouvertes.fr/tel-00701466 (accessed 19 August 2014), 2003.

EPICA community members: 8 glacial cycles from an Antarctic ice core, Nature, 429, 623–628, 2004.

Frezzotti, M., Pourchet, M., Flora, O., Gandolfi, S., Gay, M., Urbini, S., Vincent, C., Becagli, S., Gragnani, R., Proposito, M., Severi, M., Traversi, R., Udisti, R., and Fily, M.: New estimations of precipitation and surface sublimation in East Antarctica from snow accumulation measurements, Clim. Dynam., 23, 803–813, 2004.

Frezzotti, M., Scarchilli, C., Becagli, S., Proposito, M., and Urbini, S.: A synthesis of the Antarctic surface mass balance during the last 800 yr, The Cryosphere, 7, 303–319, doi:10.5194/tc-7-303-2013, 2013.

Fujita, K. and Abe, O.: Stable isotopes in daily precipitation at Dome Fuji, East Antarctica, Geophys. Res. Lett., 33, L18503, doi:10.1029/2006GL026936, 2006.

Fujita, S., Maeno, 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, J. Geophys. Res., 104, 13013–13024, 1999.

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, The Cryosphere, 5, 1057–1081, doi:10.5194/tc-5-1057-2011, 2011.

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, Clim. Past Discuss., 11, 407–445, doi:10.5194/cpd-11-407-2015, 2015.

Gallée, H., Trouvilliez, A., Agosta, C., Genthon, C., Favier, V., and Naaim-Bouvet, F.: Transport of snow by the wind: a comparison between Observations in Adélie Land, Antarctica, and Simulations made with the Regional Climate Model MAR, Bound.-Layer Meteorol., 146, 133–147, 2013.

Gersonde, R., Crosta, X., Abelmann, A., and Armand, L.: Sea-surface temperature and sea ice distribution of the Southern Ocean at the EPILOG Last Glacial Maximum – a circum-Antarctic view based on siliceous microfossil records, Quaternary Sci. Rev., 24, 869–896, 2005.

Goujon, C., Barnola, J.-M., and Ritz, C.: Modeling the densification of polar firn including heat diffusion: application to close-off characteristics and gas isotopic fractionation for Antarctica and Greenland sites, J. Geophys. Res., 108, 4792, doi:10.1029/2002JD003319, 2003.

Hirasawa, N., Nakamura, H., and Yamanouchi, T.: Abrupt changes in meteorological conditions observed at an inland Antarctic station in association with wintertime blocking, Geophys. Res. Lett., 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, J. Geophys. Res., 119, D020771, doi:10.1002/2013JD020771, 2014.

Jouzel, J. and Merlivat, L.: Deuterium and oxygen 18 in precipitation?: modeling of the isotopic effects during snow formation, J. Geophys. Res., 89, 11749–11757, 1984.

Jouzel, J., Lorius, C., Petit, J.-R., Genthon, C., Barkov, N. I., Kotlyakov, V. M., and Petrov, V. M.: Vostok ice core: a continuous isotope temperature record over the last climatic cycle (160,000 years), Nature, 329, 403–408, 1987.

Jouzel, J., Vimeux, F., Caillon, N., Delaygue, G., Hoffmann, G., Masson, V., and Parrenin, F.: Magnitude of isotope/temperature scaling for interpretation of central Antarctic ice cores, J. Geophys. Res., 108, 4361, doi:10.1029/2002JD002677, 2003.

Jouzel, J., Masson-Delmotte, V., Cattani, O., Dreyfus, G., Falourd, S., Hoffmann, G., Minster, B., Nouet, J., Barnola, J. M., Chappellaz, J., Fischer, H., Gallet, J. C., Johnsen, S., Leuenberger, M., Loulergue, L., Luethi, D., Oerter, H., Parrenin, F., Raisbeck, G., Raynaud, D., Schilt, A., Schwander, J., Selmo, E., Souchez, R., Spahni, R., Stauffer, B., Steffensen, J. P., Stenni, B., Stocker, T. F., Tison, J. L., Werner, M., and Wolff, E. W.: Orbital and millennial antarctic climate variability over the past 800 000 years, Science, 317, 793–796, doi:10.1126/science.1141038, 2007.

Kameda, T., Takahashi, S., Enomoto, H., Azuma, N., Shiraiwa, T., Komada, Y., Furukawa, T., Watanabe, O., Weidner, G. A., and Stearns, C. R.: Meteorological observations along a traverse route from coast to Dome Fuji Station, Antarctica, recorded by Automatic Weather Stations in 1995, in: Proceedings of the NIPR Symposium on Polar Meteorology and Glaciology, vol. 11, 35–50, 1997.

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., Uemura, R., Vimeux, F., Severinghaus, J. P., Matsumoto, K., Nakata, H., Nakazawa, T., Aoki, S., Jouzel, J., Fujii, Y., and Watanabe, O.: Northern Hemisphere forcing of climatic cycles over the past 360,000 years implied by absolute dating of Antarctic ice cores, Nature, 448, 912–917, doi:10.1038/nature06015, 2007.

King, J. C., Argentini, S. A., and Anderson, P. S.: Contrasts between the summertime surface energy balance and boundary layer structure at Dome C and Halley stations, Antarctica, J. Geophys. Res., 111, D02105, doi:10.1029/2005JD006130, 2006.

Krinner, G. and Genthon, C.: Altitude dependence of the surface climate over the ice sheets, Geophys. Res. Lett., 26, 2227–2230, 1999.

Lisiecki, L. E. and Raymo, M. E.: A plio-pleistocene stack of 57 globally distributed benthic δ^{18}O records, Paleoceanography, 20, PA1003, doi:10.1029/2004PA001071, 2005.

Massom, R. A., Pook, M. J., Comiso, J. C., Adams, N., Turner, J., Lachlan-Cope, T., and Gibson, T. T.: Precipitation over the interior East Antarctic ice sheet related to midlatitude blocking-high activity, J. Climate, 17, 1914–1928, 2004.

Masson-Delmotte, V., Hou, S., Ekaykin, A., Jouzel, J., Aristarain, A., Bernardo, R. T., Bromwich, D., Cattani, O., Delmotte, M., Falourd, S., Frezzotti, M., Gallée, H., Genoni, L., Isaksson, E., Landais, A., Helsen, M. M., Hoffmann, G., Lopez, J., Morgan, V., Motoyama, H., Noone, D., Oerter, H., Petit, J. R., Royer, A., Uemura, R., Schmidt, G. A., Schlosser, E., Simões, J. C., Steig, E. J., Stenni, B., Stievenard, M., van den Broeke, M. R., van de Wal, R. S. W., van de Berg, W. J., Vimeux, F., and White, J. W. C.: A review of antarctic surface snow isotopic composition: observations, atmospheric circulation, and isotopic modeling, J. Climate, 21, 3359–3387, 2008.

Masson-Delmotte, V., Buiron, D., Ekaykin, A., Frezzotti, M., Gallée, H., Jouzel, J., Krinner, G., Landais, A., Motoyama, H., Oerter, H., Pol, K., Pollard, D., Ritz, C., Schlosser, E., Sime, L. C., Sodemann, H., Stenni, B., Uemura, R., and Vimeux, F.: A comparison of the present and last interglacial periods in six Antarctic ice cores, Clim. Past, 7, 397–423, doi:10.5194/cp-7-397-2011, 2011.

Mengel, M. and Levermann, A.: Ice plug prevents irreversible discharge from East Antarctica, Nat. Clim. Change, 4, 451–455, doi:10.1038/nclimate2226, 2014.

Motoyama, H.: The second deep ice coring project at Dome Fuji, Antarctica, Sci. Drill., 5, 41–43, 2007.

Motoyama, H., Hirasawa, N., Satow, K., and Watanabe, O.: Seasonal variations in oxygen isotope ratios of daily collected precipitation and wind drift samples and in the final snow cover at Dome Fuji Station, Antarctica, J. Geophys. Res. Atmos., 110, D11106, doi:10.1029/2004JD004953, 2005.

Motoyama, H. and Dome Fuji community members: A new 3035.22 m deep ice core at Dome Fuji, Antarctica and reconstrction of global climate and environmental change over past 720 kyr, in: AGU Fall Meeting Abstracts, vol. 1, p. 76., 2007.

Parish, T. R. and Bromwich, D. H.: The surface windfield over the Antarctic ice sheets, Nature, 328, 51–54, 1987.

Parrenin, F., Remy, F., Ritz, C., Siegert, M., and Jouzel, J.: New modelling of the Vostok ice flow line and implication for the glaciological chronology of the Vostok ice core, J. Geophys. Res., 109, D20102, doi:10.1029/2004JD004561, 2004.

Parrenin, F., Barnola, J.-M., Beer, J., Blunier, T., Castellano, E., Chappellaz, J., Dreyfus, G., Fischer, H., Fujita, S., Jouzel, J., Kawamura, K., Lemieux-Dudon, B., Loulergue, L., Masson-Delmotte, V., Narcisi, B., Petit, J.-R., Raisbeck, G., Raynaud, D., Ruth, U., Schwander, J., Severi, M., Spahni, R., Steffensen, J. P., Svensson, A., Udisti, R., Waelbroeck, C., and Wolff, E.: The EDC3 chronology for the EPICA Dome C ice core, Clim. Past, 3, 485–497, doi:10.5194/cp-3-485-2007, 2007a.

Parrenin, F., Dreyfus, G., Durand, G., Fujita, S., Gagliardini, O., Gillet, F., Jouzel, 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, doi:10.5194/cp-3-243-2007, 2007b.

Parrenin, F., Masson-Delmotte, V., Köhler, P., Raynaud, D., Paillard, D., Schwander, J., Barbante, C., Landais, A., Wegner, A., and Jouzel, J.: Synchronous change of atmospheric CO_2 and Antarctic temperature during the last deglacial warming, Science, 339, 1060–1063, 2013.

Pattyn, F., Schoof, C., Perichon, L., Hindmarsh, R. C. A., Bueler, E., de Fleurian, B., Durand, G., Gagliardini, O., Gladstone, R., Goldberg, D., Gudmundsson, G. H., Huybrechts, P., Lee, V., Nick, F. M., Payne, A. J., Pollard, D., Rybak, O., Saito, F., and Vieli, A.: Results of the Marine Ice Sheet Model Intercomparison Project, MISMIP, The Cryosphere, 6, 573–588, doi:10.5194/tc-6-573-2012, 2012.

Reijmer, C. H., den Broeke, M. R., and Scheele, M. P.: Air parcel trajectories and snowfall related to five deep drilling locations in Antarctica based on the ERA-15 dataset, J. Climate, 15, 1957–1968, 2002.

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

Ritz, C., Rommelaere, V., and Dumas, C.: Modeling the evolution of Antarctic ice sheet over the last 420,000 years: implications for altitude changes in the Vostok region, J. Geophys. Res., 106, 31931–31964, 2001.

Saito, F.: Development of a three dimensional ice sheet model for numerical studies of Antarctic and Greenland ice sheet, University of Tokyo, Dept. of Earth and Planetary Science, Tokyo, May 2002.

Saito, F. and Abe-Ouchi, A.: Modelled response of the volume and thickness of the Antarctic ice sheet to the advance of the grounded area, Ann. Glaciol., 51, 41–48, 2010.

Scarchilli, C., Frezzotti, M., and Ruti, P. M.: Snow precipitation at four ice core sites in East Antarctica: provenance, seasonality and blocking factors, Clim. Dynam., 37, 2107–2125, doi:10.1007/s00382-010-0946-4, 2011.

Sigl, M., McConnell, J. R., Toohey, M., Curran, M., Das, S. B., Edwards, R., Isaksson, E., Kawamura, K., Kipfstuhl, S., Krüger, K., Layman, L, Maselli, O. J., Motizuki, Y., Motoyama, H., Pasteris, D. R., and Severi, M.: Insights from Antarctica on volcanic forcing during the Common Era, Nature Clim. Change, 4, 693–697, 2014.

Sime, L. C., Wolff, E. W., Oliver, K. I. C., and Tindall, J. C.: Evidence for warmer interglacials in East Antarctic ice cores, Nature, 462, 342–345, 2009.

Sodemann, H. and Stohl, A.: Asymmetries in the moisture origin of Antarctic precipitation, Geophys. Res. Lett., 36, L22803, doi:10.1029/2009GL040242, 2009.

Steen-Larsen, H. C., Masson-Delmotte, V., Hirabayashi, M., Winkler, R., Satow, K., Prié, F., Bayou, N., Brun, E., Cuffey, K. M., Dahl-Jensen, D., Dumont, M., Guillevic, M., Kipfstuhl, S., Landais, A., Popp, T., Risi, C., Steffen, K., Stenni, B., and Sveinbjörnsdottír, A. E.: What controls the isotopic composition of Greenland surface snow?, Clim. Past, 10, 377–392, doi:10.5194/cp-10-377-2014, 2014.

Stenni, B., Masson-Delmotte, V., Johnsen, S., Jouzel, J., Longinelli, A., Monnin, E., Röthlisberger, R., and Selmo, E.: An oceanic cold reversal during the last deglaciation, Science, 293, 2074–2077, doi:10.1126/science.1059702, 2001.

Suzuki, K., Yamanouchi, T., and Motoyama, H.: Moisture transport to Syowa and Dome Fuji stations in Antarctica, J. Geophys. Res., 113, D24114, doi:10.1029/2008JD009794, 2008.

Suzuki, K., Yamanouchi, T., Kawamura, K., and Motoyama, H.: The spatial and seasonal distributions of air-transport origins to the Antarctic based on 5-day backward trajectory analysis, Polar Science, 7, 205–213, doi:10.1016/j.polar.2013.08.001, 2013.

Tabacco, I. E., Passerini, A., Corbelli, F., and Gorman, M.: Determination of the surface and bed topography at Dome C, East Antarctica, J. Glaciol., 44, 185–191, 1998.

Takahashi, S., Ageta, Y., Fujii, Y., and Vvataabe, O.: Surface mass balance in east Dronning Maud Land, Antarctica, observed by Japanese Antarctic research expeditions, Ann. Glaciol., 20, 242–248, 1994.

Takahashi, S., Kameda, T., Enomoto, H., Motoyama, H., and Watanabe, O.: Automatic Weather Station (AWS) data collected by the 33rd to 42nd Japanese Antarctic Research Expeditions during 1993–2001, JARE Data Rep. Meteorol., 36, 1–416, 2004.

Uemura, R., Masson-Delmotte, V., Jouzel, J., Landais, A., Motoyama, H., and Stenni, B.: Ranges of moisture-source temperature estimated from Antarctic ice cores stable isotope records over glacial–interglacial cycles, Clim. Past, 8, 1109–1125, doi:10.5194/cp-8-1109-2012, 2012.

Urbini, S., Frezzotti, M., Gandolfi, S., Vincent, C., Scarchilli, C., Vittuari, L., and Fily, M.: Historical behaviour of Dome C and Talos Dome (East Antarctica) as investigated by snow accumulation and ice velocity measurements, Global Planet. Change, 60, 576–588, 2008.

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, doi:10.5194/cp-9-1733-2013, 2013.

Watanabe, O., Jouzel, J., Johnsen, S., Parrenin, F., Shoji, H., and Yoshida, N.: Homogeneous climate variability across East Antarctica over the past three glacial cycles, Nature, 422, 509–512, 2003.

Wolff, E. W., Fischer, H., Fundel, F., Ruth, U., Twarloh, B., Littot, G. C., Mulvaney, R., Röthlisberger, R., de Angelis, M., Boutron, C. F., Hansson, M., Jonsell, U., Hutterli, M. A., Lambert, F., Kaufmann, P., Stauffer, B., Stocker, T. F., Steffensen, J. P., Bigler, M., Siggaard-Andersen, M. L., Udisti, R., Becagli, S., Castellano, E., Severi, M., Wagenbach, D., Barbante, C., Gabrielli, P., and Gaspari, V.: Southern Ocean sea-ice extent, productivity and iron flux over the past eight glacial cycles, Nature, 440, 491–496, 2006.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◂◂ ▸▸
◂ ▸
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 1. Information on the two drilling sites.

Variable	Dome Fuji	EPICA Dome C	Data sources
Location	77.32° S, 39.70° E	75°06′ S, 123°21′ E	EPICA community members (2004); Watanabe et al. (2003)
Elevation on WGS84 (m)	3800	3233	EPICA community members (2004; Watanabe et al. (2003)
Ice thickness (m)	3028 (±15)	3273 (±5)	Fujita et al. (1999); Parrenin et al. (2007b)
Distance from the coast (km)	~ 930	~ 950	This study
Total length of ice core (m)	3035	3260	Motoyama et al. (2007); Parrenin et al. (2007b)
Annual mean air temperature (°C)	−54.8	−51.2[a]	Fujita and Abe (2006); King et al. (2006)
10 m snow temperature (°C)	−57.7	−54.8	Motoyama et al. (2005); L. Arnaud (personnal communication, 2015)
Annual accumulation rate (kg m^{-2})	27.3 ± 0.4[b]	26 ± 3	Frezzotti et al. (2004); Kameda et al. (2008)
Annual mean wind speed (m s^{-1})	5.9 at 10 m	3.6 at 3.3 m	Aristidi et al. (2005); Takahashi et al. (2004)
Annual mean atmospheric pressure (hPa)	598.4	644.9	Parish and Bromwich (1987); Watanabe et al. (2003)
Prevailing wind direction at the surface	NE~E	S	Aristidi et al. (2005); Kameda et al. (1997)

[a] Over the period 1984–2013.

[b] Snow stake farm.

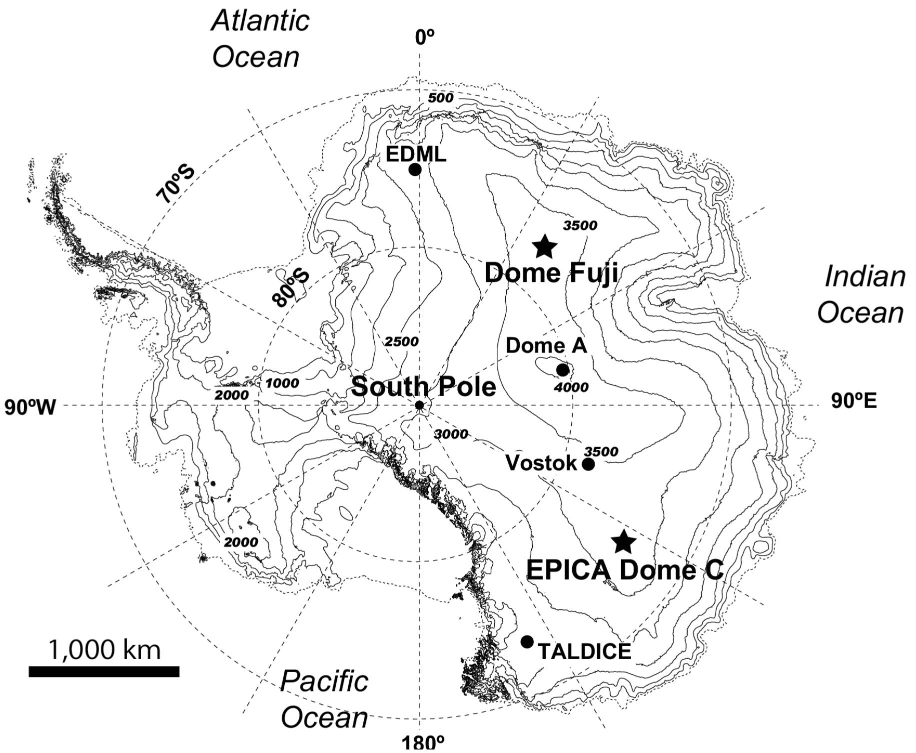

Figure 1. Map of the Antarctica continent with elevation contours every 500 m. The two ice coring sites used in this study, Dome C and Dome Fuji, are marked with stars. Other ice coring sites are marked with filled circles.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀◀
▶▶
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

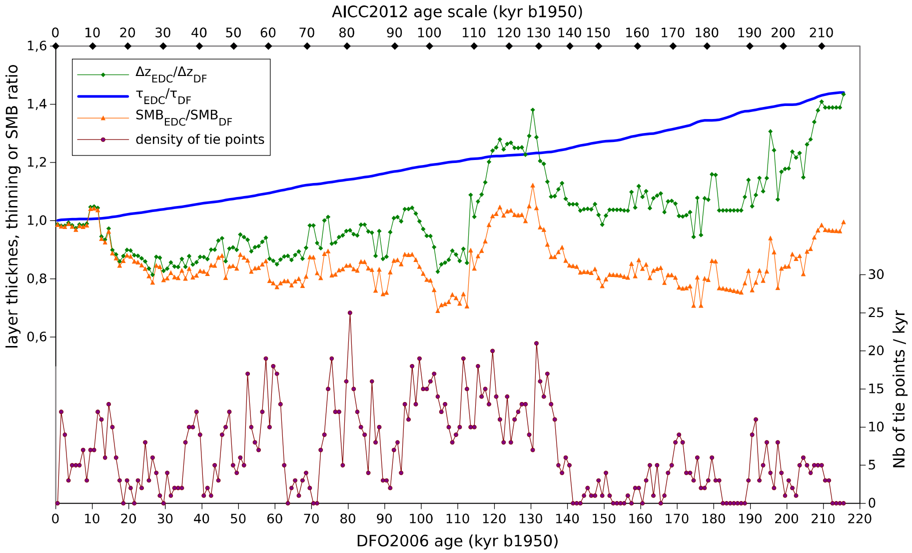

Figure 2. Ratio of layer thickness (green) or surface mass balance (orange) after correcting for the EDC-DF thinning ratio (blue). The density of tie points (violet) is indicated in the lower panel (nb of tie points per kyr). The DFO-2006 (Kawamura et al., 2007) and AICC2012 (Bazin et al., 2013; Veres et al., 2013) age scales are used.

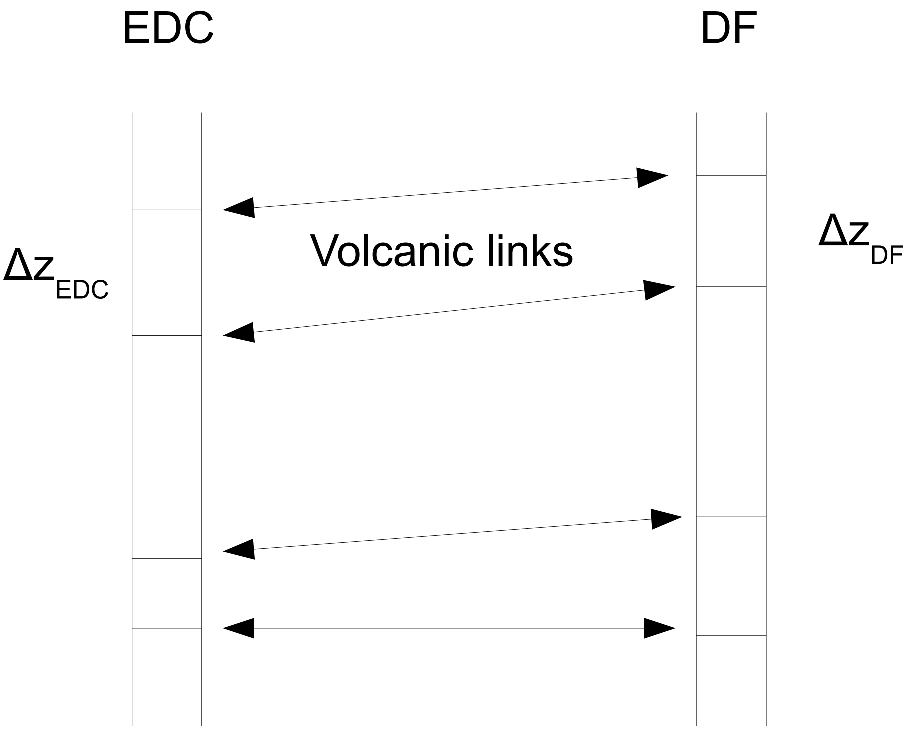

Figure 3. Scheme illustrating the derivation of the $\Delta z_{EDC}/\Delta z_{DF}$ ratio from the volcanic links in between the EDC and DF ice cores.

CPD
11, 377–405, 2015

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

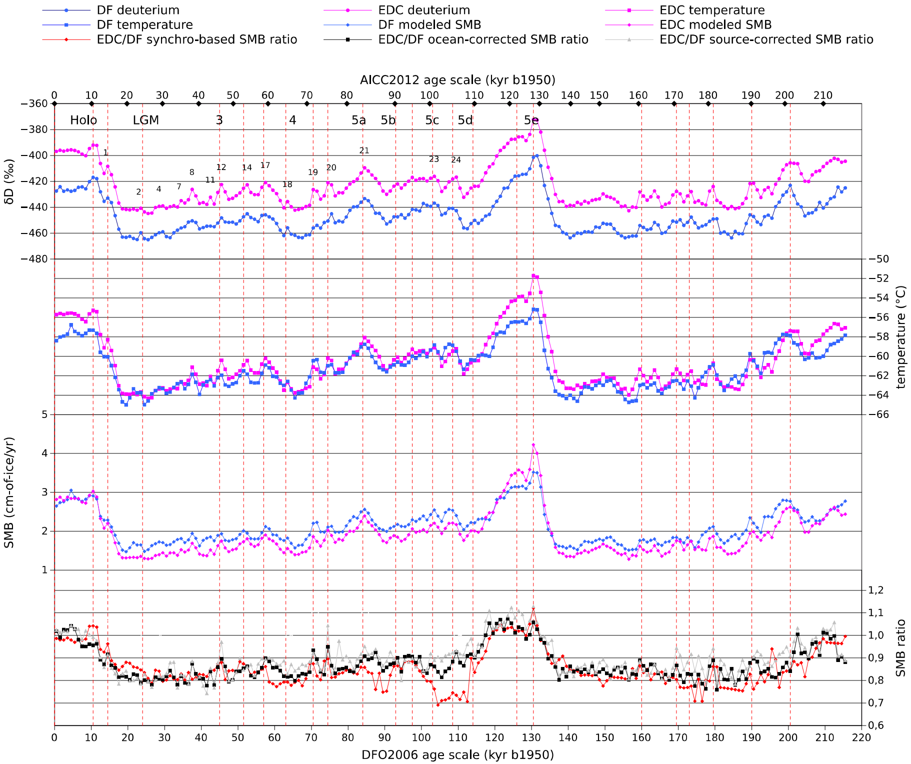

Figure 4. (top) DF (Watanabe et al., 2003) (blue) and EDC (Jouzel et al., 2007) (pink) δD_{ice} variations. Top labels indicate the Marine Isotope Stages and bottom labels indicate the Antarctic Isotopic Maxima (AIMs) events. (middle top) DF (blue) and EDC (pink) T_{site} reconstructions from ice core data (Parrenin et al., 2007b). (middle bottom) DF (blue) and EDC (pink) surface accumulation rate reconstructions based on water stable isotope data (Parrenin et al., 2007b). (bottom) Ratio of ocean-corrected (black), source-corrected (grey) and synchro-based (red) surface mass balances. The DFO-200 (Kawamura et al., 2007) and AICC2012 age scales (Bazin et al., 2013; Veres et al., 2013) are used.