Quantifying Southern Hemisphere dust sources during the Last Glacial-Interglacial Transition using rare earth elements in the EPICA Dome C ice core

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ABSTRACT. Dust deposits in ice cores provides a valuable archive of past atmospheric circulation, offering insights into climate dynamics during key climate transitions such as the last glacial termination. Here, we present a novel high-resolution reconstruction of dust provenance in the EPICA Dome C (EDC) ice core from 33.7 to 2.8 kyr BP, based on Rare Earth Element (REE) patterns. Using a statistical unmixing algorithm on 279 samples, we quantify, for the first time, contributions from key Southern Hemisphere dust sources. During the late Marine isotope 3 (MIS3), the Last Glacial Maximum (LGM) and Heinrich Stadial 1 (HS1), dust at EDC was dominated by Patagonia sources (~65–75% of total deposition), with secondary inputs from Australia (~9-11%), Southern Africa (~5-9%), New Zealand (~6-14%), and Puna-Altiplano (~2-4%). After ~14.5 kyr BP, and especially during the Holocene, ~~the~~ dust assemblage shifted toward increased contributions from low-latitude sources—Australia (21–28%), Southern Africa (~8–9%), ~~the~~ New Zealand (4-10%), and Puna–Altiplano (~8–9%)~~, and southern Africa (~8–9%)~~ —while the Patagonian contribution decreased to ~4~~9~~3-53% on average and source compositions became more variable. ~~After ~14.5 kyr BP, the dust assemblage shifted toward greater inputs from low-latitude sources – Australia, Southern Africa, and the Puna-Altiplano – culminating during the Holocene with more variable compositions and reduced Patagonian input (~49.249% on average).~~ This transition is supported by Sr-Nd isotopic calculations and aligns with changes observed in other East Antarctic ice cores. Comparison with the EDML ice core provenance record reveals overall agreement in major sources and timing of the shifts but also highlights regional variations in the secondary contributions, with EDC showing more consistent inputs from Australia and EDML from Southern Africa. The coherence of the provenance shift recorded at EDC and EDML ice cores points to a common large-scale control, in line with the influence of eustatic sea-level rise and postglacial reorganization of fluvial sediment routing and availability in southern South America.

1. Introduction

Antarctic ice cores preserve long-range atmospheric dust at high temporal resolution and provide a unique window into past changes in continental aridity, atmospheric circulation, and Earth system during major climate transitions (Lambert *et al*., 2008; Grousset and Biscaye, 2005). Variations in dust flux and composition recorded in these archives have been central to our understanding of glacial–interglacial climate dynamics, particularly through the role of mineral dust in Southern Ocean iron fertilization and its impact on atmospheric CO_2 concentrations (Martínez-García *et al*., 2014; Lambert *et al*., 2015, 2021; Weber *et al.,* 2022; Yamamoto *et al.,* 2019). However, translating Antarctic dust records into quantitative constraints on past climate processes requires robust reconstructions of dust provenance and an understanding of how source-specific emissions respond to climatic and geomorphological change.

Geochemical fingerprinting of dust and sediments from Potential Source Area (PSA) upwind of Antarctica has therefore been a central component of dust provenance studies. Southern South America (SSA), Southern Africa (SAF), Australia (AUS), New Zealand (NZ), and ice-free regions of Antarctica (ANT) have been identified as the dominant Southern Hemisphere PSAs (e.g., Grousset and Biscaye, 2005; Delmonte *et al*., 2010; Gili *et al*., 2017). While radiogenic isotope systems such as Sr–Nd and Pb have been widely used to trace dust sources, their application is limited by the relatively large sample masses required, which restricts temporal resolution—particularly at remote, high-elevation sites such as EPICA Dome C (EDC), where dust fluxes have decreased by up to a factor of ~25 from glacial to interglacial conditions (Delmonte *et al*., 2008; Delmonte *et al*., 2017). In addition, overlapping isotopic signatures among PSAs and the effects of dust mixing during transport complicate quantitative source apportionment (Gaiero *et al*., 2004; Delmonte *et al*., 2020).

Rare Earth Element patterns (i.e., the concentration profiles of the lanthanoid series) offer a promising complementary approach to overcome these limitations. Because the lanthanoid series captures multidimensional geochemical information, REE patterns allow greater discriminatory power than elemental ratios alone, while requiring substantially smaller sample sizes and thus enabling higher temporal resolution. Previous applications of REE measurements in Antarctic ice cores achieved multi-decadal resolution but were limited in their ability to quantitatively resolve mixed dust sources (e.g., Gabrielli *et al*., 2010; Wegner *et al*., 2012). Recently, Vanderstraeten *et al*., (2023) introduced a novel statistical apportionment framework based on REE pattern fitting, producing the first quantitative, decadal- to centennial-scale reconstruction of dust provenance at EPICA Dronning Maud Land (EDML) across the Last Glacial–Interglacial Transition (LGIT). That study revealed pronounced and time-dependent changes in dust source contributions to East Antarctica. During the Last Glacial Maximum, dust reaching EDML was dominated by high-latitude sources, particularly Patagonia (PAT) and New Zealand, consistent with enhanced glaciogenic sediment production, expanded continental shelves, and strong Southern Westerly Winds (Vanderstraeten *et al*., 2023). During deglaciation and the early Holocene, contributions from lower-latitude PSAs such as Southern Africa, Australia, and the Puna–Altiplano Plateau (PAP) increased as high-latitude dust emissions declined.

Beyond documenting changing provenance, Vanderstraeten *et al.*, (2023) suggested that distinct physical mechanisms controlled dust delivery at distinct stages of the LGIT. During Heinrich Stadial 1, reductions in dust flux occurred without major provenance changes pointing to enhanced atmospheric wet scavenging as the main driver of dust flux reduction. In contrast, the shift from high-to- low latitude sources after ~14.5 kyr BP likely reflects geomorphological thresholds in Patagonia. These include sea-level rise and the submergence of continental shelf, as well as and a major hydrological reorganization of Patagonian rivers (Delmonte et *al.*, 2017; Davies *et al.*, 2020; Thorndycraft *et al.*, 2019). Together, these processes would have reduced the volume of sediment available to aeolian deflation (Vanderstraeten *et al.,* 2023; Delmonte et *al.* 2017).

While EDML provides a sensitive record of dust provenance changes in the Atlantic sector of East Antarctica, it remains unclear to what extent these source shifts are representative of the broader East Antarctic Plateau. EPICA Dome C, located further inland at high elevation, receives lower dust fluxes and integrates longer atmospheric transport pathways, making it particularly sensitive to changes in large-scale circulation and dust residence time. EDC has played a central role in reconstructions of Southern Hemisphere dust variability and climate coupling, yet quantitative, high-resolution provenance across the LGIT remain limited at this site due to analytical challenges associated with low dust concentrations. Here, we apply the REE-based statistical provenance framework developed for EDML to the EPICA Dome C dust dataset of Gabrielli *et al*., (2010). Our study aims at (1) establishing a quantitative record of dust provenance in EDC throughout the LGIT and particularly during the Holocene, (2) confronting and validating the EDC results from our REE pattern-based model against Sr-Nd isotopic data published in the literature, (3) examining shifts in dust provenance at EDC in relation to regional climatic changes and (4) contrasting this new EDC provenance with the coeval record in EDML in the Atlantic sector of the Antarctic continent to assess spatial variability of dust deposition across East Antarctica during the LGIT.

2. Materials and methods

Dust rare Earth Element Pattern Over Time ("DEEPOT" algorithm)

To identify and quantify dust source contributions to ice core samples, we developed a numerical approach based on a constrained least-squares algorithm. This method solves a system of linear equations using only positive coefficients, as source contributions represent physical proportions of dust and thus cannot take negative values. The fit between the REE patterns measured in the EDC ice core and those reported in our database (Table S1) from known potential source areas (PSA) across the Southern Hemisphere is optimized using these coefficients to quantify the mixing between all PSAs. A detailed description of the methodology is provided in Vanderstraeten *et al*., (2023).

Briefly, our analysis used the REE dataset from the EDC ice core originally published by Gabrielli *et al.*, (2010) comprising 294 Dust samples from Ice Core (DIC). The dataset spans from the late MIS 3 to the late Holocene (33.699 to- 2.852 kyr BP), with an average temporal resolution of approximately 100 years, ranging from 60 to 140 years between adjacent samples. The age model follows the EDC3 chronology (Parrenin *et al*., 2007). Each sample integrates between 2–3 years of deposition during the Holocene and 4–5 years during the LGM. A sampling gap exists between 21.7 and 27.3 kyr BP, where only four samples were available.

Out of the original 294 REE patterns, 15 were excluded due to missing data for one or more of the 14 REEs analyzed. Additionally, gadolinium (Gd) concentrations were systematically removed from all samples because their low and often unreliable values introduced more noise than discriminatory power to the calculations. The remaining 279 REE patterns (each comprising 13 REE concentration values) were normalized to the Upper Continental Crust (UCC) composition (Rudnick and Gao, 2003) and corrected using element-specific factors (cf_i) as described in Gabrielli *et al.*, (2010) and Vanderstraeten *et al.*, (2023) (Eq. 1). These element-specific correction factors account for partial dissolution resulting from the acid-leaching extraction method used during REE quantification Gabrielli *et al.*, (2010). Since this method does not fully dissolve all mineral particles, we applied cf_i derived from parallel measurements of fully digested EDC samples (three replicates of one glacial and one interglacial sample) to obtain total REE concentrations allowing fitting with REE patterns from our database (Gabrielli *et al*., 2006; Vanderstraeten *et al.,* 2023).

$$cf_i = \frac{[REE_{full\ digestion}]_i}{[REE_{acid\text{-}leaching}]_i} \quad (1)$$

To fit the REE patterns from EDC, we compiled a comprehensive database of 245 REE patterns from well-established Dust Source (DS) regions across the Southern Hemisphere (Figure S1, and Table S1). This dataset includes samples from Southern South -America (SSA), subdivided into Patagonia (PAT; 39 DS covering mainland Patagonia and Tierra del Fuego), Central Western Argentina (CWA; 5 DS), and the Puna-Altiplano Plateau (PAP; 14 DS from Northern and Southern Puna and Southern Altiplano). Additional sources includesinclude Southern Africa (SAF; 23 DS from Namibia and Botswana), Australia (AUS; 107 DS, predominantly from the central and southeastern regions), New Zealand (NZ; 25 DS, from the South Island), and Antarctica (ANT; 32 DS from the McMurdo Dry Valleys, representing ice-free sources). Following Vanderstraeten *et al*., (2023), "Dust Sources" (DS) refer to individual samples collected within a given PSA. Multiple DS may originate from the same location when samples were collected during different seasons (see Table S1). As in most provenance studies, the robustness of the unmixing results ultimately depends on the representativeness of the source dataset, and additional sampling would help better capture the natural geochemical variability of the different source areas.

As for the EDC samples, all PSA REE patterns were normalized to the UCC composition of Rudnick and Gao (2003) and Gd values were removed. Dust source apportionment was conducted using a constrained least-squares approach, in which the REE pattern of each EDC sample was modeled as a linear combination of PSA end-members. The model estimates the respective Contributions of each Dust Source ($CDS^{1\ldots245}$) by solving the system of matrixes (Eq.2) with non-negativity constraints, minimizing the resulting values, and ensuring that all contributions are physically meaningful (i.e., no negative values). This optimization was implemented using the *lsqnonneg* function in MATLAB.

$$\left\| \begin{pmatrix} DS^{1}_{La} & \cdots & DS^{245}_{La} \\ \vdots & \ddots & \vdots \\ DS^{1}_{Lu} & \cdots & DS^{245}_{Lu} \end{pmatrix} X \begin{pmatrix} CDS^{1} \\ \vdots \\ CDS^{2} \end{pmatrix} - \begin{pmatrix} DIC_{La} \\ \vdots \\ DIC_{Lu} \end{pmatrix} \right\|_2^2 \qquad (2)$$

In practical terms, the source apportionment algorithm involves solving a system where the input matrix-comprising "n" rows (one for each UCC-normalized REE) and 245 columns (one for each DS) is multiplied by a vector of 245 coefficients ($CDS^{1\ldots245}$). For any given sample, this vector of 245 components represents the proportional contribution of each DS required to best approximate the REE signature of a given dust ice core (DIC_{La-Lu}) sample. The solution minimizes the residual between the modeled REE composition (i.e., the product of the input matrix and the CDS vector) and the measured DIC REE pattern. Importantly, only a subset of the 245 dust sources typically contributes to the best-fit solution for a given sample—i.e., sources with CDS > 0 while sources with CDS equal to 0 are excluded from the fit.

To evaluate the impact of uncertainties in REE concentrations of DIC samples and their associated correction factors (cf_i) on the model outputs, we performed Monte Carlo (MC) simulations for each DIC sample. Analytical uncertainties associated with REE concentrations in EDC dust range between 2% and 10% (1 relative standard deviation), depending on the specific REE - $Dust_i$ (Gabrielli *et al*., 2006). In each MC simulation, cf_i and $Dust_i$ values were randomly selected following normal distributions constrained by their respective mean values and variability to represent these uncertainties. The algorithm then recalculated the best-fit source contributions (CDS values) by minimizing Eq. (2). Each DIC sample was subjected to 2000 MC simulations generating distributions of source contributions (in % of total deposition) that form probability density functions for each dust source, subsequently aggregated by PSA or specific sub-regions. Because individual Monte Carlo (MC) realizations do not necessarily include all PSAs in the optimal solution, the resulting PDFs are not always normally distributed and may be asymmetric or even bimodal, reflecting both the most frequent contribution and the probability of negligible or absent contributions in some simulations. The median of each PSA-specific PDF was taken as the best estimate of its contribution to the total dust load of a given DIC sample. To quantify the dispersion of the MC solutions, the 25th (Q1) and 75th (Q3) percentile of each PSA-specific PDF were also calculated and reported (Table S2), providing a quantitative measure of the variability associated with the source apportionment. In addition, the robustness of the source apportionment was assessed by examining the ranking of PSAs across the ensemble of MC simulations. For each time step, PSA contributions were ranked in every simulation and the probability that a given PSA occupies a particular rank was calculated from the 2000 MC realizations.

Finally, the total dust influx to EDC—derived from non-sea-salt calcium flux ($nssCa^{2+}$ in μg m^{-2} yr^{-1}; Fischer *et al.*, 2007) — was used to convert PSA contributions into absolute dust fluxes (Figure S2). To assess the quality of each fit, we computed the correlation coefficient (R) between the measured and modeled REE patterns for every MC simulation. The 2000 R values per DIC sample formed a PDF from which the median R value was taken as the representative measure of fit quality. We determined that $R \geqslant 0.67$ corresponds to a statistically significant match ($p < 0.01$, two-tailed test, degrees of freedom = 10), confirming a robust agreement between the reconstructed and observed REE signatures.

3. Results

Out of the 279 DIC samples treated by our algorithm, 41 did not meet the R threshold ($R \geq 0.67$) and were excluded from the provenance record. Except one, these excluded samples are all younger than 14 kyr BP and have very low REE concentrations, near the detection limit. Such low concentrations are consistent with minimal dust input to EDC after HS1 (Gabrielli *et al.*, 2010; Fischer *et al.*, 2007). At these levels, element-specific analytical noise exacerbated by varying ionization efficiencies and UCC normalization distorts the REE patterns, rendering fitting meaningless. For the remaining 238 DIC samples (85.3% of the total amount of samples considered), the PSA mixes calculated by the model were considered meaningful compared to the uncertainties associated with the measurement and characterized by an average correlation coefficient ~~of~~ (R) of ~~=~~ 0.852. These DIC samples span from 33.7 kyr BP to 2.8 kyr BP and form the basis of the dust provenance record presented here. Figure 1 and Table S2 summarize the relative contributions (in % of total deposition) while the flux from specific PSA are presented in Figure S3. In addition, Figure 1 displays the probability that each PSA occupies a given contribution rank across the 2000 MC simulations (grayscale shading). Darker shades indicate a higher likelihood that a source consistently occupies that rank, providing a visual indication of the stability of the source apportionment through time. Our record comprises major climatic intervals: the end of Marine Isotope Stage 3 (MIS3: 57–29 kyr BP), the Last Glacial Maximum (LGM: 29–18 kyr BP), Heinrich Stadial 1 (HS1: 18–14.7 kyr BP), the Antarctic Cold Reversal (ACR: 14.7–12.9 kyr BP), the Younger Dryas (YD: 12.9–11.7 kyr BP), and the Holocene (11.7–2.8 kyr BP; with Early Holocene 11.7-8.2 kyr BP and Middle Holocene 8.2-2.8 kyr BP) (Veres *et al.*, 2013).

Patagonia is the dominant dust source throughout most of the record, a result also reflected by the high probability that this source occupies the first rank in the Monte Carlo ensemble. It contributes 71.8% and 65.4% (i.e. mean of the contributions – Table S3) of the total dust deposition during the end of MIS 3 and the LGM respectively, increasing to 75.4% during HS1. Overall, the PSA dust assemblage during HS1 is marked by a stable and homogeneous apportionment. During the ACR and YD, contributions of

PAT declined to 68.5% and 62.5% (average contributions), respectively, with the downward trend continuing into the early Holocene. Three distinct minima in PAT contributions occur at 10, 8.6, and 6.3 kyr BP. The Holocene interval is also characterized by a marked increase in high-frequency variability in PAT contributions (and lower PSA ranking) compared to the relatively stable glacial conditions. Despite increased variability, PAT remains the primary source of dust during the Early to Middle Holocene, contributing to 43.3-53.4% of -total deposition. Among the 39 DS from PAT, our algorithm highlights three specific REE patterns collected in or near the Valdes Peninsula. The latter DS represent aeolian materials gathered during dust sampling campaigns and therefore reflects regional mixed input rather than single lithological sources (Gili *et al.*, 2017; Gaiero *et al.*, 2004). Their mafic compositions, reflected by LREE (light REE) depletions, show positive Eu anomalies relative to UCC (Gili *et al.*, 2017; Gaiero *et al.*, 2004).

Other Southern Hemisphere PSAs contribute over the LGIT to EDC dust deposition with inputs from: AUS, SAF, PAP, NZ, and ANT in decreasing order of importance (Table S3). In contrast to PAT, those PSA generally occupy lower and more variable ranks within the MC ensemble, reflecting their secondary contributions and strong competition among sources. During MIS 3, the LGM, and HS1, AUS accounted, on average, for 9.1, 10.8 and 11.2% of total dust deposition, respectively. AUS contributions rose slightly after 14.5 kyr BP at 11.5% during the ACR, ~15% during the YD, and 23.9% during the Holocene, with two prominent maxima centered around 9.5–10 kyr BP and ~6.3 kyr BP (Figure 1 – Table S3). SAF maintained relatively stable contributions ranging between ~5 and 9% on average during MIS3, the LGM, HS1 and the ACR, followed by a sharp increase during the YD with 13.3%. Although SAF input drops to minimal levels (~2%) between 9.5 and 12 kyr BP, it rebounds in the Holocene, averaging ~8.8%. NZ was the second-largest contributor during the LGM with an average of 13.8% but its influence steadily declines over time: 6.4% during HS1, and 6%, 3.3%, and 6.1% during the ACR, YD, and the Holocene, respectively. The PAP contributes modestly during the MIS3, the LGM and HS1, with average values below 4%, increasing to 5.4% during the ACR, primarily from the South Puna region. In the Holocene, a compositional shift occurs, marked by the emergence of South Altiplano dust, which even becomes dominant in several samples, contributing over 90% (% total deposition) at 11.2, 10, 8.6, 6, and 3.5 kyr BP. In contrast, contributions of the Southern Puna, when present, remained consistently below 20% during this interval (Figure S4). On average, PAP accounts for 8.6% of the total Holocene dust input to EDC ice core (Table S3). Antarctic dust contributions (ANT) are rare and very low prior to ~13 kyr BP however increased during the ACR, YD and Holocene to reach on average ~ 4%. Other PSA, including CWA did not contribute measurably to EDC dust assemblage during the studied interval (see Table S2).

4. Discussion

We present the first quantitative record of dust provenance in the EPICA Dome C ice core spanning the entire LGIT (Figure 1). Our results indicate that, during the LGM, atmospheric dust deposition at EDC was dominated by inputs from PAT, with smaller but measurable contributions from NZ, AUS, SAF and PAP dust (in decreasing order of importance). This composition remained relatively stable throughout HS1, despite a pronounced decline in total dust deposition after ~18 kyr BP. A shift in dust source contributions becomes evident after ~14.5 kyr BP, characterized by larger proportions from AUS, SAF, PAP, and ANT, while the relative contributions from PAT and NZ declined. In the following sections, we evaluate the consistency of our provenance reconstruction with the isotopic composition of dust measured in EDC and other East Antarctic ice cores; discuss the shift in dust provenance occurring along the LGIT in conjunction with regional climatic evolution; and compare our provenance record from EDC with that of the EDML ice core (Vanderstraeten *et al*., 2023).

4.1 Isotopic and REE compositions of dust in EDC

Our calculations highlight a major shift in dust provenance occurred at the onset of the ACR, marking a transition from a dust assemblage dominated by high-latitude sources—namely PAT and NZ—to a more diverse mixture with significantly increased contributions from low-latitude sources, including AUS, SAF and PAP. This shift already described by Gili *et al*., (2022) and Vanderstraeten *et al*., (2023) appears to be consistent with the changes in isotopic composition of dust deposited at EDC between glacial and interglacial periods. For instance, Delmonte *et al*., (2004a) reported $^{87}Sr/^{86}Sr$ ratios of ~0.708 and ε_{Nd} values ranging from -1.66 to -2.46 for LGM dust at EDC, whereas Holocene dust typically displays more radiogenic $^{87}Sr/^{86}Sr$ ratios (~0.710) and more negative ε_{Nd} values (-4.51 to -5.68). Similar shifts in dust isotopic composition observed for the Holocene in dust from the Vostok ice core further support the hypothesis of a change in source regions (Basile *et al*., 1997; Delmonte *et al*., 2008). This Holocene change is also accompanied by a much larger variability of the Nd-Sr signature measured in the dust (Figure 2). To compare our REE-based source apportionment with isotopic evidence, we calculated the expected $^{87}Sr/^{86}Sr$ and ε_{Nd} signatures of EDC dust from the modeled source contributions (Figure 2). For each time interval of the LGIT, the relative contribution of each PSA (CONTR) was multiplied by its average Sr and Nd concentrations, $[Sr]_{PSA}$, $[Nd]_{PSA}$, to obtain concentration-weighted contributions, $[X]_{mix}$ (Table S4, *i.e.* Eq.3).

$$[X]_{mix} = \sum(CONTR_{PSA} * [X]_{PSA}) \quad (3)$$

Where "X" is the Sr or the Nd concentration. The composite isotopic ratios (CIR_{mix}) were then calculated for ($^{87}Sr/^{86}Sr$) and ε_{Nd} in Eq.4, where the mean isotopic signatures are represented by CIR_{PSA} (Table S4 and associated graph).

$$CIR_{mix} = \sum(CIR_{PSA} * CONTR_{PSA} * \frac{[X]_{PSA}}{[X]_{mix}}) \quad (4)$$

The modeled isotopic signatures for the LGM in Figure 2 cluster around lower $^{87}Sr/^{86}Sr$ and higher ε_{Nd} values, consistent with a provenance dominated by less weathered, mafic lithologies in accordance with large Patagonian and New Zealand contributions (modeled isotopic signature for the end of MIS3, HS1, ACR, and the YD are shown in Figure S5). In the Holocene, the modeled and measured isotopic compositions (Table S5) show a broad range, trending toward more radiogenic Sr and less radiogenic Nd isotopic values. This indicates a more heterogeneous and weathered source assemblage—consistent with greater inputs from AUS, SAF, and PAP (Figure 2 and S5). The slightly broader range of modeled LGM and Holocene values relative to the measurements primarily reflects the much higher temporal resolution of the REE-based record compared to the sparse isotopic dataset. The isotopic data, compiled from different sites and available only for a few discrete time intervals likely represent time-averaged conditions and therefore underestimate the variability of dust sources. In contrast, the quasi-continuous REE record enables the model to resolve short-term variability and transient source-mixing events. Despite those limitations, our modeled isotopic compositions generally agree with those measured in EDC (and with other East Antarctic dust records) during both glacial and interglacial intervals supporting the robustness of our DEEPOT algorithm and reinforcing the interpretation that a distinctive shift in dust provenance occurred over the LGIT.

4.2 Persistence of high-latitude dust source to EDC before 14.5 kyr BP

During cold periods, glacial outwash plains played an important role in sediment mobilization and dust supply to the atmosphere in the Southern Hemisphere (Bullard *et al*., 2016). Extensive ice sheets produced large amounts of fine sediment which were effectively spread by wide, migrating braided river systems. Exposed to arid, cold conditions and strong westerly winds, those deposits would routinely dry out and provide a major source of dust for long range transport (Sugden *et al*., 2009). Such conditions were especially prevalent in PAT where the Patagonian Ice Sheet reached its maximum spatial extent between ~34 and 29.4 kyr BP, covering much of the Andes with an ice mass 2090 km long and 350 km wide (Davies *et al*., 2020). Concomitantly, sea level was ~135 m lower than present-day, exposing additional land and expanding Patagonian outwash plains by ~763.10^3 km^2 relative to modern conditions (Vanderstraeten *et al*., 2023). These factors collectively explain the predominance and relative stability of PAT dust contributions and, by extension, those from SSA- to EDC during the LGM and MIS3. Isotopic studies consistently demonstrate the significance of Patagonian sources in glacial dust deposited across East Antarctica (EA) (e.g., Grousset *et al*., 1992; Basile *et al*., 1997; Gaiero, 2007; Gili *et al*., 2017; Delmonte *et al*., 2020). Model simulations (i.e., Albani *et al*., 2012; Krätschmer *et al*., 2022) also support this view, estimating that SSA and AUS sources together supplied 70-90% (here, PAT+AUS is ~76.2%) of the dust reaching EA during the LGM. Based on Sr–Nd isotopes, Coppo *et al*., (2022) estimated LGM dust composition over EA as 64% from SSA, 15% from Antarctica, 11% from AUS, 5% from SAF, and 5% from NZ.

Our results for SSA, which include here PAT + PAP (+ CWA), are in general agreement with those of Coppo *et al.*, (2022), with a combined contribution of ~69.4% during LGM, alongside ~10,8% from AUS (Figure 3 and S6; Table S3). However, we find a higher average contribution from NZ (13.8%), making it the second-largest dust source to EDC during the LGM. This contrasts with Koffman *et al.*, (2021), who argued against significant NZ dust input to EA on the basis of combined Sr-Nd-Pb isotope compositions. Nevertheless, the extensive South Island ice sheet, the enlarged NZ continental shelf (~62,000 km^2, Vanderstraeten *et al.*, 2023; 75,000 km^2 in Koffman *et al.*, 2021), and cold, windy LGM conditions likely favored enhanced NZ dust emissions capable of reaching Antarctica (Williams *et al.*, 2015). Consistent with this interpretation, present-day forward air-mass trajectories indicates that NZ dust could contribute 14–32% to inland Antarctic deposition (Neff and Bertler, 2015). Our previous EDML ice core work detected an average NZ contribution of ~6% throughout the LGM (Vanderstraeten *et al.*, 2023). In contrast, PAP contributions during the LGM were minimal (4%), likely due to persistent wet conditions in the South Altiplano linked to the Sajsi and Tauca lake phases (Blard *et al.*, 2011; Placzek *et al.*, 2006). Consistently, Pampean Loess accumulation rates—largely sourced from PAP dust—were low during both the LGM and HS1 (Coppo *et al.*, 2022).

Although CWA has been proposed as an important PSA in southern South America during LGM (Gili *et al.*, 2017), it is notably absent from our EDC provenance record. A similar absence was observed in the EDML record (Vanderstraeten *et al.*, 2023), despite this site being the closest to, and directly downwind of, SSA. The REE patterns of CWA are relatively flat when normalized to UCC, with most samples showing overall REE depletion, a slight enrichment of HREE, and a moderate positive Eu anomaly. Because this REE composition differs markedly from the dominant Patagonian sources, a substantial contribution from CWA would leave a clear geochemical imprint in the REE composition of EDC dust. In addition, ~~The distinctive REE patterns of CWA, characterized by pronounced negative LREE and HREE anomalies, would be expected to produce a clear imprint if CWA were a major contributor to either ice core. T~~the CWA "hypothesis" is based on isotopic evidence; however, the strong overlap between the isotopic signatures of CWA ($\varepsilon Nd \approx -4$ to 0; $^{87}Sr/^{86}Sr \approx 0.707$–0.712; Gili *et al.*, 2017) and those of Patagonia, Southern Puna, the Darling Basin, southeastern Australia and New-Zealand complicates the clear discrimination of these sources (Figure 2). Taken together, these lines of evidence suggest that CWA is unlikely to represent a major dust source in the EDC and EDML records.

Overall, the LGM dust assemblage at EDC was dominated by high-latitude, fluvio-glaciogenic sources—PAT and NZ—which together accounted for ~79.2% of total deposition, on average. Lower-latitude PSAs (AUS, SAF, PAP) supplied the remaining ~20.5% of the LGM dust (Figure 3 and S6; Table S3). This dominance persisted into HS1, with high-latitude sources amounting to 81.7% despite a sharp decline in dust flux to EDC starting at ~18 kyr BP (Figure S2 and S3). Because vegetation cover and aridity in Eastern Patagonia remained broadly similar during HS1 relative to LGM (Markgraf *et al.*, 2007; Quade and Kaplan, 2017), the most plausible explanation for the stability in the dust composition is intensified enhanced "rainout" during long-range transport, particularly in the mid-~~latitudes,~~ latitudes, - acting as an effective barrier to polar dust delivery (Markle *et al*., 2018). This reduced transport efficiency coincides with rising temperatures between 18 and 15 kyr BP, as indicated by elevated $\delta^{18}O$ values in EDC (Figure S3). The persistence of high-latitude dominance before 14.5 kyr BP reflect a transport regime sustained by extensive ice sheets, widespread outwash plains, and strong westerly winds -a system that maintained a remarkably stable provenance pattern until the onset of the LGIT. The following section examines how this balance shifted under the warmer, wetter, and more variable climate of the deglaciation and Holocene (from 14.5 kyr BP until 2.8 kyr BP).

4.3 Drivers of dust provenance variability after 14.5 kyr BP

After the HS1-ACR transition, our unmixing model reveals a marked increase in the variability of dust provenance at EDC (Figure 1), characterized by higher-frequency changes in sources contributions compared to LGM. This observation is also a defining feature of our provenance record in EDML (Vanderstraeten *et al*., 2023). This increased variability reflects a fundamental reorganization of the dust cycle following deglaciation, driven by a combination of changes in dust sources availability and atmospheric transport efficiency. Three interrelated processes likely govern the variability of dust composition after 14.5 kyr BP. First, the decline of the availability of fluvio-glaciogenic sediment subjected to deflation on the eastern flanks of Patagonia (and South Island in NZ) reduced the dominance of large sources that had characterized East Antarctic dust deposition during LGM and HS1 (see above in section 4.2 and Vanderstraeten *et al*., 2023 for detailed discussion). Second, rising temperatures and enhanced hydrological cycling in the atmosphere after 14.5 kyr BP increased wet scavenging along transport pathways, reducing airborne particle lifetime, hence limiting the efficiency of long-range dust transport (Lambert *et al*., 2008; Markle *et al*., 2018). Third, a lengthening of transport trajectories with a northward shift of moisture sources feeding into Antarctica (evidenced by deuterium-excess values after 14.5 kyr BP (Figure S3, Stenni *et al*., 2010).

Together, these processes favored a more diverse and temporally variable mixture of dust sources reaching the East Antarctic Plateau and are reflected in a clear shift from high- to lower-latitude dust contributions after 14.5 kyr BP. Average Holocene inputs from AUS, PAP, and SAF reach 23.9%, 8.6%, and 8.8%, respectively, compared to 10.8%, 5.7%, and 4.0% during the LGM (Table S3). Conversely, average contributions from PAT and NZ decline during the Holocene to 49.2% and 6.1%, respectively (vs. 65.4% and 13.8% during LGM). Those proportions are broadly consistent with present-day Antarctic dust deposition from the DustCOMM model that estimates contributions from SSA to EA at 70 ± 20% (Kok *et al*., 2021) — compared to 57.8% in our record when combining PAT, CWA, and PAP, in the Holocene (2.8 to 11.7 kyr BP). DustCOMM model also predicts dust contributions from AUS and SAF at 18% (ranging from 6% to 36%) and 10% (ranging from 3% to 13%), respectively (Kok *et al*., 2021), which aligns reasonably well with our results for AUS and SAF (Table S3). A similar transition from high- to low-latitude dust sources was observed by Coppo *et al.*, (2022), although their model indicates a much more pronounced reduction in SSA input -down to 30 ± 11% - compared to our SSA estimate of 57.8% (Table S3). Their results show comparable contributions from AUS and SAF – i.e., 23% and 14%, respectively vs. 23.9% and 8.8%, here - and a large Antarctic component (24% vs 3.5% here), specifically from the McMurdo Dry Valleys and nearby Southern Victoria Land volcanoes. Although our dust source database cover also McMurdo dry valleys, our results suggest only very limited inputs (see discussion in section 4.4). The resulting shift toward lower-latitude dust sources after 14.5 kyr BP is expressed through distinct regional emission dynamics, discussed below for each major source region, and is further assessed at the East Antarctic scale through comparison of the EDC and EDML provenance records in Section 4.5.

4.4 Regional source responses to glacial-interglacial transition

Following a pronounced decline after ~14.5 kyr BP, Patagonian contributions reach minimum values around 10 kyr BP (Figure 4). Interestingly, those minima coincide with an early Holocene thermal maximum (11-9 kyr BP) which is clearly expressed in the $\delta^{18}O$ record from EDC and more broadly across Antarctica (Masson *et al.*, 2000) as well as in other Southern Hemisphere records (Kilian and Lamy~~*et al.*,~~ 2012; Bianchi ~~&~~and Gersonde, 2004). Those climatic conditions likely reduced the thermal gradient between the mid and high latitudes, resulting in persistently weakened wind intensities. Such conditions are recorded at Macquarie Island (sub Antarctic southwest Pacific 54°S - Saunders *et al.*, 2018), in Potrok Aike maar (52°S, Patagonia; Lisé-Pronovost *et al.*, 2015) and in the Southern Ocean south and east of New Zealand (Fletcher ~~et *al*~~and Moreno~~.~~, 2011). These changes may be linked to a poleward shift of Southern Westly Winds (SWW) belt (Quake and Kaplan, 2017; Moreno *et al.*, 2010). At first glance, those conditions appear~~s~~ unfavorable for dust emissions from Patagonia. However, this interval also corresponds to drier conditions and widespread increase in fire activity in eastern Patagonia (Figure 4 - Moreno *et al.*, 2010; Power *et al.*, 2008; Markgraf *et al.,* 2007). Such conditions likely enhanced dust emissions through vegetation loss and soil destabilization making sediments more susceptible to aeolian deflation upon the return of stronger SWW (Dukes *et al.*, 2018; Wagner *et al.*, 2021). After ~8 kyr BP, the strengthening of the SWW coincide with elevated PAT contribution between ~8-7 kyr BP. Apart from a marked drop in PAT contributions between 6-6.5 kyr BP, strong SWW conditions have prevailed since ~5 kyr BP in south Patagonia and correspond to on average PAT contribution of ~50%~~-~~.

Regarding Australia, our algorithm identifies it as the second-most important supplier of dust to EDC during Holocene (with the Darling sub-basin as the dominant source region in agreement with Pb isotope evidence De Deccker *et al.*, 2010). Although Gili *et al.*, (2016) dismissed AUS as a major Antarctic dust source, later studies re-evaluated its role, suggesting Australian dust reached TALDICE and Taylor Glacier mainly during interglacials (de Deckker *et al.*, 2019, 2020). Modeling and back-trajectory analyses further indicate that modern Australian dust dominates over the Pacific Southern Ocean and western Antarctic coasts and can reach EDC (Albani *et al*., 2012; Krinner *et al*., 2010; Li *et al*., 2008; Neff and Bertler, 2015). Hydrological reconstructions indicate that central Australia—particularly the Lake Eyre and Lake Frome basins—experienced prolonged wet conditions between ~4 and 14.5 kyr BP (Magee *et al*., 2004; Singh and Luly, 1991). These humid intervals would have substantially suppressed dust emissions from central Australia. In contrast, the Darling Basin underwent a pronounced dry phase between ~11.5 and 9.5 kyr BP that coincides with a peak in AUS dust contributions to EDC. Conversely, two humid phases in the Darling Basin (~13.5–11.5 and 9.5–7.5 kyr BP, potentially extending to 5.5 kyr BP) correspond to reduced dust fluxes from AUS (Gingele *et al.*, 2007; Stanley and De Deckker, 2002). The mid- to late Holocene (post-8.2 kyr BP) in Australia is characterized by increasing climatic instability with alternating wet and dry periods likely influenced by El-Nino-Southern Oscillation (ENSO) or Interdecadal Pacific Oscillation (IPO) variability (Gingele *et al*., 2007; Stanley and De Deckker, 2002; Bullard and McTainsh, 2003; Lamb *et al*., 2009). This climatic variability is consistent with the large fluctuations in AUS contributions to EDC during this interval.

Southern African ~~(SAF)~~ dust sources are associated with three systems: the Makgadikgadi Complex (including Sua Pan), the Etosha Pan, and ephemeral river valleys along the Namibian coast (Wiggs *et al*., 2022; Gili *et al*., 2022; Prospero *et al*., 2002). During the Holocene, our results show an increasing trend in SAF dust contribution to EDC ice core (Figures 1 and S4), which is consistent with an enhanced aeolian deposition of fine-grained material recorded in sediment core from the Walvis Ridge in South-east Atlantic Ocean suggesting increasing aridity in southern western Africa (Stuut *et al*., 2002). Among SAF sources, the Namibian coast and ephemeral riverbeds were detected most frequently, though their overall contributions were smaller than those from the Etosha and Makgadikgadi systems. This pattern aligns with the large spatial extent and the strong climatic sensitivity of ephemeral Namibian rivers, which experienced episodic flow and channel aggradation in response to Holocene climate variability and now constitute the primary source of dust plumes (Stone *et al*., 2010).

The Puna - Altiplano Plateau emerges as a secondary dust contributor to EDC after 14.5 kyr BP, consistent with its strong sensitivity to aridification and the desiccation of riverbeds, alluvial fans, and paleolake systems. Dust from the South Puna contributes throughout the record, whereas the Southern Altiplano becomes active only after ~11.2 kyr BP (Figure S4), which coincide with the final desiccation of paleolake Coipasa and the establishment of persistent arid conditions (Condom *et al*., 2004; Blard *et al*., 2011; Placzek *et al*., 2006). Although Northern Puna has been suggested in several studies as a major source to EA (e.g., Gili *et al*., 2017; Gili *et al*. 2022; Gaiero *et al*., 2013), marked differences in Ce, Sm, Eu and LREE contents allow our algorithm to distinguish between Northern and Southern Puna revealing a clear dominance of South Puna contribution in the EDC. Recently, Pullen *et al.*, (2022) showed that South Puna was an active dust source area during the late Pleistocene and Holocene periods. The combined PAP dust assemblage—comprising a mafic component from the South Puna and a crustal component from the Southern Altiplano—is also consistent with Sr-Nd isotopic compositions of SSA sources and that of the Pampean loess reported by Coppo *et al*., (2022). Overall, the relatively important contribution of PAP to Est Antarctica during interglacial periods is consistent with previous provenance studies (Gili *et al*., 2016; 2017; Gaiero *et a.l*, 2013; Gili *et al*., 2022).

Antarctic dust from the McMurdo dry valleys is only detected in EDC after 13 kyr BP which is consistent with the deglaciation timing of the low-elevation valleys included in the DS database (Diaz *et al*., 2020). In contrast, higher-elevation valleys in McMurdo regions have remained ice-free since the Miocene and have accumulated substantial atmospheric material from distal sources - especially during glacial periods. As a result, those areas display REE patterns strongly influenced by deposition from Australia, Patagonia, New Zealand (Diaz *et al*., 2020). In order to avoid the risk of conflating distal and local Antarctic signals potentially leading to overestimation of the Antarctic contribution, we excluded those high-elevation areas from the DS database. Furthermore, dust transport from ice-free coastal areas to EDC have been shown very limited (Delmonte *et al*., 2013).

4.5 Spatial and temporal comparisons of EDC and EDML dust provenance records

Although several studies have proposed quantitative estimates of dust provenance in East Antarctic ice cores for specific climatic intervals, the only quasi-continuous record directly comparable to our EDC reconstruction is our recent study on the EDML ice core ~~The only quantitative dust provenance record in EA available for comparison with our EDC data comes from our recent study on the EDML ice core~~ (Vanderstraeten *et al*., 2023). In Figures 5 and 6 (for millennial trends), ~~we compared~~we compared the contributions of PAT, NZ, SAF, AUS, ANT and PAP from both cores between 7.5 and 27 kyr BP. Note however that results for ACR and YD are tentative due to the limited number samples covering those periods in EDC (8 and 9 samples in ACR and YD, respectively, compared to 49 and 28 in EDML). At first glance in Figure 6, the dust provenance compositions of the two cores appear broadly similar, supporting the idea that atmospheric dust deposition across East Antarctica during the LGIT was relatively uniform. This hypothesis had been previously proposed for the LGM, MIS 4, and MIS 6 by Fischer *et al*., (2007) and Marino *et al*., (2009), based on similar geochemical dust emission patterns and major element signatures in both cores, suggesting a shared glaciogenic dust source from SSA. A more detailed comparison, however, reveals subtle differences between EDC and EDML provenance contributions highlighting how atmospheric circulation modulates dust delivery to Antarctica (Delmonte *et al*., 2004b).

Average dust source contributions during the LGM indicate that EDC received a greater proportion of NZ dust than EDML (+7.9%, i.e., [PSA average LGM contributions in EDC] – [PSA average LGM contributions in EDML] Figure 5 based on Table S3), compensated by an equivalent reduction in contributions from PAT (-7.7%). During HS1, provenance compositions at both cores converge, with differences in PSA contributions not exceeding ~4.4%. In contrast, the ACR and YD intervals exhibit a slight enrichment of Patagonian dust (+8.7 and +8.0%) in EDC, primarily at the expense of Southern African and Australian contributions. In the Holocene, the discrepancies become more pronounced: EDC appears to receive substantially less PAT dust (-7.7%) but higher contributions of Australian dust (+13.3%) than EDML. These differences are consistent with the geographic positioning of the two sites: EDML is exposed to the storm track in the Atlantic sector, and thus well positioned to receive dust from Patagonia brought in the mid-troposphere by the SWW. In contrast, EDC, located at the interior of EAP and the Indian Ocean sector, is comparatively insulated from such mid-latitude air masses incursions by the polar vortex. Nevertheless, planetary Rossby waves can disturb this polar vortex, allowing intrusions of mid-latitude or even low-latitude air masses (Baldwin &and Dunkerton, 2001; Woollings et *al.*, 2023). In such cases, dust from low-latitude PSAs—either uplifted to high altitudes (~6–10 km a.s.l.) or directly deflated from elevated terrains such as the Puna–Altiplano Plateau—can be entrained southwestward by the subtropical jet (STJ) into the polar front jet (PFJ) and transported to central Antarctica. For example, dust from the high-altitude Puna–Altiplano has been observed to follow this pathway beyond 50°S (Gili *et al*., 2017; Gaiero *et al*., 2013), while similar mechanisms over southeast Australia can inject dust into the STJ–PFJ system (Yang *et al*., 2024). Nguyen *et al*., (2019) demonstrated that prevailing southwesterly winds in central and southeastern Australia, combined with the Great Dividing Range, can uplift dust to altitudes of 4–6 km, enabling its long-range transport to the Indian Ocean sector of Antarctica. Other studies have similarly identified regions in Australia as significant contributors to both western and eastern Antarctica (De Deccker *et al*., 2019; Revel-Rolland *et al*., 2006; Vallelonga *et al*., 2002). The enhanced contributions of low-latitude sources to EDC during the Holocene reflect both warmer climate circulation patterns— favoring poleward STJ trajectories and interactions with PFJ (Ding *et al*., 2011) - and increased aridity in low-latitude regions (see above), which likely amplified dust emissions and transport from these sources.

In addition to the regional differences in dust provenance between EDC and EDML, both records reveal synchronous millennial-scale changes in dust source contributions. Notably, between 15 and 14 kyr BP, both ice cores show a marked decline in Patagonian dust contributions (Figure 6), accompanied by increasing inputs from Australia, Southern Africa and PAP. This shift from high- to lower-latitude dust sources is effectively decoupled from the earlier, more gradual yet massive decline in total dust deposition that began around 19-18 kyr BP and continued until ~15 kyr BP in both cores (Figures S2, S3 and S4). As detailed in Vanderstraeten *et al*., (2023), this provenance shift coincides with several major large-scale events: the large Antarctic Iceberg Discharge AID6, the onset of the Bølling interstadial in the Northern Hemisphere, and the rapid sea-level rise associated with Meltwater Pulse 1A (Weber *et al*., 2014). This transgression submerged vast areas of the Patagonian and New Zealand continental shelves, significantly reducing the availability of exposed, deflatable sediments and thereby curtailing PAT and NZ dust emissions to Antarctica. Simultaneously, the progressive deglaciation of the Patagonian Ice Sheet triggered substantial changes in regional riverine systems. New drainage pathways opened up effectively redirecting large portion of river catchment from the Atlantic to the Pacific Ocean, hence decreasing sediment supply and changing the planform (from breaded to meandering) of rivers flowing on the eastern flank of Patagonia (Thorndycraft *et al*., 2019; Davies *et al*., 2020; Skirrow *et al*., 2021; Gaiero *et al*., 2003; Caldenius, 1932). These hydrological and geomorphological transformations further limited the potential for dust production in Patagonia. The combined effects of continental shelf submergence in Patagonia (and New Zealand), along with drainage reversals and reorganized river networks, led to a persistent decline in high-latitude dust contributions. Those phenomena induced a relative increase in dust input from lower-latitude source regions such as Australia, Southern Africa, and the Puna-Altiplano, further enhanced by the long-term trend of increasing aridity in these regions and the greater efficiency of long-range atmospheric transport from low-latitude to Antarctica (see above). Collectively, the patterns observed at both EDC and EDML suggest that eustatic sea-level rise and postglacial hydrological reorganization in Patagonia had broad and long-lasting effects on Antarctic dust composition during the LGIT.

~~Importantly, our data demonstrate that these feedback mechanisms influenced dust deposition not only in EDML (in the Atlantic sector of East Antarctica) but also in EDC, thus extending their impact across to the Indian Ocean sector. This highlights the spatially extensive and long-lasting effects of eustatic sea-level rise and postglacial hydrological reorganization on the composition of Antarctic dust assemblages during the LGIT.~~

1. Conclusion

This study presents the first high-resolution quantitative reconstruction of dust provenance in the EDC ice core over the Last Glacial-Interglacial Transition (LGIT). Our results reveal a distinct shift in dust source composition from glacial to interglacial periods. During the MIS3, LGM and Heinrich Stadial 1, dust reaching EDC was predominantly derived from high-latitude glaciogenic sources, particularly Patagonia and New Zealand, reflecting the extensive outwash plains, cold and arid conditions, and efficient dust mobilization mechanisms in those regions. From ~14.5 kyr BP onward, a marked reorganization in dust provenance occurred, characterized by a relative decline in high-latitude PSA contributions and a corresponding rise in dust from low-latitude sources such as Australia, Southern Africa and the Puna-Altiplano Plateau~~, and Southern Africa~~. As such, those results confirm our previous study on the EDML dust record showing similar shift that we ascribed to a complex interplay of hydrological rearrangement processes in Patagonia and the rapid submersion of its shelf. This shift in provenance is effectively decoupled from the massive decline in dust deposition that occurred between 18 and 15 kyr BP due to changing atmospheric transport dynamics. Comparisons with the EDML record reveal both broad similarities and specific key regional differences in dust provenance across East Antarctica: while millennial-scale changes were broadly synchronous, the relative contributions of PAT, SAF, NZ and AUS differed reflecting regional climatic dynamics in their respective source areas.

Finally, our findings emphasize the role of glacial-eustatic and hydrological feedbacks—particularly sea-level rise, drainage reversals, and paleolake desiccation—in reshaping dust source activation and transport. These processes, in turn, contributed to the persistent reorganization of the Southern Hemisphere dust cycle during the LGIT, with implications for biogeochemical fluxes, atmospheric circulation (chemistry and physics), and climate feedbacks on glacial-interglacial timescales.

CODE/DATA AVAILABILITY. All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials and/or https://doi.org/10.5281/zenodo.19021686. Additional data related to the paper may be requested from the authors. Correspondence and requests should be addressed to Si.B. and St. B.

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APPENDIX S. SUPPLEMENTARY DATA. Supplementary data to this article

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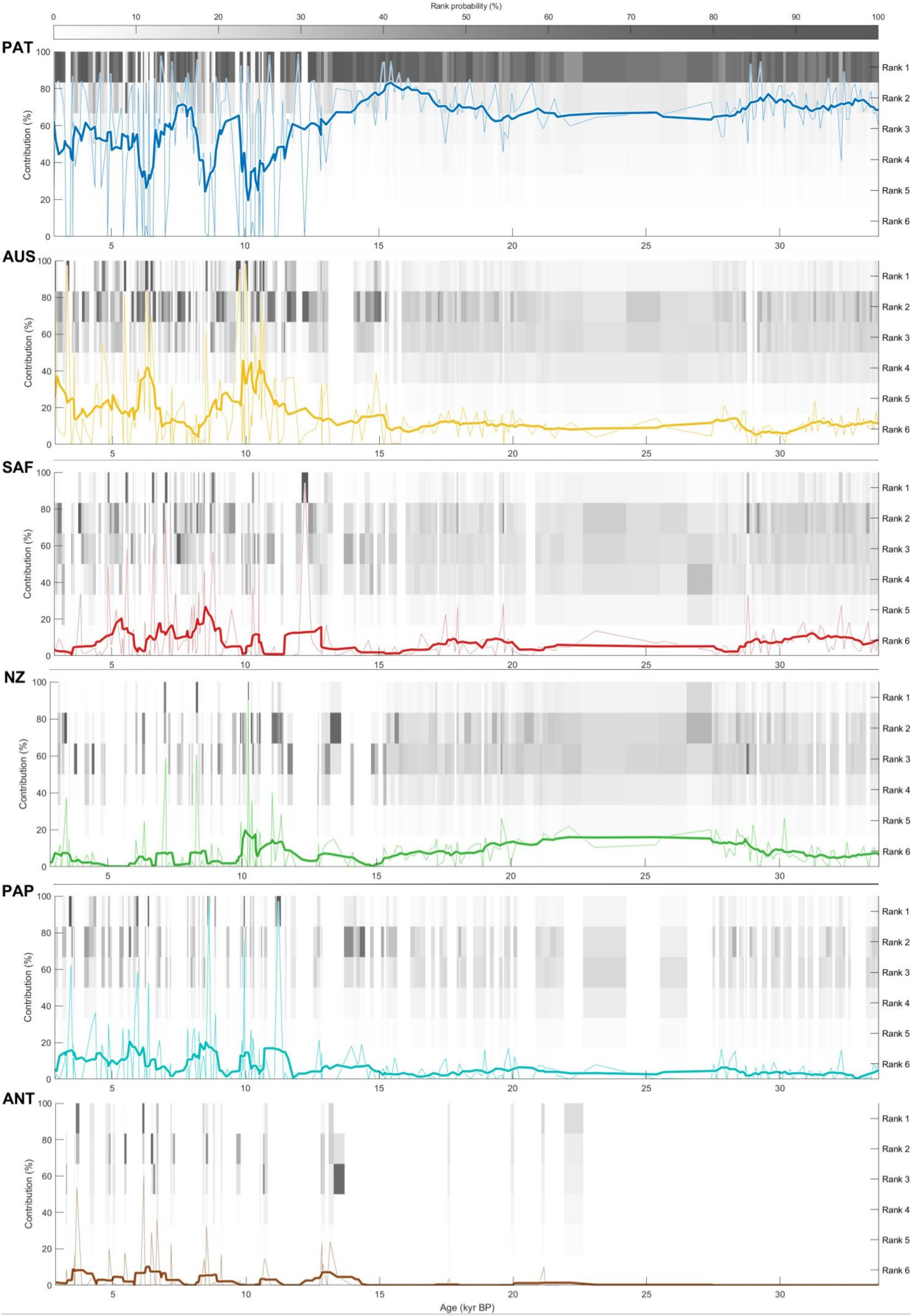
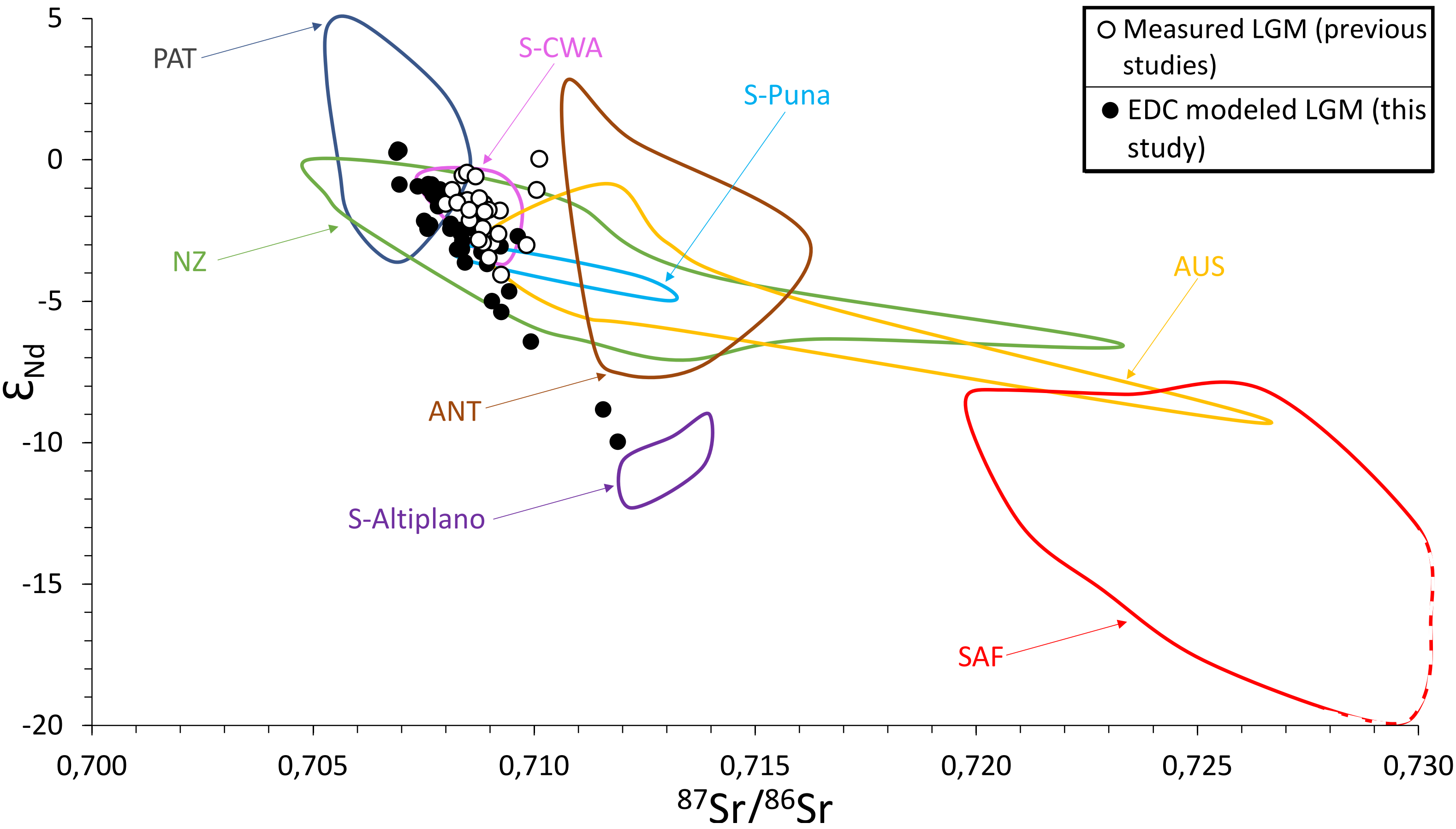
Figures



Rank probability (%)
0
10
20
30
40
50
60
70
80
90
100
PAT
AUS
SAF
NZ
PAP
ANT
Contribution (%)
Rank 1
Rank 2
Rank 3
Rank 4
Rank 5
Rank 6
Age (kyr BP)

Figure 1: Evolution of dust PSA contributions to EDC ice core between 2.852 to 33.699 yr BP (% of total dust deposition for each PSA – Table S2). Bold lines denote the mobile average over 9 steps. Central -Western -Argentina is not shown as it does not contribute to the dust assemblage. Darker shades indicate a higher likelihood (over the 2000 Monte Carlo simulations) that a source occupies that rank, providing a visual indication of the stability of the source apportionment through time.


Measured LGM (previous studies)
EDC modeled LGM (this study)
PAT
S-CWA
S-Puna
NZ
AUS
ANT
S-Altiplano
SAF
εNd
87Sr/86Sr
5
0
-5
-10
-15
-20
0,700
0,705
0,710
0,715
0,720
0,725
0,730

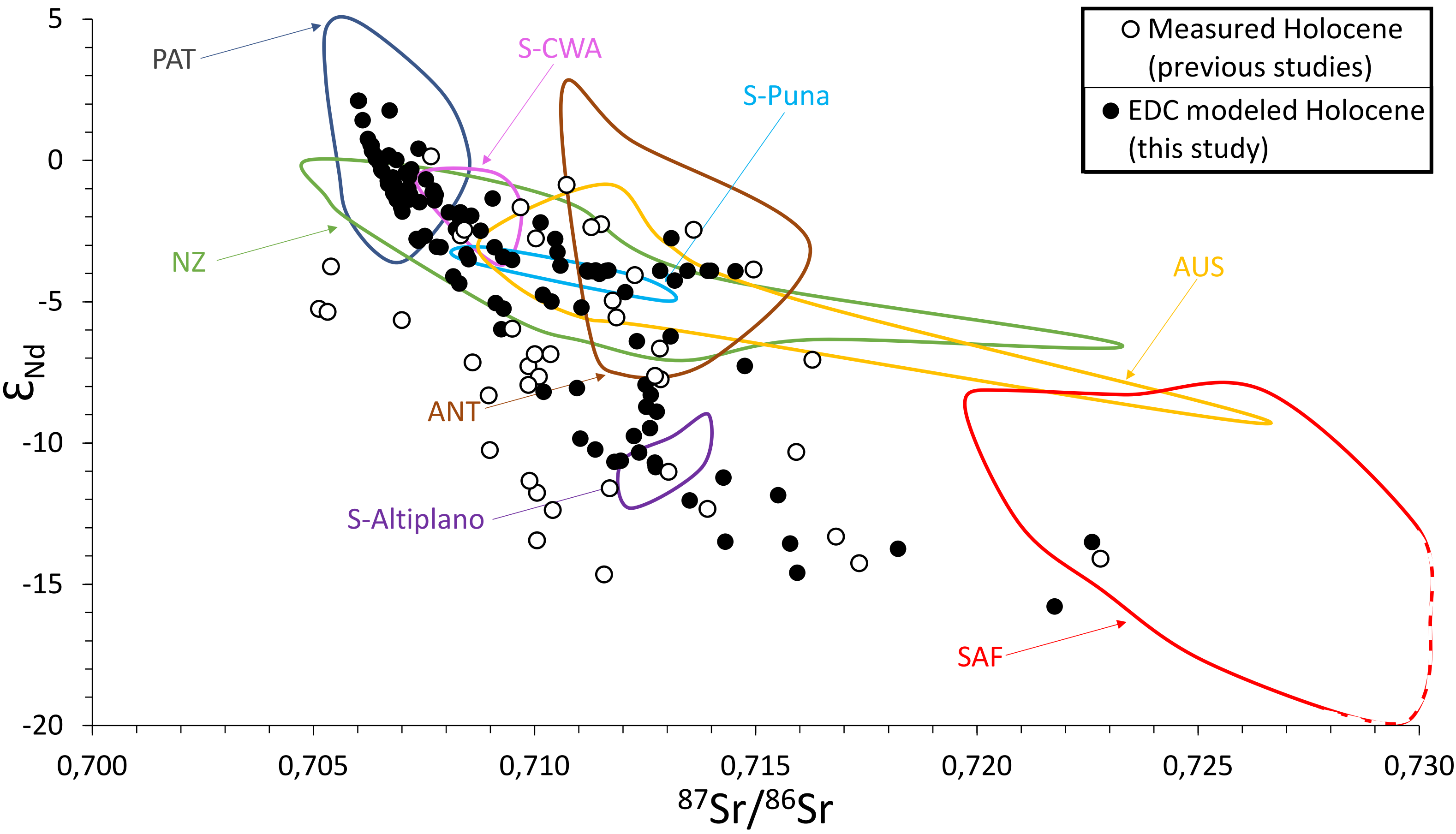
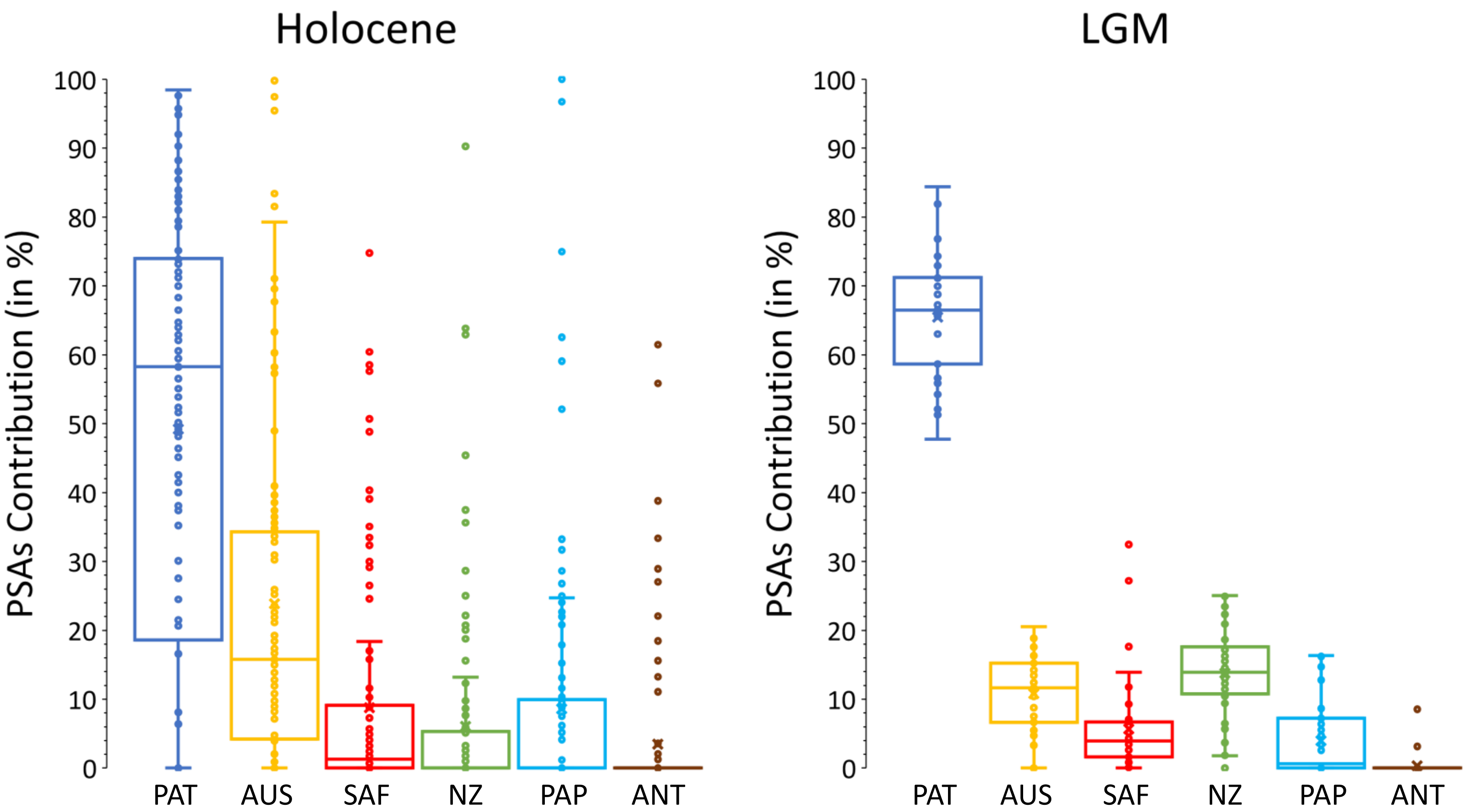

Measured Holocene (previous studies)
EDC modeled Holocene (this study)
PAT
S-CWA
S-Puna
NZ
AUS
ANT
S-Altiplano
SAF
εNd
87Sr/86Sr
5
0
-5
-10
-15
-20
0,700
0,705
0,710
0,715
0,720
0,725
0,730

Figure 2: (a) Measured $^{87}Sr/^{86}Sr$ and $\varepsilon_{Nd(0)}$ isotopic compositions of dust in EDC, Taylor Dome, Taylor Glacier, Komsomolskaya, Dome B, Old dome C ice cores during the LGM (Table S5, open symbols) are compared with isotopic values calculated using the REE mixing model applied to EDC samples (solid dots; see section 4.1). (b) Measured isotopic compositions of modern dust collected on Berkner Island and Holocene dust from Taylor glacier, Talos Dome (Table S5, open symbols), representative of Holocene dust depositions, are compared with isotopic values calculated for the Holocene using the REE mixing model applied to EDC samples (solid dots). Colored frames indicate the isotopic fields of the main dust potential source areas (PSAs) (data from Grousset *et al.,* 1992; Delmonte *et al.,* 2004; Gingele and De Deckker, 2005; De Deckker *et al.,* 2014; Revel-Rolland *et al.,* 2006; Gaiero, 2007; Gili *et al.,* 2017; Gili *et al.,* 2022; Li *et al.,* 2020; Koffman *et al.,* 2021; Blakowski *et al.,* 2014; Diaz *et al.,* 2020). Note that the SAF domain is more extensive than shown in the figure. For details on calculation see Table S4.Compilation of $^{87}Sr/^{86}Sr$ and ε_{Nd} isotopic compositions representative of PSA, dust in ice cores, modern dust in Berkner Island (refs. Table S1, - open symbols) and calculated isotopic values using REE contributions from EDC - solid dots (see section 4.1 for details). Colored frame areas denote the domains of isotopic values of respective PSA used for the isotope calculation i.e., involved in the dust assemblage (data from Grousset *et al*., 1992; Delmonte *et al*., 2004; Gingele and De Deckker, 2005; De Deckker *et al*., 2014; Revel-Rolland *et al*., 2006; Gaiero, 2007; Blakowski et al. 2016; Gili *et al*., 2017; Gili *et al*., 2022; Li *et al*., 2020; Koffman *et al*., 2021). Note that the SAF domain is more extended than showed in the Figure. REE-based calculated isotopic composition were obtained from (i) the % contributions of PSA and (ii) the isotopic fingerprint (Table S4) and elemental concentration of the PSAs end-members (Table S3).



Holocene
LGM
PSAs Contribution (in %)
100
90
80
70
60
50
40
30
20
10
0
PAT
AUS
SAF
NZ
PAP
ANT

Figure 3: Box plots of provenance contributions (in %) of Holocene~~,~~ and Last Glacial Maximum (LGM) dust depositions in EDC ice core. Horizontal lines in the boxes indicate the median values of contribution for each source, cross symbols denote the mean and the extremes of the colored boxes indicate the first and third quartiles, and the whiskers indicate the lower and upper extremes. Box plots for HS1, ACR and YD are illustrated in Figure S6.

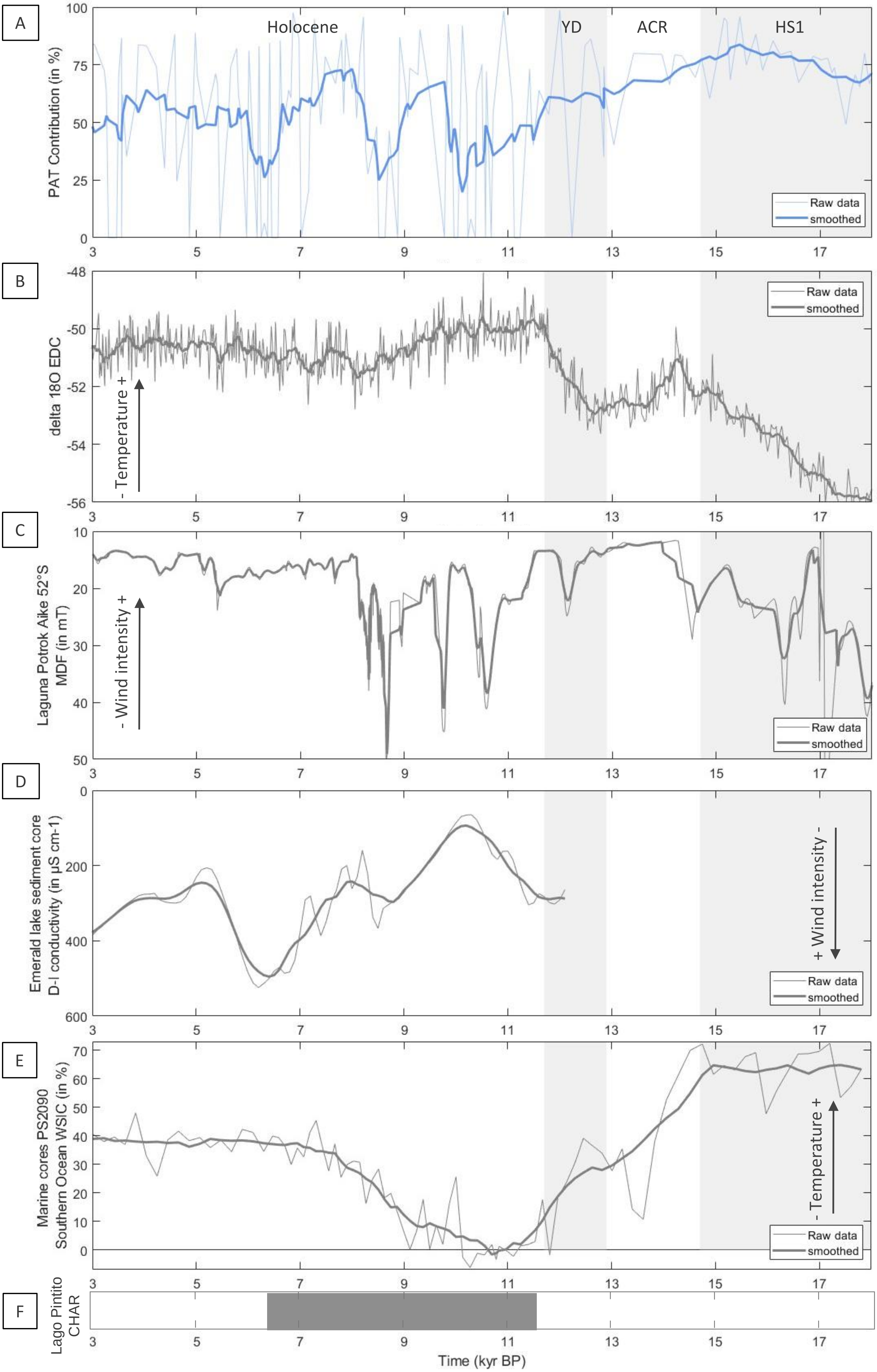

A
PAT Contribution (in %)
Holocene
YD
ACR
HS1
Raw data
smoothed
B
delta 18O EDC
- Temperature +
C
Laguna Potrok Aike 52°S
MDF (in mT)
- Wind intensity +
D
Emerald lake sediment core
D-I conductivity (in µS cm-1)
+ Wind intensity -
E
Marine cores PS2090
Southern Ocean WSIC (in %)
- Temperature +
F
Lago Pintito
CHAR
Time (kyr BP)

Figure 4: Comparison of Patagonian dust contribution with temperature, wind intensity and fire~~s~~ proxies. (A) Contribution of Patagonian dust to EDC ice core; (B) $\delta^{18}O$ from the EDC ice core (EPICA Community Members, 2006); (C) Median Destructive Field (MDF) of isothermal remanent magnetization from Laguna Potrok Aike in Southern Patagonia (Lisé-Pronovost *et al.*, 2015); (D) Diatom-inferred (D-I) conductivity from the Emerald lake in Macquarie Island (in $\mu S\ cm^{-1}$) (Saunders *et al.*, ~~(~~2018); (E) Southern Ocean winter sea-ice concentration from marine core PS2090 (WSIC in %) (Bianchi ~~&~~and Gersonde, 2004, Saunders *et al.*, 2018); (F) Macroscopic charcoal accumulation rates with gray band marking increased accumulation rate in Lago Pintito (Patagonia) (Moreno *et al.*, 2021). Bold lines in panels denote the mobile average over 9 steps.

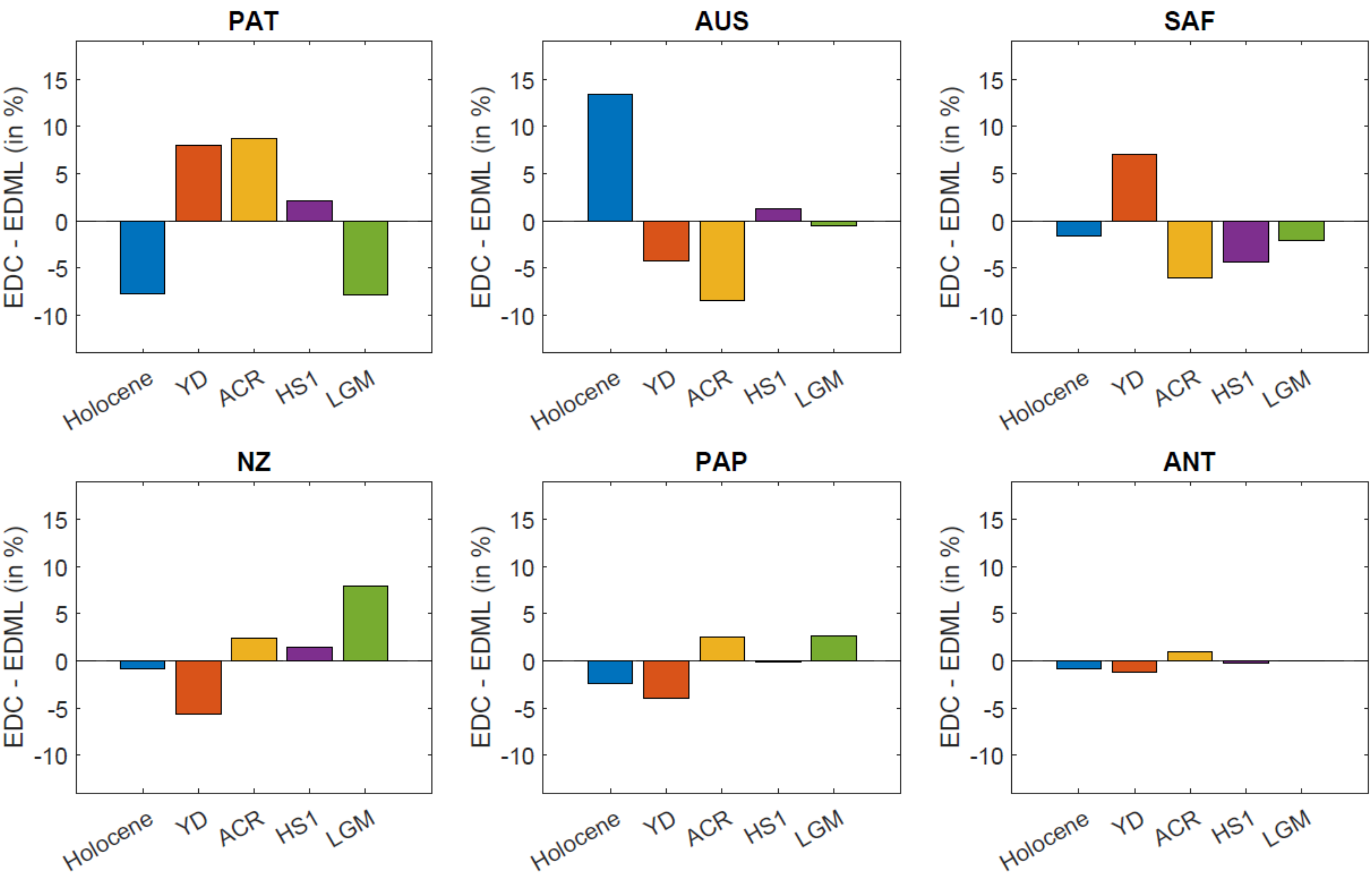
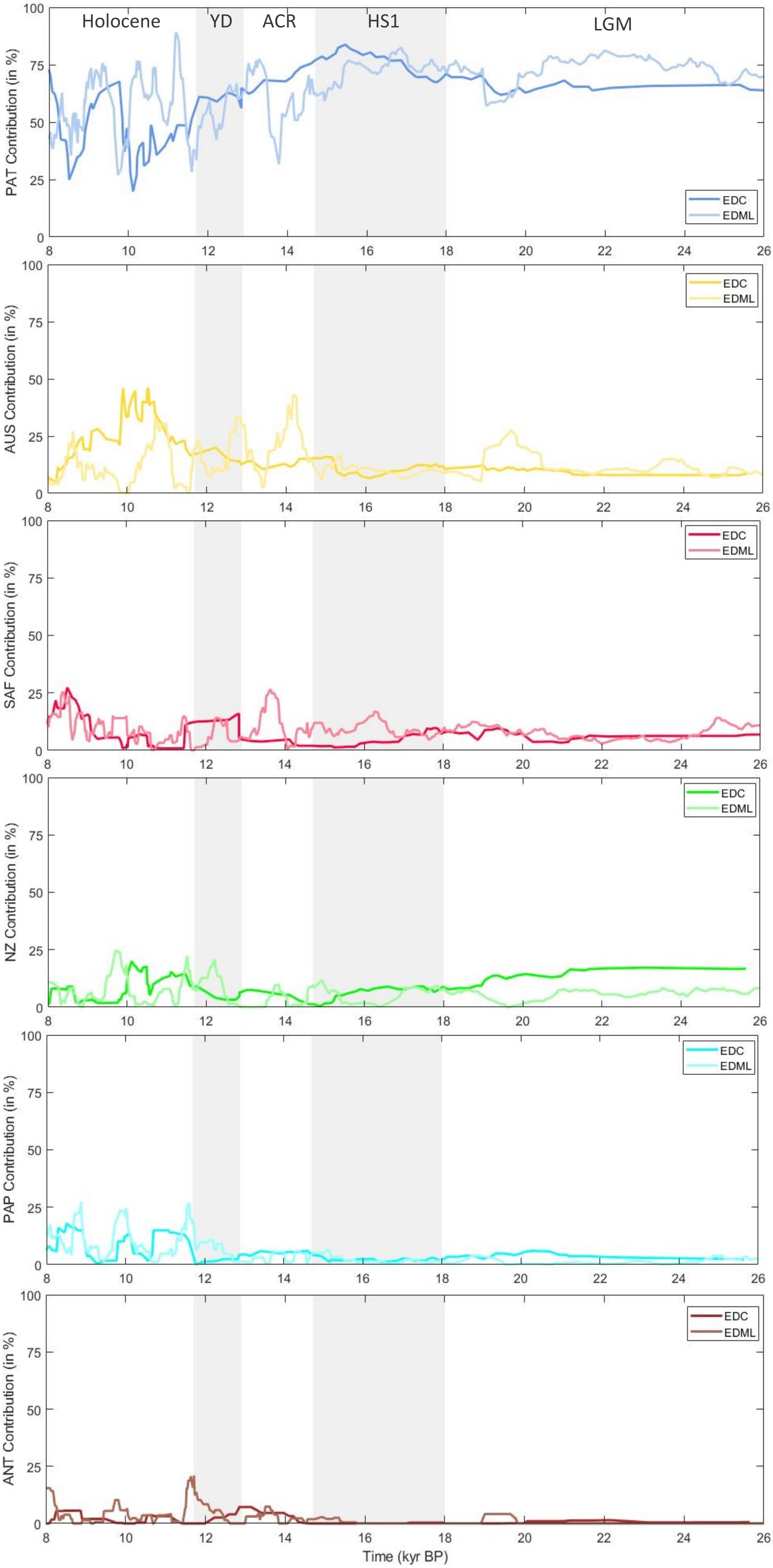

PAT
AUS
SAF
NZ
PAP
ANT
EDC - EDML (in %)
15
10
5
0
-5
-10
Holocene
YD
ACR
HS1
LGM

Figure 5: Histograms representing the differences in provenance contributions ([PSA average contributions in EDC] – [PSA average contributions in EDML] in %) averaged over periods for each PSA between EDC and EDML ice cores (see Table S3).



Holocene
YD
ACR
HS1
LGM
PAT Contribution (in %)
AUS Contribution (in %)
SAF Contribution (in %)
NZ Contribution (in %)
PAP Contribution (in %)
ANT Contribution (in %)
EDC
EDML
Time (kyr BP)

Figure 6: Comparison of the total contributions of the main dust PSAs int the EDC (Table S2) and EDML ice cores (Vanderstraeten *et al*., 2023) across the LGIT (9-steps moving average).