Topographic effect creates non-climatic variations in ice-core based temperature records of the last millennium

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Abstract

Past temperature reconstructions from polar ice sheets are commonly based on stable water isotope records in ice-cores. However, despite major efforts in the understanding of the ice-core signal formation, the temperature reconstructions of the last millennium in Antarctica remain highly uncertain. Here, using a 100 km scale representative surface water isotope dataset, we show that the spatial variability of local surface topography and accumulation rate anomalies influences the isotopic composition of the upper-meter snowpack. The magnitude of this non-temperature effect on water isotopes is similar to changes of the last millennium. We demonstrate that these spatial anomalies are advected into the deeper firn and ice column, and are translated into an artificial centennial to millennial scale variability in the isotope record. Additionally, we provide an estimation of areas where this effect is relevant for last millennium temperature reconstructions.

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Key points:

- The isotopic composition in surface snow is anti-correlated to local accumulation rate anomalies, driven by the local surface topography.
- Spatial variability is advected into an ice-core site by ice-flow, inducing millennial scale non-climatic variation in the isotopic record.
- Map of time scales variations due to topography effect in East Antarctica for consideration in the interpretation of records from ice-cores.

Key words:

Antarctic isotope record, surface topography, accumulation rate, spatial and temporal variability, paleoclimate reconstructions

Abstract

Past temperature reconstructions from polar ice sheets are commonly based on stable water isotope records in ice-cores. However, despite major efforts in the understanding of the ice-core signal formation, the temperature reconstructions of the last millennium in Antarctica remain highly uncertain. Here, using a 100 km scale representative surface water isotope dataset, we show that the spatial variability of local surface topography and accumulation rate anomalies influences the isotopic composition of the upper-meter snowpack. The magnitude of this non-temperature effect on water isotopes is similar to changes of the last millennium. We demonstrate that these spatial anomalies are advected into the deeper firn and ice column, and are translated into an artificial centennial to millennial scale variability in the isotope record. Additionally, we provide an estimation of areas where this effect is relevant for last millennium temperature reconstructions.

Plain Language Summary

Stable water isotopes measured in ice-cores are commonly used as a paleothermometer. However, these records can be affected by multiple processes and their reliability is unclear, particularly for centennial to millennial time scales in Antarctica. We demonstrate that in low accumulation rate regions, the local topography can create significant spatial variability in water isotopes. This can create temporal variability in ice-core records as these anomalies are advected into the core by ice-flow. This mechanism creating non-temperature related water isotope variations on time-scales from centuries to millennia is likely omnipresent within the continent, potentially affecting numerous ice-cores. We estimate relevant areas with respect to this effect to assist future coring efforts, as well as the careful interpretation of existing records.

1. Background and motivation

Stable water isotopes in ice are commonly used as a proxy for paleotemperatures (Jouzel et al., 1997) and allow reconstructions of past temperature from ice-cores (PAGES 2k Consortium, 2013, Steig et al., 2013). Despite major advances in the analysis methods and field studies to understand signal formation of the isotope signal preserved in the firn and ice (Casado et al., 2018; Münch et al., 2017; Münch & Laepple, 2018), temperature reconstructions from East-Antarctic ice cores are still highly uncertain on centennial to millennial scale and often show a low correlation with observations and simulations (Jones et al., 2016; Klein et al., 2019; Stenni et al., 2017).

Stratigraphic noise (Fischer et al., 1985, Münch et al., 2017) masks climate signals from interannual to multi-decadal scales but can be minimized by averaging multiple records or taking temporal averages (Münch et al., 2016). Post-depositional effects near the surface might affect the isotopic composition (Neumann & Waddington, 2004; Town et al., 2008) but their importance for ice-core records is under discussion (Münch et al., 2017). Precipitation intermittency acts on longer spatial scales and leads to strong noise in water isotope records but is generally well understood and averages out on long-timescales (Casado et al., 2020).

While these processes create a strong non-climatic variability, they cannot explain observed differences in the nearby ice-core isotope records that can last for several centuries. One example is the ice-core site B31 in Dronning Maud Land, with a drop in stable water isotopic composition accompanied by a sudden increase in accumulation rate (Oerter et al., 2004). The nearby core B32 does not confirm these changes. Radar-data within the ~100 km distance between sites show strong local variations of accumulation rate within short distances (up to ~30 kg m^{-2} a^{-1}, i.e. ~50%, Rotschky et al., 2004). Precipitation varying only slightly on such scale, these variations were related to surface undulations caused by bedrock topography (Eisen et al., 2004; Rotschky et al., 2004), providing a first hint to a relation of topography, accumulation and isotopic composition.

A relationship between these variables has been suggested by previous studies. First, surface undulations were found to lead to spatial changes in deposition of snow (Arcone et al., 2005; Black & Budd, 1964; Eisen et al., 2005; Frezzoti et al., 2002a, 2004; Fujita et al., 2011; Rotschky et al., 2004, 2007; Whillans, 1975). Second, Ekaykin et al. (2016) observed significant variations of the upper-meter isotopic composition along the slopes of a surface undulation within a megadune area near Vostok station. They proposed that the spatial variability can lead to temporal non-climatic variations of the record (Ekaykin et al., 2016), due to the upwind drift of the dune (Frezzotti et al., 2002a). This situation is limited to particular areas covering only small parts of the Antarctica ice sheet (Fahnestock et al., 2000), but raises the question to what extend variations in paleo-climate records may be biased by local topography-induced variations in accumulation rate.

Motivated by these findings we designed a specific study to evaluate the effect of surface topography on the stable-water-isotopic composition. Strongly replicated sampling of the top meter of snow, together with Ground Penetrating Radar (GPR) and Global Positioning System (GPS) data on a 115 km traverse including the B31 site allowed us for the first time a representative characterization of the near-surface isotopic composition on a large-scale and its relationship with the local topography.

2. Methods and data

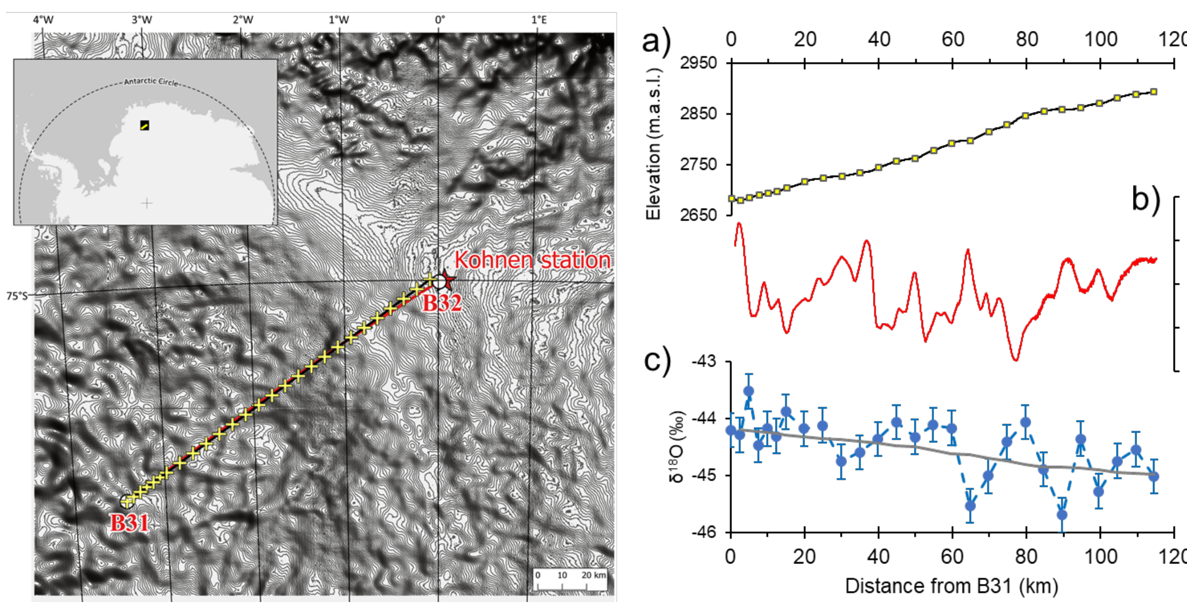

Figure 1. The area of investigation (left) and the field work results (right).

Left panel: Traverses -00/01 (red line) and -18/19 (this study, black line) in between the B31 and B32 sites (white circles). The sampling sites of season 18/19 are indicated with yellow crosses. The topography is shown as 1m elevation contours (Howat et al., 2019). Right panel: a) The elevation along the traverse-18/19 (black line) with yellow points marking the sampling sites. b) Accumulation rate along the traverse-00/01 (red line, Rotschky et al., 2004). c) ^{18}O at sites, (blue markers connected by dashed line) with the error-bars indicating the estimated remaining uncertainty (1 standard-error) from stratigraphic noise. The solid gray line represents the linear trend of ^{18}O versus elevation.

In the austral field season 2018/2019 we performed a 115 km long traverse (hereafter traverse-18/19) in the interior of Dronning Maud Land, East Antarctica (Fig. 1) connecting the B31 ice-core site (3°25.82´W 75°34.890 S, 2680 m.a.s.l.) to the B32 ice-core site (0°00.42´E 75°00.14´S, 2892 m.a.s.l) and Kohnen station (EDML deep ice-core site, 0°04E 75°00 S, 2892 m.a.s.l.).

A post-processed kinematic (PPK) global positioning system mounted at the living container sampled geodetic positions at 1 Hz (i.e. ~3.5 m), and allowed to derive the surface elevation profile of the traverse (Fig. 1).

We further make use of accumulation data based on GPS and GPR measurements (Eisen et al., 2004; Rotschky et al., 2004) from a traverse in 2000/2001 (hereafter traverse-00/01) to estimate the surface mass-balance profile (Fig. 1). For this, we use the internal radar reflection horizon corresponding to AD1817 ± 5 a (i.e. ± 2.5% on accumulation rate) (Rotschky et al. 2004).

2.1 Stable water isotopes sampling positions and strategy

Along the route-18/19, 27 sampling sites were chosen with regard to the decorrelation length of the topographic anomalies, i.e. 2.5 km distance between sites for the first 15 km of the traverse, and 5 km later on (Fig. 1). With the knowledge gained from trench studies (Laepple et al., 2016; Münch et al., 2016) and the use of a newly developed fast sampling tool (Dallmayr et al., 2020), we extracted and averaged at each site 10 upper-meter samples with 10 m distance to minimize the uncertainty from stratigraphic noise (Fisher et al., 1985). The mean value of uncertainty is estimated as 0.3 ‰, (1 standard-error) from the remaining variability of the replicated one-meter averages. (see Text S1 and Table S1, supporting information).

2.2 Measurement of stable water isotopes

All samples were kept frozen during shipment and storage until measurement at the Alfred-Wegener-Institut Helmholtz-Zentrum für Polar-und Meeresforschung (AWI) in Bremerhaven and Potsdam, Germany. The stable water isotope ratios of ^{18}O and D were measured by means of cavity ring-down spectroscopy (Picarro Inc. L-2120-i, and L-2140-i in AWI-Bremerhaven, L-2130-i in AWI-Potsdam.) and calibrated to the international VSMOW/VSLAP scale. Single measurements are provided with a precision of 0.1 and 1.0 ‰ (1sd) for ^{18}O and D. The accuracy of the measurement determined by a quality standard in each measurement run is 0,16 ‰ for ^{18}O and 1,1 for D ‰.

2.3 Data processing – Small-scale anomalies

The heavy stable water isotopes exhibit a depletion along the traverse with increasing altitude (Dansgaard, 1964) (Fig. 1 c). The observed relationship (-0.0037 ‰ per meter of elevation, Fig. 1c) is consistent to the magnitude of trends expected from isotope enabled climate models within the studied area (ECHAM5-wiso model; Münch & Werner, 2020). Thus, to study the effect of local topography on water isotopic composition, we removed the observed linear trend of ^{18}O against elevation along the route.

We derived the local heights (i.e. local topography) by first removing the long-term trend by subtracting a 20 km running mean and then reducing the noise and the small-scale variations from sastrugis by applying a 1 km running mean (Fig.2a). The local surface slope (Fig. 2b) is computed as the spatial derivative of the local heights. Similarly, local variations of accumulation rate (accumulation rate anomalies, Fig. 2) are derived as the residuals of the accumulation rate and its 20 km running mean.

3 Results and discussion

3.1 Small-scale spatial variability of accumulation rate and isotopic composition

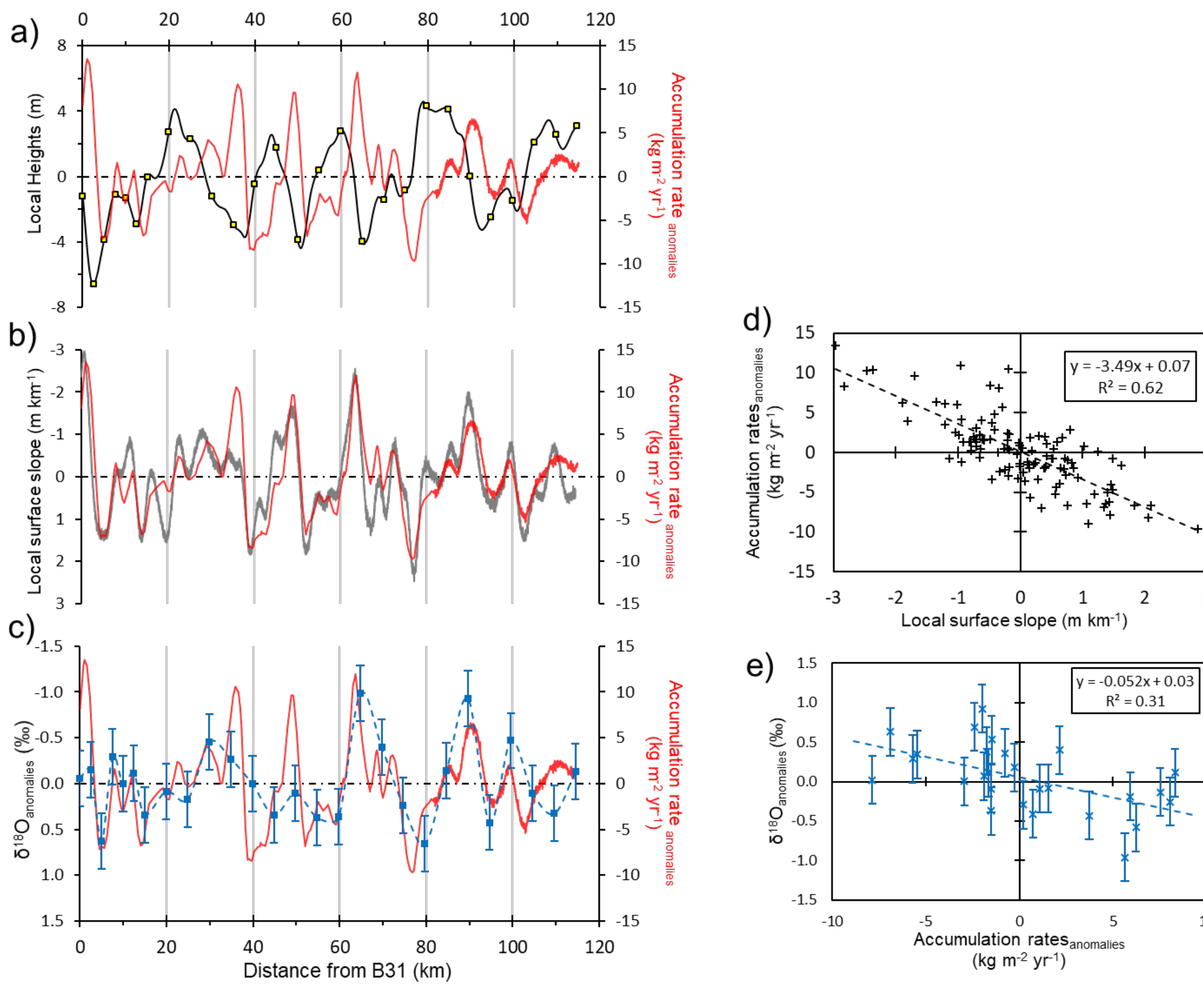

Figure 2. Small-scale anomalies of accumulation rate related to local topography (a, b, d) and to isotopic composition anomalies (c, e).

The variation of local accumulation (red lines) is superposed to the local height of surface undulations (a, black line, left axis) and the surface slope (b, grey line, left axis reversed). Regression of local accumulation against local slope (d) (N=115, 100 m average every kilometer, standard-errors of 0.1 m km^{-1} and 0.05 kg m^{-2} yr^{-1}, respectively). The local topography at sampling sites is shown (a, yellow markers). The derived ^{18}O anomalies along the route (c, left axis reversed, blue points connected by dashed line) are superposed to the local accumulation. Error bars in c) and d) indicate 1 standard error. Regression of ^{18}O anomalies (N=27) against the 100 m average of the local accumulation at sites (e) (standard-error of 0.04 kg m^{-2} yr^{-1}).

3.1.1 Relation of local accumulation rate and local surface topography

Extrema of local accumulation rate (maxima at kilometers 1.5, 36, 50, 64, 91, minima at kilometers 5, 40, 52, 77) surround the four distinct topographic features along the route (Fig. 2a) within a range of variation of 18.4 kg m^{-2} yr^{-1}. With a prevailing wind in the area from North East to South West (Fujita et al., 2011), the deposition of drifted snow follows the pattern of increased and reduced accumulation rate in the hollows and bumps, a relationship that is well established (King et al., 2004).

Moreover, we find a strong relationship between the local surface slope and the accumulation rate anomalies (R^2 = 0.62, p-value <0.001, Fig. 2b, Fig. 2d). This observation underlines the sensitivity of deposition to the slope of the surface (Fujita et al., 2011) as visible in the well-spread intervals of increased and reduced accumulation rate along the windward- and leeward-slopes of the surface, respectively (Arcone et al., 2005; Whillans, 1975).

3.1.2 Relation of local accumulation rate and isotopic composition of snow

The ^{18}O anomalies along the traverse show strong variations (>2 ‰) that seem to be coupled to the local accumulation. Negative anomalies of ^{18}O were generally found in regions with positive local accumulation rate anomalies and vice versa (Fig. 2c). A linear regression analysis (Fig. 2e) shows a statistically significant negative linear relationship (R^2= 0.31, p-value 0.0029) between both variables. We note that the remaining stratigraphic noise on our isotopic anomalies likely explains the relatively low correlation and the true underlying relationship is likely stronger. Our finding implies that a change in accumulation rate of +10 kg m^{-2} yr^{-1} leads to a depletion of -0.52 ‰ in ^{18}O (i.e. a sensitivity of -0.052 ‰ per kg m^{-2} yr^{-1}). This sensitivity is furthermore fully consistent with the enrichment of ^{18}O composition (+0.5 ‰ per kilometer) towards a reduced accumulation rate site (-8 kg m^{-2} yr^{-1}) observed over a 5 km transect in the vicinity of Kohnen station (Dallmayr et al., 2020).

Importantly, the range of spatial variations in ^{18}O is similar to the temporal variations observed in Antarctic ice-cores over the last millennium (Stenni et al., 2017) but has the opposite direction to the temporal climatic relationship between precipitation and temperature, with more precipitation linked to warmer temperatures (Frieler et al., 2015).

There are several hypotheses to explain this spatial relationship:

(a) Seasonal redistribution of snow: a larger redistribution during winter due to higher wind speeds (Birnbaum et al., 2010) and smaller snow crystal sizes would lead to more isotopically depleted winter summer snow in the hollows and enriched summer snow in the bumps, respectively. (Ekaykin et al., 2002).

(b) Post-depositional effects: as a consequence of the reduced accumulation, the surface snow is subject to longer and stronger post-depositional modifications, which are characterized by an enrichment in heavier isotopes as described by

Town et al. (2008). Evidence for this hypothesis was found by Ekaykin et al., (2016) interpreting the change in deuterium excess and ^{17}O. This idea is further supported by recent studies (Hughes et al., 2021; Ma et al., 2020a, 2020b).

While the data here doesn't allow to distinguish between both hypotheses, in either case the relationship of isotopes and local accumulation rate anomalies would have direct implications for the interpretation of ice-core records if the spatial changes also affect the downcore ice-core records. Ekaykin et al. (2016) suggested that a changing topography induced by moving megadunes together with an influence of topography on isotopes could create isotopic variations in ice-core records. While this only applies particularly to megadune areas, even stationary surface conditions (topography, accumulation rate, isotopic composition) will irremediably be advected by the ice flow over time and thus translate spatially varying surface conditions into temporal variations in ice-cores.

3.2 The B31-core: a spatial to temporal transfer induced by flowing ice

As an example, we study the B31 ice-core site. Here, the analysis of available radar profiles (Eisen et al., 2004; Rotchky et al., 2004) suggests that the topography of the study area was stationary over the last millennium, as constrained by bedrock topography (Steinhage et al., 1999). The ice sheet slowly flows towards South West at a velocity 3 m yr^{-1} at the B31 site (satellite measurement, Fig. S1 in supporting information), and the topography upstream of the location exhibits a hollow with the lowest point ~2.5 km from the core-site (Fig. 3a). We independently estimated the ice-flow velocity from the GPR data (Arcone et al., 2005) by tracking the position of the lowest point over the last millennium in five dated internal reflection horizons (Eisen et al., 2004) (Fig. 3b). We find 3.8 m yr^{-1} ($\pm$0.6 m yr^{-1}, 1sd) towards SW, consistent with the satellite data. Considering the uncertainties of both methods, we assume a velocity of 3.5 m yr^{-1} to estimate the original position of the dated horizons (Fig. 3b). The results show that the recent horizons are advected into the B31 column from the windward slope and older horizons from the leeward slope >2.5 km upstream.

In the 1500 years old B31 record, (Oerter et al., 2004), the accumulation rate shows a steep increase around 1000AD followed by a stable accumulation rate with a broad local maximum at 1500AD (Fig. 3c). The ^{18}O record shows the inverse behavior; a decrease of around 2.5 ‰ from 500AD to 1000AD and more stable, slightly increasing values afterwards (Fig. 3d).

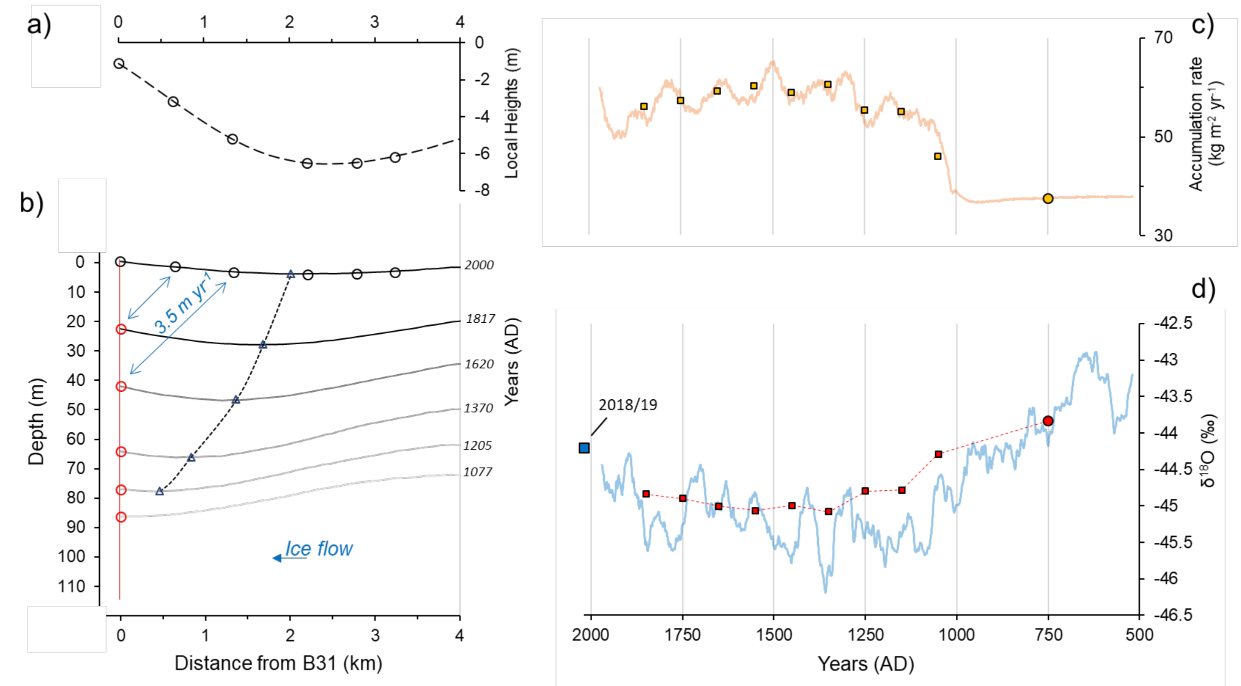

Figure 3. The B31 case: (a, b) upstream surface topography advected into the column at site, and records of (c) accumulation rate and (d) ^{18}O composition.

a) the surface origins related to the local heights. b) The 114 m long B31-core (red line) and the depth profiles of the five internal reflection horizons with their age estimate (Eisen et al., 2004). The dotted black line connects the nearest bottom of the upstream hollow (triangle) used for estimation of flow velocity. The black circles indicate the original surface positions of each age horizon along the core (red circles) assuming a constant flow of 3.5 m yr^{-1} towards SW. c) 50 yr running mean of accumulation-rate record (orange line). The mean of the period 500-1000AD is marked with a circle, and the means of the nine 100 yr periods as squares. d) 50 yr running mean ^{18}O record (blue line) and measurement of snow value of season 18/19 (blue marker). The predicted 100 yr ^{18}O composition as induced by topography are shown by red squares (connected by dashed red line), with the mean of period 500-1000AD (red circle).

3.3 ^{18}O record compared to the expected variations from the topographic effect

To predict the effect of the temporal ^{18}O variations from the advection of the spatial variability, we assume that in first order, the accumulation rate at the site was constant over time. This assumption is supported by the analysis of B32 near Kohnen station that shows a nearly constant accumulation rate over time (Table S2, supporting information). This allows us to use the derived empirical relationship between isotopic anomalies and accumulation rate anomalies (i.e.

-0.052 ‰ per kg m^{-2} yr^{-1}, section 3.1.2) together with the changes in accumulation rate to estimate the ^{18}O anomalies induced by the topography ($\delta^{18}O_{\text{topo}}$)

$$\delta^{18}O_{\text{topo}}(t) = -0.052 * \Delta A\,(t - t_0) + \delta^{18}O(t_0) \ (1)$$

ΔA(t-t_0) (in kg m^{-2} yr^{-1}) refers to the accumulation rate anomaly between time (t) and the initial period (t_0) and ^{18}O (t_0) is the initial isotopic composition. We choose 500–1000AD as the initial time period and perform the analysis on 100 yr mean values.

The resulting dataset is superposed to the 50 yr smoothed ^{18}O temporal variations (Fig. 3c). The similar 1000-years trend between signals supports the hypothesis that this slow variation might be predominantly generated by the effect of topography, and not climate driven. This is further supported by comparing the B31 and B32 records over the last 1500 years (Fig. S2, supporting information). Being on the divide, the B32 site is not expected to be affected by the topography effect on millennial time-scales (as we show later, see Fig. 4) but due to their proximity (100km distance) we can assume similar climatic imprints. In contrast to B31, the isotope and accumulation time-series of B32 are rather constant but feature similar decadal to centennial variability, and the offset between both isotopic records can be explained by the difference in elevation between sites (~0.8 ‰ based on the depletion-elevation trend, Fig. 1c). This supports that the 1000-yrs variation observed in the B31 record are consistent to the expected upstream topographic anomaly.

4. Implications for other ice-cores and temperature reconstructions of the last millennium

To study how this interaction of spatial isotope variations linked to the local topography and ice-flow may affect other ice-core records, we derive a spatial map of the time scales that might be affected by this topographic effect. Assuming that a significant relationship between local topography and ^{18}O anomalies also exists beyond our study area, and the ideal cases of stationary topography and constant ice-flow during the time period of interest, the affected time scales are the product of the length scale of surface undulations and the ice-flow velocity. We use the surface velocity distribution available across the continent (Mouginot et al., 2019) together with an estimated average 5 km length scale of surface undulation computed from Howat et al. (2019) (Text S2, supporting information).

The resulting map of the time scales potentially affected by the topographic-effect (Fig. 4) shows a wide range of affected timescales from several thousand years on the ice-divides down to centuries in regions with higher ice-flow. At the B32 site, the map predicts that the topographic effect does not act on millennial and faster time scales, whereas the map indicated time scale of around 1000 years at the B31 site, consistent with our detailed analysis.

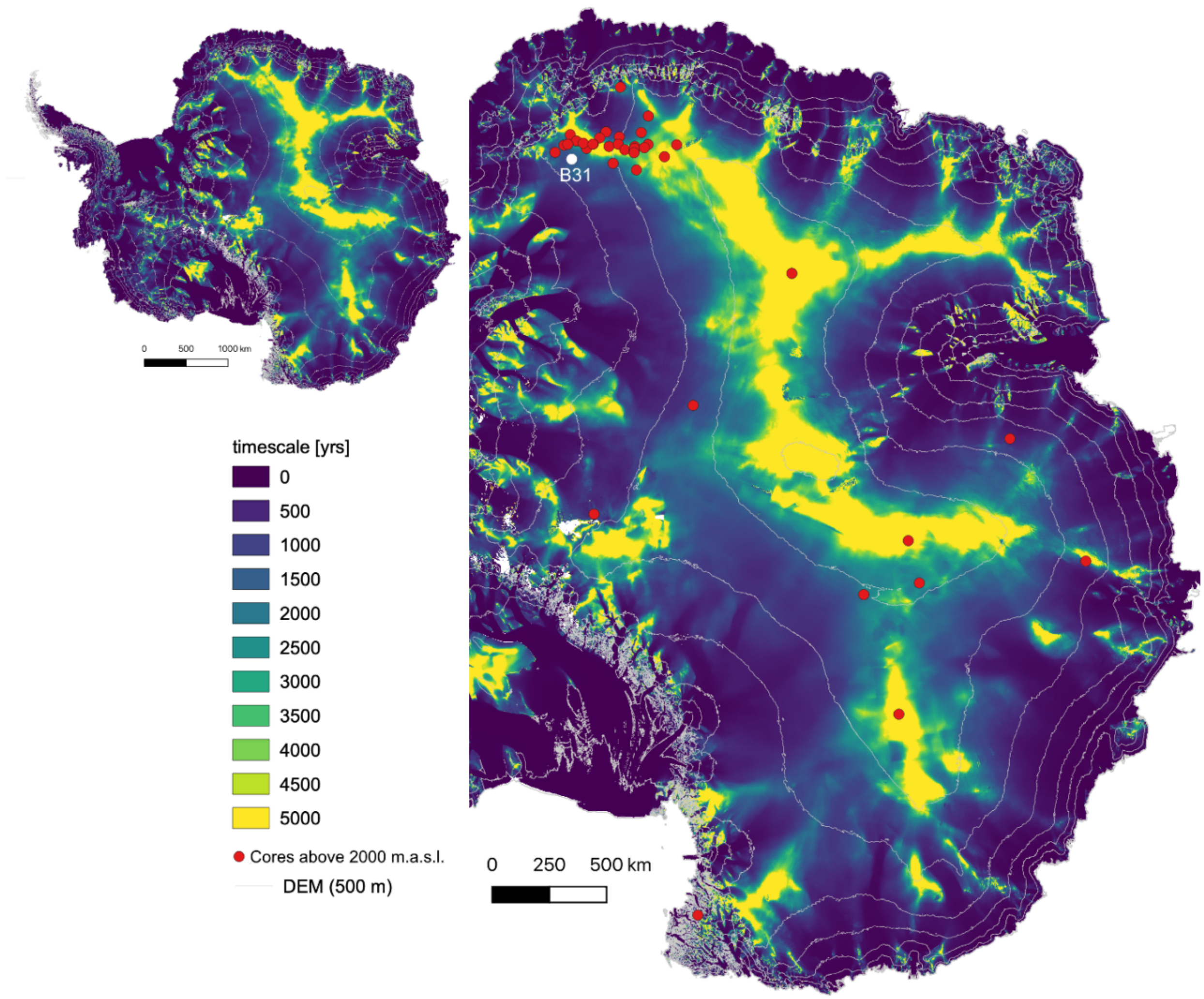

Figure 4. Map of estimated time scale variations in the records due to the topographic effect induced by ice flow in Antarctica (left), and overview of East-Antarctica (right). Ice cores from plateau sites > 2000 m.a.s.l. used in the Antarctica 2k temperature reconstruction (Stenni et al., 2017) are indicated as red points, including the B31 site (white point). The grey contours show the 500 m elevation lines (Howat et al., 2019).

The core B31 was used in the community temperature reconstruction of the last millennium (Antarctica 2k) (Stenni et al., 2017) without special consideration of its non-climatic variability in the lowermost section. We can identify several additional cores included in the database located in similar ~1000 years scale variability estimation (red points in Fig. 4). For these cores, an analysis of the relationship between accumulation rate and isotopic records can provide further insight, as a negative relation might be a signature of the topographic effect (section 3.1.2). In such case using the records for climate reconstruction should be avoided, carefully apprehended by an adequate upstream correction (beyond the scope of this study), or filtered by interpreting only the safe time scales. Finally, if the topographic effect that we propose here is confirmed by other studies, it should be also considered in the choice of future drilling sites.

5. Conclusions

We performed a 115 km traverse on the plateau of Dronning Maud Land with representative snow sampling (10 x 1 m snow liner per site) on 27 sites resolving the small-scale topographic variations combined with GPR and GPS. The high precision of the mean ^{18}O snowpack values from averaging out stratigraphic noise allowed us to identify a significant negative relationship between the local anomalies of ^{18}O and deposition driven by the topography ('topographic effect'). We propose and demonstrate on the example of the B31 site that ice-flow advects these spatial anomalies into centennial to multi-millennial isotopic anomalies in ice cores and the topographic effect is thus highly relevant for the interpretation of ice-core. Confronting the estimated 'topographic effect' for the B31 core with the measured isotope record demonstrates that most of the millennial changes in this core can be explained without invoking climatic changes. As in many regions the topography on millennial scales is linked to the bedrock and thus stationary in time, we extrapolate our findings and provide a map of the potential topographic effect on ice-cores. This suggests that several ice-cores used in the reconstruction of the last millennium might be also affected by these non-climatic variations. Further studies on the physical origin of this relationship and its strength beyond our study region will help to refine our understanding, potentially allow for a correction of affected records and thus a more robust reconstruction of the Antarctic climate of the last millennia.

Data Availability

The GPR related data (traverse-00/01) is archived at https://doi.pangaea.de/10.1594/PANGAEA.935129 and https://doi.pangaea.de/10.1594/PANGAEA.935031, The traverse-18/19 data under https://doi.pangaea.de/10.1594/PANGAEA.935030, https://doi.pangaea.de/10.1594/PANGAEA.935029.

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Authors contribution

T.L. and M.H. enabled the project. T.L. M.H. and J.F. designed the traverse, performed the field-work, and provided support and guidance to the first author for the preparation of the manuscript. M.H. supervised this part of the PhD project. F.W. contributed to the discussion sections and edited the language of the paper. D.J. provided the Figure 4 using the geographic information system Q-GIS, and MB conducted all isotopic measurements at AWI-Bremerhaven. R.D. performed the field-work, analyzed the data and prepared this manuscript, reviewed by all co-authors.

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