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Constraints on post-depositional isotope modifications in East Antarctic firn from analysing temporal changes of isotope profiles

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Abstract. Stable water isotopes in firn and ice cores are extensively used to infer past climate changes. In low-accumulation regions their interpretation is however challenged by poorly constrained effects that may influence the initial isotope signal during and after deposition. This is reflected in snow-pit isotope data from Kohnen Station, Antarctica, which exhibit a clear seasonal cycle but also strong inter-annual variations that contradict local temperature observations. These inconsistencies persist even after averaging many profiles and are thus not explained by local stratigraphic noise. Previous studies have suggested that post-depositional processes may significantly influence the isotopic composition of East Antarctic firn. Here, we reject the hypothesis of post-depositional change within the open-porous firn beyond diffusion and densification. To this end, we analyse 22 stable water isotope profiles obtained from two snow trenches at Kohnen Station and examine the temporal isotope modifications by comparing the new with published trench data extracted 2 years earlier. The initial isotope profiles undergo changes over time due to downward-advection, firn diffusion and densification in magnitudes consistent with independent estimates. Beyond that, we find no evidence for additional modification of the original isotope record. These results show that the discrepancy between local temperatures and isotopes most likely originates from spatially coherent processes prior to or during deposition, such as precipitation intermittency or systematic isotope modifications acting on drifting or loose surface snow.

1 Introduction

Stable water isotopes from ice cores are important climate proxies. Their abundance ratios in falling snow are shaped by different fractionation processes in between the moisture source and the precipitation site, including evaporation (Craig and Gordon, 1965), air-mass advection and Rayleigh distillation (Dansgaard, 1964), and snow formation (Jouzel and Merlivat, 1984). Hence, stable water isotope ratios can be linked to the climatic conditions at the local or moisture source site. For instance, physical modelling of the large-scale hydrological cycle and the fractionation processes has validated the link between the isotopic composition of precipitation and local temperature (Jouzel et al., 1997, 2003, and references therein). For polar ice sheets, observational evidence has suggested a robust relationship at large spatial scales (i.e. continental) between the isotopic composition of snow and annual-mean temperature at the sampling sites (Dansgaard, 1964; Lorius et al., 1969; Masson-

Delmotte et al., 2008). Isotope data archived in polar ice cores have therefore become an invaluable means to infer past site temperature variations (e.g. Petit et al., 1999; NEEM community members, 2013) or changes in the moisture sources (e.g. Vimeux et al., 2001; Uemura et al., 2012), and show, at least qualitatively, a globally consistent picture of glacial–interglacial to millennial-scale climate changes (EPICA community members, 2004, 2006; NGRIP members, 2004). However, it is questioned whether the assumption that pre-depositional fractionation processes are the main influence on firn and ice isotope ratios, while seemingly fulfilled for large spatial and temporal scales, holds in general. Particularly in low-accumulation areas for which the snow surface is exposed to the atmosphere for a substantial time, a variety of processes are thought to considerably modify the original atmospheric isotope signal during or after deposition of the snow, thus from seasonal to inter-annual timescales (e.g. Ekaykin et al., 2014, 2016; Hoshina et al., 2014; Touzeau et al., 2016; Casado et al., 2016).

For the East Antarctic Plateau, isotopic modifications during and after deposition are generally expected. The isotope ratios of buried snow are affected by diffusion of interstitial water vapour (Johnsen, 1977; Whillans and Grootes, 1985; Cuffey and Steig, 1998; Johnsen et al., 2000; Gkinis et al., 2014) and firn densification (Hörhold et al., 2011; Freitag et al., 2013); however, these processes only smooth and compress the original signal without changing the net isotopic composition of the snow. In contrast, the low local annual accumulation rates and potential seasonal intermittency of precipitation increase the time the surface is exposed to the atmosphere (Town et al., 2008; Hoshina et al., 2014) and therefore to processes that might alter the snow's original isotopic composition. These processes can act either on loose snow in the post-condensational phase (falling or drifting snow), on deposited surface snow or on buried snow in the open-porous firn column which is no longer subject to erosion but still in contact with the atmosphere. For instance, exchange of water vapour between the first metre of firn and the overlying atmosphere through diffusion and wind-driven ventilation (Waddington et al., 2002; Neumann and Waddington, 2004; Town et al., 2008) can introduce vapour with a different isotopic signature to the firn and significantly change the isotopic composition. Isotopic exchanges between the top layer of snow and the lower atmosphere have been observed at the NEEM site in Greenland (Steen-Larsen et al., 2014) and at Kohnen Station in East Antarctica (Ritter et al., 2016). Isotopic fractionation associated with sublimation, condensation and recrystallisation processes at or within the near-surface firn might change the initial isotope signal, as indicated by observations (Moser and Stichler, 1974; Stichler et al., 2001) and lab experiments (Hachikubo et al., 2000; Sokratov and Golubev, 2009). However, for East Antarctica, a quantitative assessment based on field data is still outstanding, and the importance of these processes for shaping the isotopic signal in the near-surface firn remains poorly constrained.

One way to address the question of post-depositional modification is to compare two firn-core isotope profiles obtained at different times and to measure the nature in which the first profile has been modified. However, this approach is complicated by spatial variability from stratigraphic noise (Fisher et al., 1985), caused by uneven deposition and the constant wind-driven erosion, redistribution and vertical mixing of the snow surface. Thus, the comparison of two single records sampled at different times will always confound temporal isotope changes and spatial variability. A previous study from East Antarctica has shown that the spatial variability can be overcome by averaging across a suitable number of single profiles extracted from snow trenches drilled at Kohnen Station in Dronning Maud Land (Münch et al., 2016). This yielded a spatially representative isotope signal on a horizontal scale of approximately $500\,\mathrm{m}$. However, contrasting the isotope data with instrumental observations from

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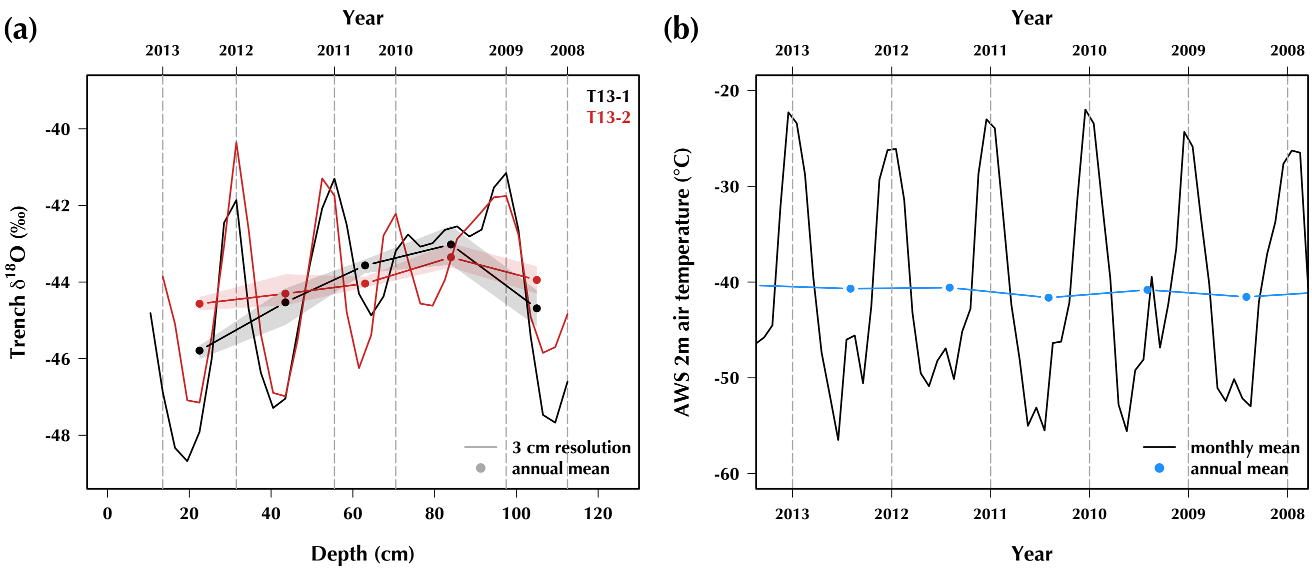

Figure 1. Comparison of oxygen isotope data and 2 m air temperature at Kohnen Station, Antarctica. (**a**) Mean δ^{18}O profiles of trenches T13–1 (black) and T13–2 (red) (modified after Münch et al. (2016)) on original 3 cm (lines) as well as annual resolution (points with uncertainty shading from shifting the range of the annual bins). (**b**) 2 m air temperature (black lines: monthly means, blue points: annual means) recorded by the automatic weather station AWS9 located at Kohnen Station < 1 km from the trench excavation sites. Note the different timescales (**a**: based on counting and binning the extrema of the isotope data, **b**: true calendar dates). The mean of the 2 m air temperature shown here lies about 3.5 °C above the published local 10 m firn temperature (Table 1).

a nearby automatic weather station (AWS, Reijmer and van den Broeke (2003)) suggests that this regional signal does not necessarily represent a regional temperature signal (Fig. 1). Whereas the isotope record shows strong year-to-year variability, the observed temperature variations are characterised by a regular seasonal cycle and small inter-annual changes. This discrepancy stresses the importance of contributions other than regional temperature alone to the formation of the isotope signal.

In this study, we investigate whether post-depositional isotope modifications in the open-porous firn contribute to the observed discrepancy between isotopes and local temperature at Kohnen Station. We present new data from an extensive field work campaign, yielding 22 profiles of stable water isotope ratios obtained from two snow trenches, and compare these with the data of the previous trench campaign conducted 2 years earlier. By enabling representative records from the spatial averaging of single profiles, we have designed our study such that it allows for the first time to quantitatively follow the isotopic changes and thus to test for post-depositional effects over a time span of 2 years. Therefore, beyond simply stating the problem of local isotope–temperature discrepancy we go further and can quantitatively estimate, based on the data and our theoretical understanding of stratigraphic noise, the influence of post-depositional change for our study site. This is an important step towards better constraining the isotope signal formation in East Antartic firn.

Table 1. Information on the EPICA Dronning Maud Land (EDML) drilling site at Kohnen Station, Antarctica. Listed are approximate position (latitude, longitude), elevation, $10\,\mathrm{m}$ firn temperature $\overline{T}_{\mathrm{firn}}$, mean annual accumulation rate of snow $\overline{b}$, and mean monthly wind speed $\overline{v}_{\mathrm{wind}}$ (± 1 standard deviation).

Drilling site	*Latitude*	*Longitude*	*Elevation*	$\overline{T}_{\mathrm{firn}}$	$\overline{b}$	$\overline{v}_{\mathrm{wind}}$
	°N	°E	m a.s.l.	°C	$\mathrm{mm\,w.eq.\,yr^{-1}}$	$\mathrm{m\,s^{-1}}$
EDML	-75.0^{a}	0.1^{a}	2892^{a}	-44.5^{a}	64^{a} / 82.5^{b}	4.2 ± 1.1^{c}

[a] EPICA community members (2006). [b] Mean of snow stake measurements 2013–2015. [c] AWS9 data 1998–2013.

2 Data and methods

2.1 Sampling and measurements

A pair of firn trenches, each with a horizontal length of $50\,\mathrm{m}$ and a depth of $3.4\,\mathrm{m}$, was excavated using a snow blower in the austral summer field season 2014/2015 near Kohnen Station (Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung, 2016), the location of the EPICA Dronning Maud Land deep ice core drilling site (Fig. 2 and Table 1). This campaign extends the published oxygen isotope data set obtained from two shallower ($\sim 1\,\mathrm{m}$) trenches in 2012/2013 (Münch et al., 2016). From the new trenches, we present the top $1.75\,\mathrm{m}$ of the data which are estimated to cover the period imprinted in the trenches of the first campaign. To avoid contamination, the new trench positions were shifted relative to the previous ones by $160\,\mathrm{m}$ and $300\,\mathrm{m}$, respectively, and are separated by $550\,\mathrm{m}$ (Fig. 2). In the remaining part of the manuscript, "T13" will refer to the pair of previous trenches from 2012/2013, "T15" to the pair of new trenches from 2014/2015.

Field works of the new T15 trench campaign were conducted as follows. Horizontal profiles of the surface height variations were obtained along each trench using a levelling instrument. The uncertainty of these profiles is estimated from the reading accuracy of the levelling rod of $0.5\,\mathrm{cm}$. The windward walls of the trenches were cleaned after excavation by slicing off a thin firn layer. Firn profiles were then sampled directly off the wall with a vertical resolution of $3\,\mathrm{cm}$ and a horizontal spacing of $5\,\mathrm{m}$, yielding 11 profiles in each trench. The vertical resolution is small enough to evaluate the seasonal cycle of the istope data of $\sim 20\,\mathrm{cm}$ (Münch et al., 2016); the inter-profile distance of $5\,\mathrm{m}$ corresponds approximately to three times the decorrelation length of the stratigraphic noise observed in the T13 record (Münch et al., 2016). At both trenches, excavation and subsequent sampling of the profiles was conducted in two consecutive stages (2 times $\sim 1\,\mathrm{m}$ depth); each stage was completed within 24 h. All firn samples ($N = 1214$) were stored in plastic bags, tightly packed, transported to Germany in frozen state and analysed for stable water isotope ratios at the isotope laboratory of the Alfred Wegener Institute (AWI) in Potsdam, using a cavity ring-down spectrometer (L2130i, Picarro Inc.). The results are reported in the usual delta notation (oxygen isotopes: $\delta^{18}\mathrm{O}$, deuterium: $\delta\mathrm{D}$) in per mil (‰) relative to the international V-SMOW/SLAP scale. Calibration and correction of the raw measurements was performed as described in Münch et al. (2016). The mean combined measurement uncertainty is $0.08\,‰$

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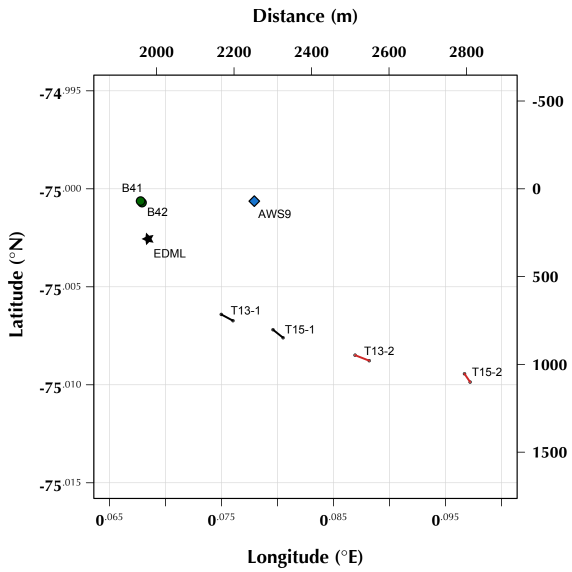

Figure 2. Map of the study area at Kohnen Station. Snow trenches are shown as black and red lines, firn-core sites as green filled circles. The drilling site of the EPICA Dronning Maud Land (EDML) ice core is shown as a black star, the position of the automatic weather station (AWS9) as a blue filled diamond. The trenches were aligned perpendicularly to the local snow-dune direction.

for δ^{18}O (root-mean square deviation, RMSD) and $0.8‰$ for δD, assessed by evaluating a standard not used in the calibration and correction procedure.

2.2 Trench depth scale

Following Münch et al. (2016), we record and display the trench isotope data with respect to an absolute height reference given by the respective maximum of the surface height profile of each trench. Note that the near-surface layer of the trench records is incomplete on this depth scale (up to $\sim 10\,\mathrm{cm}$ for T13 and $\sim 18\,\mathrm{cm}$ for T15) due to the surface undulations. Averaging of trench profiles is performed relative to the absolute height reference. Therefore, the number of data points contributing to a mean profile is lower and varies in the near-surface layer. This part is marked by dashed lines for all mean profiles and is excluded from all quantitative calculations. Our conclusions are therefore limited to firn depths below $\sim 10\,\mathrm{cm}$ but are however, as will be shown, not essentially changed when including the near-surface layer.

2.3 Spatial variability of average trench profiles

Spatial variability arising from stratigraphic noise is a major contribution to the overall variability of individual trench isotope profiles (Münch et al., 2016). Its magnitude ω can be estimated from the horizontal variability of the trench isotope record. Averaging across individual trench profiles reduces the total noise variability. Specifically, stratigraphic noise can be modelled

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Table 2. Sampling and statistical properties of the trench δ^{18}O records from the field seasons 2012/2013 (T13, Münch et al. (2016)) and 2014/2015 (T15, this study). Listed are: Number and distance of sampled profiles, δ^{18}O values and variability, correlation of mean trench profiles, and estimated signal-to-noise variance ratios (SNR) after Münch et al. (2016). Correlations are maximised through allowing relative vertical shifts (optimal shift given in brackets).

Trench record:	*T13–1*	*T13–2*	*T15–1*	*T15–2*
number of profiles:	38	4	11	11
profile distances (m):	~ 0.1–2.5	10, 20	5	5
δ^{18}O (‰):				
range: min/max	$-54/-34$	$-50/-38$	$-56/-32$	$-55/-33$
mean (SD)	$-44.4\,(3.1)$	$-44.0\,(2.7)$	$-44.7\,(3.8)$	$-44.5\,(3.8)$
δ^{18}O variance ((‰)^2):				
mean horizontal	5.9	5.3	7.0	6.6
mean vertical	9.5	7.3	13.8	14.2
mean profile correlation (optimal shift)	0.81 (+3 cm)		0.91 (-0.5 cm)	
signal-to-noise ratio	0.9 ± 0.4	0.5 ± 0.5	1.0 ± 0.3	1.5 ± 0.5

by a first-order autoregressive process with a horizontal decorrelation length for the study region of $\lambda \simeq 1.5\,\mathrm{m}$ (Münch et al., 2016). Then, the residual noise variability of a mean profile built by averaging across N individual records is

$$\varepsilon_{\mathrm{res}} = \frac{\omega}{N^2}\Big(N + f(N,d;\lambda)\Big) \equiv \frac{\omega}{N_{\mathrm{eff}}}, \quad (1)$$

where $f(N,d;\lambda)$ is a function of the number of averaged profiles, of the inter-profile distances d and of the horizontal decorrelation length of the stratigraphic noise, λ. Eq. (1) equivalently can be expressed through the effective number of records, N_{eff}. For independent noise (zero autocorrelation, $\lambda \to 0$), $N_{\mathrm{eff}} \to N$, as expected.

2.4 Quantification of downward-advection, firn densification and firn diffusion

We expect that within 2 years the original T13 isotope profiles have been compressed through densification of the firn, advected downwards due to new snow fall and smoothed by firn diffusion. To quantify these effects, certain site-specific parameters have to be known.

Firn densities are provided independently of the trench data by high-resolution X-ray Computer Tomography data (Freitag et al., 2013) of the firn cores B41 and B42 (core distance $\sim 10\,\mathrm{m}$, Laepple et al. (2016)) drilled in vicinity to the trenches ($\sim 1\,\mathrm{km}$, Fig. 2). The average firn density in the first metre is $\sim 330\,\mathrm{kg\,m^{-3}}$. The densification rate relative to the surface is $\sim 2\,\%\,\mathrm{m^{-1}}$ when regressing density against depth over the first $2\,\mathrm{m}$, $\sim 7\,\%\,\mathrm{m^{-1}}$ when regressing over the first $5\,\mathrm{m}$.

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The local annual accumulation rate of snow was $29\,\mathrm{cm}$ in the year 2013 and $21\,\mathrm{cm}$ in 2014, which was estimated from an array of snow stake measurements conducted near the trench excavation sites. In general, the recent local accumulation rate strongly depends on the measurement site, with values ranging from 20–30 cm of snow per year which is up to $50\,\%$ larger than the published longtime mean (Table 1).

The smoothing effect of firn diffusion on an isotope profile can be described as the convolution with a Gaussian kernel (Johnsen et al., 2000). The amount of smoothing (the width of the Gaussian convolution kernel) is controlled by the diffusion length σ which increases monotonically in the upper firn layer (Johnsen et al., 2000). We model σ according to Gkinis et al. (2014) with diffusivity after Johnsen et al. (2000). Firn density is a main input to the depth dependency of the diffusion length. For the calculations we smooth the stacked B41/B42 density data by fitting a quadratic polynomial in the square root of the depth. For the concept of differential diffusion, we consider a firn layer which is located at the average depth z_1 and has thickness Δz over which the increase in diffusion length ($\Delta\sigma$) is small compared to the layer thickness, $\Delta\sigma/\Delta z \ll 1$. Now the firn layer is advected downwards to the depth z_2. The total amount of diffusion that acted since the layer has been at the surface is the convolution of the layer's initial isotope profile at the surface, δ_0, with a diffusion length $\sigma(z_2)$. Equivalently, since the Gaussian convolution is a linear operation, we can express this as the diffusion of δ_0 with $\sigma(z_1)$, followed by diffusion of the resulting profile with the differential diffusion length

$$\tilde{\sigma} = \sqrt{\sigma^2(z_2) - \sigma^2(z_1)}. \tag{2}$$

For the T13 isotope profiles, we account for an approximate average effect of differential diffusion over 2 years by considering the average diffusion lengths calculated over the depth of the T13 profiles before and after downward-advection.

2.5 Statistical tests

We use the Kolmogorov–Smirnov (KS) test to assess whether differences between mean trench profiles are identically distributed. Autocorrelation of the data is accounted for with a modified version of the standard test adopting effective degrees of freedom of $n(1-a)$ (Xu, 2013). Here, n is the total number of data points for each profile and a the estimated autocorrelation parameter at lag 1.

3 Results

3.1 New T15 isotope data and qualitative comparison with T13

The two new T15 δ^{18}O trench records measured in 2015/16 (Fig. 3a, b) are qualitatively consistent with the T13 data (Münch et al., 2016) measured 2 years earlier. The isotopic variability within the first metres of firn is characterised by roughly horizontal, alternating layers of enriched and depleted isotopic composition (Fig. 3a, b) separated on average by approximately the local annual layer thickness of snow (20–30 cm) and thus representing the climatic seasonal cycle. In addition, stratigraphic noise leads to significant horizontal variability, becoming visible through discontinuous and inhomogeneous layering as well as patchy features, for example at the surface of trench T15–2 (Fig. 3b). We also find similar statistical properties for the data

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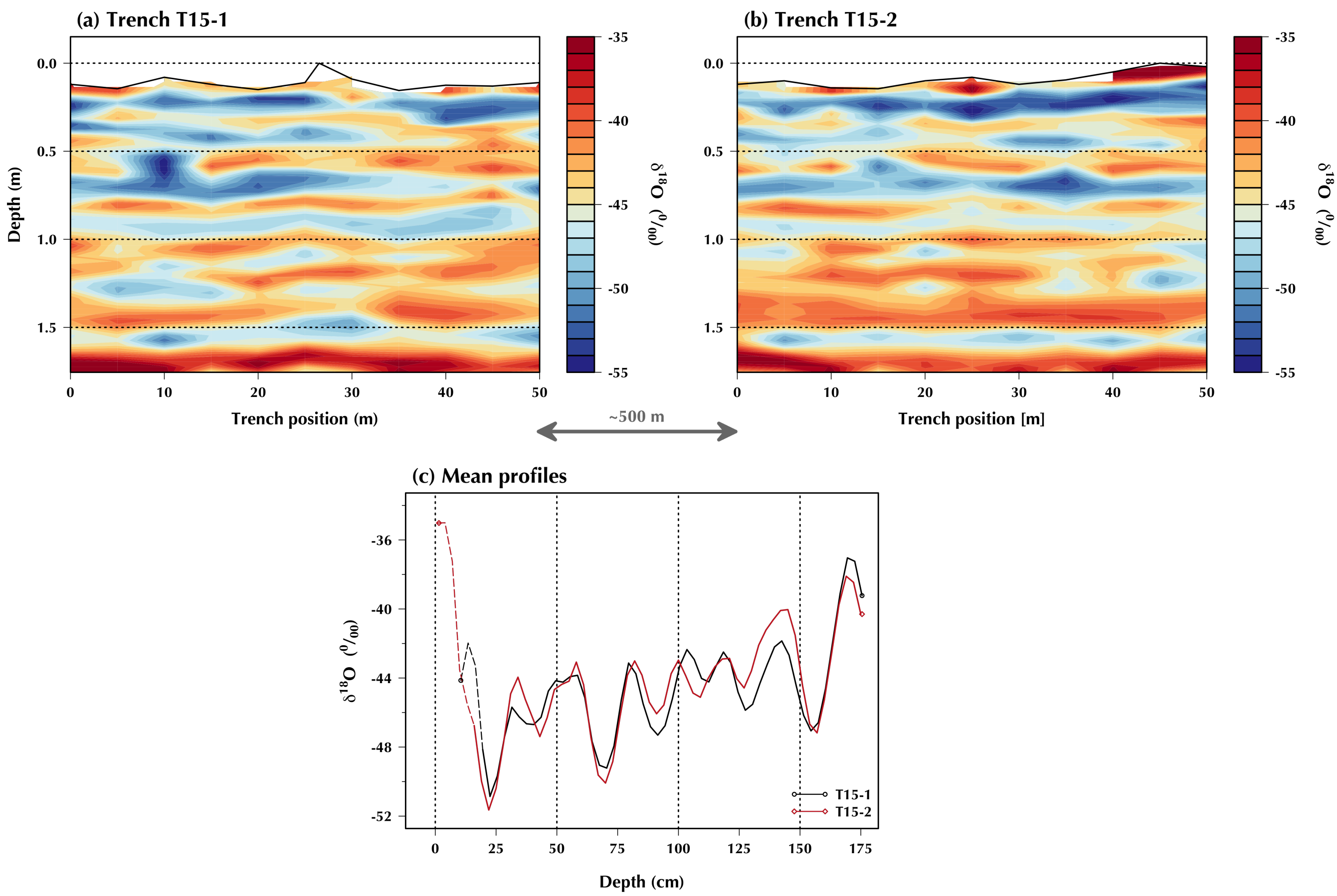

Figure 3. The new T15 δ^{18}O data set. Displayed are the isotope records of trench T15–1 (**a**) and trench T15–2 (**b**) as two-dimensional colour images, and the mean profiles from averaging across the individual profiles of each trench (**c**), displayed after optimal shifting of T15–2 (see text). The trench surface height profiles are given by solid black lines, the near-surface part of each mean profile is marked by dashed lines since the trench data are incomplete there (see Data and methods). The vertical scale in **a** and **b** is strongly exaggerated.

of each trench campaign (Table 2). The higher variances in vertical direction of the T15 records are partly expected for auto-correlated data in combination with a larger record length, in addition to the contribution by the strongly enriched layer around $170\,\mathrm{cm}$ depth.

Averaging across all individual profiles of each T15 trench reduces the noise level and yields mean profiles that are highly correlated (correlation $r = 0.91$, RMSD $\sim 1.2\,‰$, Fig. 3c) and thus spatially representative. We maximised this match by allowing vertical shifts of the T15–2 profile. Using linearly interpolated data on a resolution of $0.5\,\mathrm{cm}$, we find an optimal shift of $-0.5\,\mathrm{cm}$. We note the exceptionally high delta values at the top of the T5–2 mean profile which stem from a prominent dune at the trench surface (Fig. 3). However, this top part has no overlap on the absolute depth scale with the T15–1 mean profile and therefore does not contribute to the total T15 mean profile discussed below. Despite their representativity, the T15–1 and

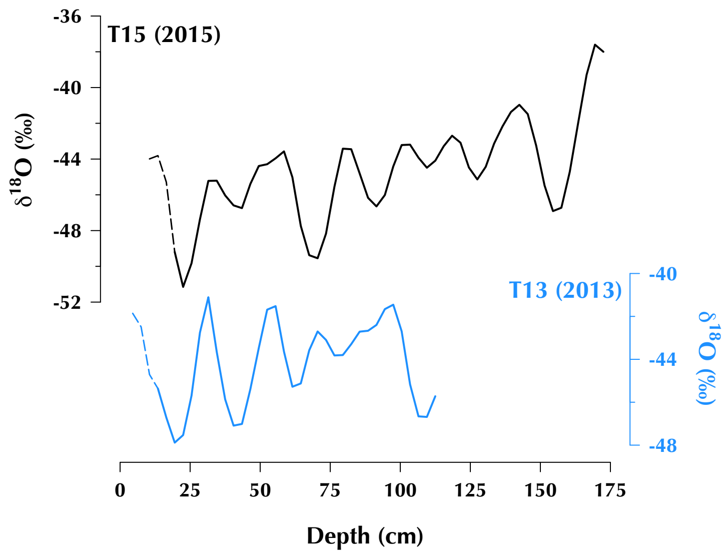

Figure 4. The mean oxygen isotope profiles of the T15 (this study) and T13 (Münch et al. (2016)) trenches. The incomplete near-surface layer of the trenches is marked by dashed lines.

T15–2 mean profiles show strong year-to-year variability confirming the discrepancy to local temperature previously found for T13 (Fig. 1).

Our first findings show that at our study site both the nature of the regional isotope signal and the stratigraphic noise are comparable between the two trench campaigns. In the following sections we quantitatively assess to what extent the original T13 signal can be recovered with the T15 trenches obtained 2 years later. For this task, we use a single data set for T13 and T15 from averaging across each pair of mean profiles (Fig. 4), accounting for the optimal vertical shifts that maximise each inter-trench correlation (Table 2).

3.2 Expected isotope profile changes between 2013 and 2015

We analyse to what extent the T13 record can be recovered from the new T15 data, and which changes have modified the original record. In the 2 years, the T13 isotope profiles are advected downwards, compressed by densification and smoothed by firn diffusion. Testing for additional isotopic modifications hence requires estimating at first the magnitudes of those known processes. We do this in two ways: Firstly, we use data independent of the trench records. Secondly, to check consistency with the first estimate, we determine the parameter set that optimally quantifies the processes by minimising the difference between the T13 and T15 mean profiles.

Using the independent snow stake and density data sets, we obtain the following estimates. The annual accumulation rates suggest a downward-advection of the T13 profiles after 2 years of $50\,\mathrm{cm}$. Further, we expect, based on the theory of firn diffusion, an additional diffusion of the T13 δ^{18}O profiles over the course of 2 years according to a differential diffusion

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length (Eq. 2) of $\tilde{\sigma} \sim 1.9\,\mathrm{cm}$. This value is obtained by comparing the average diffusion length over the depths covered by the T13 record before (0–$100\,\mathrm{cm}$) and after the expected downward-advection (50–$150\,\mathrm{cm}$). The estimated densification rate of ~ 2–$7\,\%\,\mathrm{m}^{-1}$ at the study site implies a compression of the T13 profiles after 2 years of approximately 1–$4\,\mathrm{cm}$.

For the second estimate, we vary the three parameters (downward-advection Δ, differential diffusion length $\tilde{\sigma}$, compression γ) in order to minimise the root-mean square deviation between the T15 and T13 mean profiles: For the downward-advection, we apply vertical shifts between $\Delta = 40$ and $60\,\mathrm{cm}$, comprising the snow-stake based range of the recent annual accumulation rates; additional diffusion of the original T13 mean profile is modelled with differential diffusion lengths $\tilde{\sigma}$ from 0 to $8\,\mathrm{cm}$; and compression is applied for values between $\gamma = 0$ and $10\,\mathrm{cm}$. We obtain the best agreement (RMSD = $0.92\,‰$, Fig. 5; $r = 0.93$) between the T15 and the modified T13 mean profile (= T13*) for the optimal parameters $\Delta_{\mathrm{opt}} = 50.5\,\mathrm{cm}$, $\tilde{\sigma}_{\mathrm{opt}} = 2.3\,\mathrm{cm}$ and $\gamma_{\mathrm{opt}} = 3.5\,\mathrm{cm}$ (Fig. 6). These trench-based parameter estimates agree reasonably well with the independent estimates from above, showing that the trench data are compatible with our assumptions for downward-advection, densification and diffusion. Indeed, using the independent parameter estimates ($\Delta_{\mathrm{ind}} = 50\,\mathrm{cm}$, $\tilde{\sigma}_{\mathrm{ind}} = 1.9\,\mathrm{cm}$, $\gamma_{\mathrm{ind}} = 2.2\,\mathrm{cm}$ from mean over estimated densification rate) to modify the original T13 mean profile (= T13**), results only in a slightly higher deviation from T15 (RMSD = $0.94\,‰$, $r = 0.93$) compared to T13*.

The visual agreement of both mean profiles after modifying T13 is remarkable regarding cyclicity and, to a lesser extent, the amplitude of the isotopic variations (Fig. 6b). However, deviations especially remain around the isotopic extreme values, in particular for the first overlapping cycle and the depths around ~ 100 and ~ 125–$140\,\mathrm{cm}$. These differences are relatively large compared to the influence of firn diffusion and densification on the original T13 profile (Fig. 6a). Nevertheless, both processes play a significant role in explaining part of the temporal changes. This can be seen if we only shift the T13 mean profile vertically to find the maximum correlation with T15, without accounting for diffusion and densification. This gives a best shift of $48.5\,\mathrm{cm}$, but clearly the agreement is less pronounced (RMSD = $1.1\,‰$, $r = 0.88$) compared to using T13* or T13**.

3.3 Do the remaining differences represent temporal or spatial variability?

We have shown that downward-advection, firn diffusion and densification contribute as expected to the temporal modification of the original T13 profiles. Taking these processes into account leads to a good match of the trench mean profiles (Fig. 6b). However, deviations on the order of 0.9–$1\,‰$ remain. These can have two causes: firstly, additional temporal changes driven by unaccounted post-depositional processes; secondly, remaining spatial variability since we average a large but finite number of records which do not originate from the exact same position. We can thus deduce the importance of additional post-depositional change for our study site if we quantify the contribution of spatial varibility. In the following, this is done in two ways: (1) by using the statistical model for stratigraphic noise, and (2) by analysing the distributions of the profile differences.

According to the statistical noise model, the effective number of profiles that contribute to the T13 and T15 mean profiles (Eq. 1) is $N_{\mathrm{eff}} = 13$ for T13 and $N_{\mathrm{eff}} = 20$ for T15. The residual noise of the mean profiles arising from spatial variability is thus the noise level before averaging ($\omega \sim 5$–$7\,(‰)^2$, Table 2) divided by 13 and 20, respectively. We can assume that the residual noise terms are independent of each other. Therefore, the uncertainty of the difference between the T13 and T15 mean

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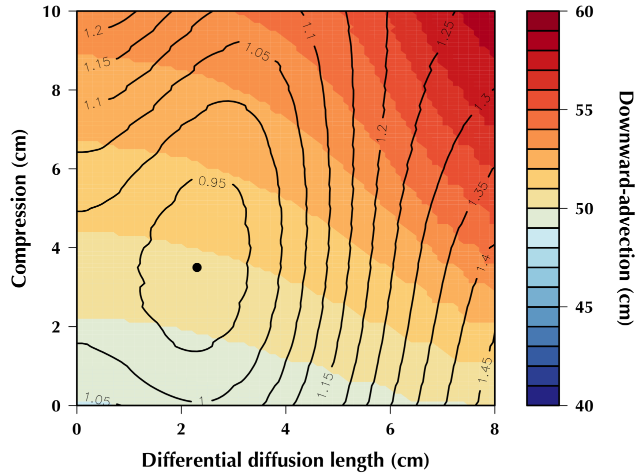

Figure 5. Effect of downward-advection, firn diffusion and linear compression due to densification on the misfit between the T15 and the modified T13 mean profile. For each parameter set of compression and diffusion, we record the minimum root-mean square deviation of the profiles (contour lines) for the optimal downward-advection value (colour scale). The global minimum in RMSD is marked with a black dot.

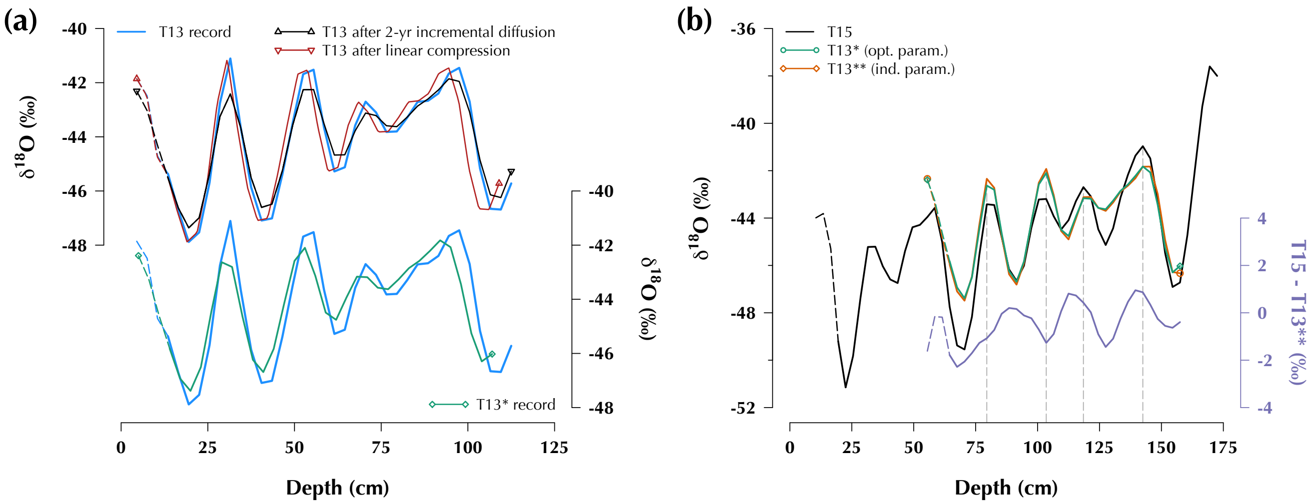

Figure 6. Expected changes of the T13 and comparison to the T15 mean profile. **a**: (Upper panel) The original T13 mean profile (blue) and its modification by diffusion (black: 2-year diffusion with differential diffusion length $\tilde{\sigma} = 2.3\,\mathrm{cm}$) as well as densification (red: linear compression of $\gamma = 3.5\,\mathrm{cm}$). (Lower panel) The original T13 mean profile (blue) compared to the joint effect of 2-year diffusion and linear compression (green, T13*). **b**: The T15 mean profile (black) in comparison to the T13 mean profile after modifying the latter according to (1) the optimal parameters for downward-advection, incremental diffusion and linear densification (green, T13*), and to (2) the corresponding parameters obtained independently from the trench records (orange, T13**). Additionally, the difference between T15 and T13** is shown (violet lines, axis to the right). Vertical dashed lines mark the isotopic summer maxima which are not in phase with the difference curve.

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profiles is the sum of each residual spatial variability, or ~ 0.6–$0.9\,(‰)^2$. For comparison, the square of the RMSD between the T13* and T15 mean profile is $0.85\,(‰)^2$. The agreement of both estimates indicates that the remaining profile differences between the modified T13 mean profile and T15 (Fig. 6b) can be entirely explained by spatial variability through stratigraphic noise. We note however that the squared RMSD lies at the upper end of the estimated range of residual stratigraphic noise, which also applies to the RMSD between the T15–1 and T15–2 mean profiles (square of RMSD of $1.44\,(‰)^2$ vs. uncertainty from residual stratigraphic noise of ~ 1.0–$1.4\,(‰)^2$). This could indicate that part of the spatial variability on the scale of the inter-trench distances ($\sim 500\,\mathrm{m}$) is not explained by our stratigraphic noise model.

We therefore make a formal statistical test comparing spatial and temporal variability which accounts for the full extent of spatial uncertainty by analysing the deviations between the mean trench profiles. We find that the distributions of the spatial differences between the mean profiles of each trench campaign (T13–1 vs. T13–2 and T15–1 vs. T15–2, Fig. 7a) are statistically indistinguishable ($p > 0.5$ from modified KS test, combining all possible directions of calculating the differences). This suggests that the spatial variability on the inter-trench scale is comparable between the two field campaigns. More importantly, the combined distribution of spatial variability is also indistinguishable from the distribution of the temporal differences between the T15 and the modified T13 mean profile (all $p > 0.5$ for using T13** to avoid overfitting, Fig. 7b).

In summary, both methods show no evidence for any temporal changes of the trench record over the course of 2 years apart from downward-advection accompanied by firn diffusion and densification. The remaining deviations that are observed between the mean profiles of the two trench campaigns can be entirely explained by residual spatial variability arising to a large extent from stratigraphic noise.

4 Discussion

We presented and analysed a new extensive data set of 22 oxygen isotope profiles obtained at Kohnen Station from two $50\,\mathrm{m}$ long and $\sim 180\,\mathrm{cm}$ deep snow trenches. The new trench campaign was designed such that it allows for a direct comparison with a trench data set obtained from the same site 2 years earlier in order to test for post-depositional effects. In the following, we first discuss our results concerning the expected processes that have influenced the trench isotope profiles over the observed time period, then our findings regarding the possibility of additional post-depositional changes.

4.1 Densification, diffusion and stratigraphic noise

We found a strong resemblance between the mean oxygen isotope profiles from the trench field campaigns of 2013 and 2015 after taking into acount the effects of downward-advection, water vapour diffusion within the firn and firn densification that occured during the 2 years. The estimated magnitudes of these processes obtained from matching both records are consistent with independent estimates from snow stakes, diffusion theory and independent density profiles.

The estimated small compression of the T13 profiles is reasonable given the densification rate observed in the top metres of nearby firn cores. However, our assumption of a linear profile compression with depth is certainly a rough approximation given the actually observed seasonal firn density variation (Laepple et al., 2016). Our data-based estimate of differential firn

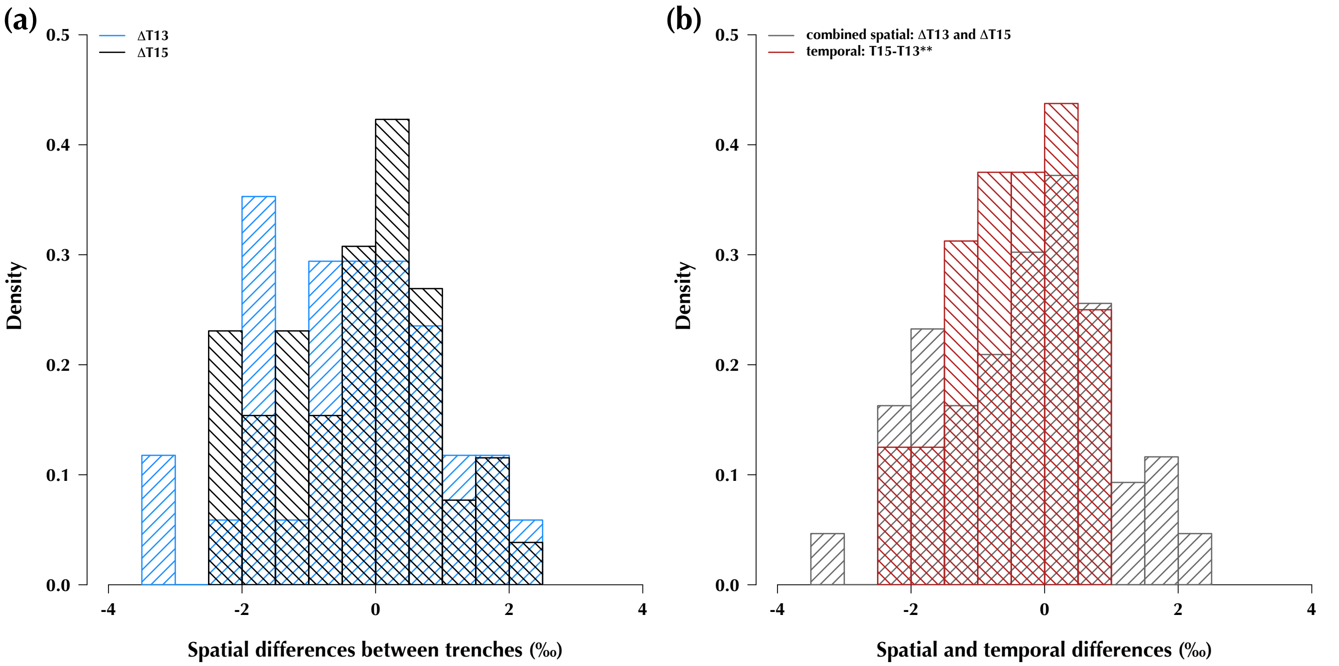

Figure 7. Variability of the trench data sets. The histograms depict (**a**) the distribution of the spatial differences between the two mean profiles of the T13 (T13-1 vs. T13-2, blue) and of the T15 trenches (T15-1 vs. T15-2, black), and (**b**) the combined distribution from **a** (grey) compared to the distribution of the temporal differences between the T15 and the T13** mean profiles (red).

diffusion agrees with theoretical expectations and in total reduces the RMSD between the T13 and T15 mean profiles. In detail, the diffusion correction improves the match of the trench mean profiles in the medium depth range but also results in higher deviations of the profile minima at the top and bottom part of the overlap (Fig. 6). Part of this mismatch might be reduced by accounting for the seasonally varying firn temperature resulting in stronger (weaker) diffusion for summer (winter) seasons (Simonsen et al., 2011). In general, firn diffusion is still an active area of research (van der Wel et al., 2015), and progress in this field could conceivably result in an improved understanding of our data.

Stratigraphic noise is a major contribution to the overall variability of isotope profiles (Fisher et al., 1985; Karlöf et al., 2006). Our large trench data set allows a significant reduction of the noise level by averaging across the single profiles. This is done in two steps: First, we average across the local (intra-trench) scale; then, we average the resulting mean profiles to account for potential uncertainties on the 500 m (inter-trench) scale. Furthermore, we can estimate, based on our theoretical understanding of stratigraphic noise, the remaining uncertainty of the trench mean profiles. As a result, we have found that the difference of the T13 and T15 mean profiles still exhibits an uncertainty of ~ 0.77–0.95 ‰. Thus, the trench data allow us to detect any additional post-depositional changes of the T13 profiles that exceed, on average, a detection limit of ~ 1 ‰. Obviously, a lower detection limit would be beneficial but is in practice constrained by the amount of field work, given the high local stratigraphic noise level (assessed with the mean horizontal isotope variability, Table 2).

4.2 Additional post-depositional modifications

Based on the above results we have shown that the remaining differences between the 2013 and 2015 data sets are, after accounting for downward-advection, firn diffusion and densification, consistent with spatial variability from stratigraphic noise. In other words, we conclude that at our study site the impact of any additional post-depositional changes of the isotopic composition of the firn, below $\sim 10\,\mathrm{cm}$, must be on average clearly below the residual stratigraphic noise level, thus $\ll 1\,‰$. We limited our conclusion to this depth range due to the applied absolute depth scale resulting in a lower and varying number of available data points in the near-surface layer. However, looking at the near-surface part of the modified T13 mean profile (dashed lines of T13* or T13**, Fig. 6b) also does not show any solid evidence for additional post-depositional changes to have occurred.

This conclusion is also supported by comparing the qualitative nature of the differences between the mean profiles (Fig. 6b) with the expected effect of post-depositional modification. Sublimation led in lab studies to isotopic enrichment (Sokratov and Golubev, 2009); modelling of post-depositional modification by wind-driven firn ventilation resulted in annual-mean enrichment from the enrichment of isotopic winter layers (Town et al., 2008). Specifically for South Pole conditions (annual-mean temperature $-50\,°\mathrm{C}$, accumulation rate $84\,\mathrm{mm\,w.eq.\,yr^{-1}}$, surface wind speed $5\,\mathrm{m\,s^{-1}}$), the firn isotopic composition showed annual-mean enrichment by firn ventilation after several years of $\sim 3\,‰$ (Town et al., 2008). The environmental conditions at the South Pole are comparable to the observations at Kohnen Station (Table 1). The higher temperatures at Kohnen would even lead to slightly stronger enrichments by wind-driven firn ventilation (Town et al., 2008). However, contrary to these expectations, the T15 mean profile shows, if anything, more depleted δ^{18}O values compared to the T13** record (Fig. 6b). For the first overlapping annual cycle, T15 exhibits an average difference from T13** of $-1.6\,‰$ ($-1.3\,‰$ including the surface region), for the other annual cycles the averages are -0.4, ± 0 and $-0.1\,‰$. We note that the RMSD corresponding to the first value is above our stated detection limit. This limit applies, however, to the average over the record's entire overlap and does not account for the likely possibility of seasonally varying and thus autocorrelated stratigraphic noise levels. Furthermore, the difference curve (Fig. 6b) does not show any clear seasonal timing which might be expected for a systematic post-depositional modification. Instead, minimum and maximum differences appear rather randomly across the seasons, which supports our conclusion that the effect we see here arises from the statistical nature of stratigraphic noise, smoothed by diffusion. We nevertheless note the possibility that post-depositional changes by wind-driven firn ventilation are present at Kohnen Station but that their effect is unexpectedly weak and thus masked by the stratigraphic noise level. One possible explanation for the discrepancy between the model results and our data could be that the model misrepresents the isotopic signature of the surface vapour advected into the firn. Another possibility are weaker firn temperature gradients at Kohnen Station compared to the South Pole, preventing significant vapour deposition. However, assessing these possibilities in detail is beyond the scope of our study.

Finally, we note the small tendency towards negative values of the differences between the T15 and T13** mean profiles (Fig. 6), which is also indicated by the slight skewness of the corresponding histogram (Fig. 7). However, from the statistical analysis of the differences we cannot reject the null hypothesis that both spatial and residual temporal differences originate from the same distribution, underpinning our conclusion that the temporal differences are unlikely to arise from additional post-depositional modifications. In addition, we obtain similar results (not shown) when we apply our analysis to the trench d-excess ($d := \delta \mathrm{D} - 8 \cdot \delta^{18}\mathrm{O}$) data, a second-order parameter potentially more sensitive to post-depositional fractionation processes (Touzeau et al., 2016). The spatial and residual temporal differences between the corresponding d-excess mean profiles are indistinguishable ($p > 0.5$), the histogram of the temporal differences is even more symmetric than for $\delta^{18}\mathrm{O}$.

Our study underlined the pronounced discrepancy at Kohnen Station between inter-annual variations of stable water isotopes and local temperature and showed that this feature is not only spatially (over distances of $\sim 500\,\mathrm{m}$) but also temporally representative over a time span of 2 years. Furthermore, given the sum of our above findings, it is highly unlikely that post-depositional modifications of the isotopic composition of the open-porous firn (below depths of $\sim 10\,\mathrm{cm}$, and likely also not in shallower depths), are the cause of the observed discrepancy. Since a strong relationship between isotopes in precipitation samples and local temperature has been observed at different sites of the East Antarctic Plateau (Fujita and Abe, 2006; Touzeau et al., 2016), this cause must instead be seeked in processes working directly at or above the firn surface. At least two explanations for this seem possible. (1) Seasonal variation and intermittency of precipitation cause the discrepancy between isotope and local temperature data (Sime et al., 2009, 2011; Persson et al., 2011; Laepple et al., 2011). At Kohnen Station, a large part of the annual accumulation is assumed to occur in winter since little or no precipitation is observed in the summer field seasons. However, the exact seasonal and inter-annual variation of accumulation is still unclear due to the lack of sufficiently precise, year-round observations (Helsen et al., 2005). (2) Isotopic modification occurring directly at or above the surface is the key driver for shaping the inter-annual isotope variations. Such processes might be acting on falling, loose or drifting snow, or on the top layer (first few centimetres) of deposited snow (Ritter et al., 2016; Casado et al., 2016). The fact that our trench records are reproducible on spatial scales of at least $500\,\mathrm{m}$ implies that the atmospheric parameters and conditions controlling potential processes would also need to be spatially coherent.

5 Conclusions

Many studies, including our present one, show that inter-annual isotope records from the dry East Antarctic Plateau are inconsistent with local temperature variations. However, beyond simply stating the problem, we take two steps further: (1) We use the average over 2×11 isotope profiles to obtain a spatially representative record. (2) We designed our study such that it allows testing for post-depositional effects over a time span of 2 years.

Our results provide important constraints on the formation of the stable water isotope signal and its propagation with depth in East Antarctic firn: The trench records show a pure downward-advection of the isotope signal within the open-porous firn, further influenced only by firn diffusion and densification, with no evidence for substantial additional post-depositional modification. Hence, once the signal is archived at this stage, we do not expect any significant change of the mean values deeper down, reinforcing the credibility of palaeoclimate studies using ice core isotope data. However, by ruling out post-depositional changes in the open-porous firn we conclude that the observed discrepant isotope–temperature relationship on the inter-annual timescale must be caused either by processes prior to or during deposition.

To improve our understanding of the inter-annual isotope signal, we suggest a mixture of field and modelling efforts. Year-long isotope studies (e.g. in seasonal intervals) focussing on the near-surface would help to constrain isotope modifications at the interface of surface snow and atmosphere. Further, the role of precipitation and accumulation intermittency has to be clarified, e.g. through measuring wet-depositioned tracers and improved accumulation measurements. These studies should optimally be accompanied by monitoring and modelling of the atmospheric water vapour isotopic composition as well as modelling of the potential exchange and fractionation processes between the loose or deposited snow at the surface and the overlying atmosphere.

Our results again underline the role of stratigraphic noise for the total variability of isotope records. Spatial averging is thus essential to improve the signal-to-noise ratio and thereby to separate spatial from temporal variability. Alternatively, single records can only be compared faithfully for temporal changes when their spatial separation is well below the spatial decorrelation length of the stratigraphic noise. The effects of potential isotopic modifications depend substantially on the time the surface layer is exposed to the atmosphere, thus on accumulation rate and seasonal timing of precipitation. Comparable recovering efforts at other ice-coring sites are hence highly needed. Our data indicate that present models might overestimate the expected influence of wind-driven firn ventilation; however, regions with higher wind speeds and lower accumulation rates might still be susceptible for post-depositional changes within the open-porous firn. A deeper understanding of the isotope signal formation in Antarctic firn is, beyond holding intrinsic interest, essential to decipher the temperature signal archived in ice core records and thus crucial for their palaeoclimatic interpretation.

Data availability. The trench stable water isotope data presented in this study are archived at the PANGAEA database (http://www.pangaea.de) under doi (link will follow). PANGAEA is hosted by the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI), Bremerhaven, and the Center for Marine Environmental Sciences (MARUM), Bremen, Germany.

Author contributions. Thomas Münch, Thomas Laepple, Sepp Kipfstuhl and Johannes Freitag designed the trench campaign, Sepp Kipfstuhl and Thomas Münch led the field work. Thomas Münch and Thomas Laepple designed the analysis. Thomas Münch performed the research and wrote the manuscript. Hanno Meyer supervised the isotope measurements. All authors contributed significantly to the discussion of the results and the refinement of the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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