



Regional variability in East Antarctic surface accumulation over the past 162 kyr inferred from englacial stratigraphy at the southern flank of Dome A

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Abstract. Accurate reconstructions of past surface mass balance are critical for understanding Antarctic Ice Sheet evolution. Ice cores can provide valuable records of surface mass balance history, but individual core sites may not fully capture regional variability. In this study, we infer the surface mass balance history along the southern flank of Dome A, East Antarctica, with recently acquired englacial radiostratigraphy. We first estimate the average accumulation rate for the past 4.9 kyr. We then use a 2.5-D flowband model constrained by eight dated englacial horizons from 4.9 ka to 161.9 ka to infer temporal variations in the surface mass balance history. We find that applying the normalized temporal accumulation history from the EPICA Dome C (EDC) ice core leads to a substantial mismatch between modeled and observed englacial stratigraphy along the southern flank of Dome A. To match the observed stratigraphy within the range of uncertainties, the model requires accumulation rates approximately 5%–33% higher than EDC-derived values between 10.9 and 40.8 ka, 30%–98% higher between 40.8 and 87.9 ka, and 18%–38% lower between 87.9 and 161.9 ka. Accumulation histories derived from individual deep ice cores, while valuable, may not fully represent the spatial and temporal variability across different sectors of Antarctica. This work underscores the need to combine ice-core chronologies, radar-derived stratigraphy, and ice-flow modeling to build regionally appropriate reconstructions of climate history.

1. Introduction

Characterizing the spatial variability and temporal evolution of Antarctic surface mass balance (SMB) is necessary for reconstructing the long-term history of the Antarctic Ice Sheet. SMB controls the net input of mass to the ice sheet, and different SMB forcings can therefore influence estimates of ice-sheet geometry, grounding-zone evolution, ice-stream and ice-shelf stability, and past and future contributions to sea-level change (e.g., Coulon et al., 2024; Kingslake et al., 2018; Mottram et al., 2021; Ritz et al., 2001; Wirths et al., 2024). In addition to these ice-dynamic and sea-level implications, past accumulation is a first-order control on the age–depth structure of the ice column. This is particularly important for old-ice exploration, where areas with relatively low and stable accumulation are favorable for preserving continuous, highly resolved records (Fischer et al., 2013; Van Liefferinge and Pattyn, 2013; Young et al., 2017). Identifying such sites therefore



requires robust reconstructions of both modern accumulation patterns and their evolution through glacial–interglacial climate cycles.

Ice cores provide some of the most direct and highest-resolution records of past accumulation history (e.g., Bouchet et al., 2023). Yet their geographic coverage is limited. Most long, continuous ice-core records come from domes and ice divides, which may not best characterize the accumulation variability across all regions in Antarctica (Brook and Buizert, 2018). Recent comparisons between ice-core and radar-derived SMB further show that point measurements can be strongly influenced by local spatial variability (e.g., Cavitte et al., 2022, 2023; Leysinger Vieli et al., 2011).

Englacial radiostratigraphy mapped by ice-penetrating radar sounding offers a way to extend core-derived information beyond individual drilling sites. Internal-reflection horizons are generally assumed to be isochronous (see recent review by Bingham et al., 2025), and can be combined with ice-flow modeling to reconstruct spatially distributed accumulation histories and to test whether accumulation histories inferred at major ice-core sites are transferable to surrounding regions (e.g., Cavitte et al., 2023; Leysinger Vieli et al., 2011; Wang et al., 2023).

The National Science Foundation Center for Oldest Ice Exploration (NSF COLDEX) was funded to identify locations in Antarctica that may preserve the oldest continuous ice core, with the broader aim of advancing understanding of Earth’s climate history. For NSF COLDEX, both present-day surface accumulation and its past evolution are important for ice-flow models because they help constrain the age–depth structure of the ice column and improve understanding of past changes in ice dynamics, thereby supporting the search for old ice. In this study, we integrate englacial stratigraphy mapped from the new NSF COLDEX ice-penetrating radar dataset with numerical ice-flow modeling to (1) constrain the contemporary surface accumulation rate and pattern and (2) constrain its past evolution at the southern flank of Dome A.

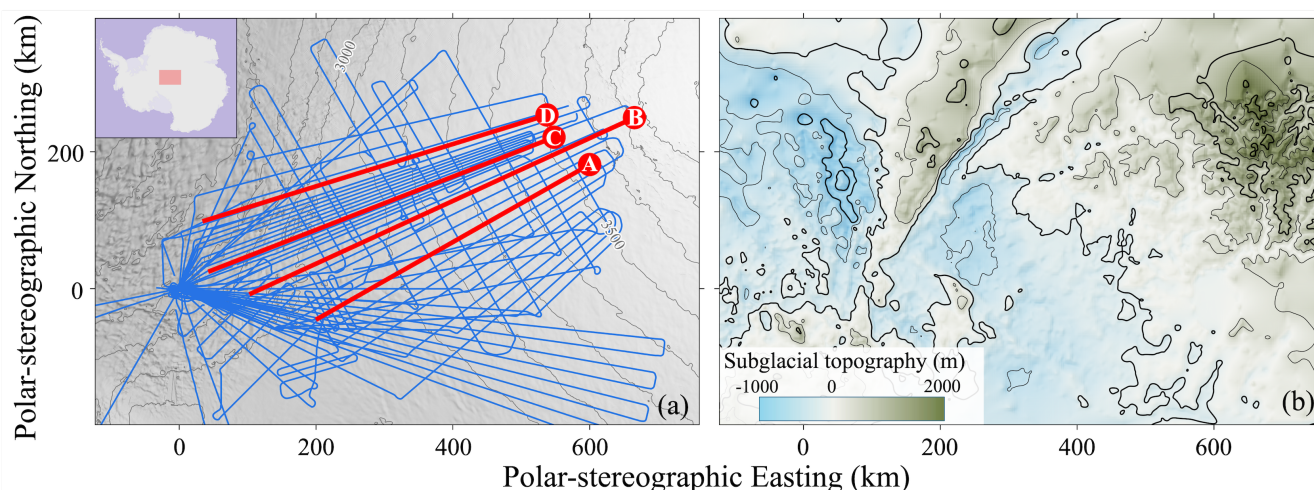
2. Englacial radiostratigraphy at the southern flank of Dome A, East Antarctica

During the austral summers of 2022–23 and 2023–24, NSF COLDEX conducted two seasons of airborne geophysical surveys at the southern flank of Dome A, East Antarctica (Fig. 1) (Young et al., 2025a). The survey geometry was designed primarily to align flight lines as closely as logistically feasible with the modern ice-flow direction (grid northeast to grid southwest in Fig. 1), which is advantageous for subsequent ice-flow modeling (described in Sect. 4). Supplementary cross-flow lines were acquired to facilitate tracing of englacial stratigraphy across transects and to support leveling of airborne potential-field measurements, including gravity and magnetic data. Together, these surveys provide new observations of ice thickness, englacial stratigraphy, and subglacial topography, as well as broader constraints on regional subglacial hydrologic and geologic conditions (Kerr et al., 2024, 2026; Young et al., 2025b).

The NSF COLDEX airborne geophysical survey platform is equipped with the MARFA ice-penetrating radar system, which is a coherent 60 MHz radar system developed by the University of Texas Institute for Geophysics (Peters et al., 2005; Young et al., 2025a). The MARFA system provides an effective balance between deep penetration and stratigraphic resolution,



65 allowing the full ice column to be imaged while preserving sufficient vertical detail to identify continuous englacial reflections. Following pulse compression and along-track focusing (Peters et al., 2007), the processed radar data have a vertical resolution of approximately 8.5 m in ice and an along-track resolution of approximately 44 m (Cavitte et al., 2018). The englacial stratigraphy can then be mapped using the DecisionSpace Geosciences 10ep software package, which provides semi-automatic tracing tools and enables cross-transect tracing and comparison at intersecting points (Yan et al., 2025).



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Figure 1. Maps of the southern flank of Dome A, East Antarctica. (a) Surface elevation with 100 m contours in gray (Howat et al., 2022), overlain by NSF COLDEX airborne geophysical survey lines in blue (Young et al., 2025a). The four profiles selected for flowband modeling are highlighted in red. The inset shows the location of the study region within Antarctica. **(b)** Subglacial topography of the study region (Young et al., 2025a). Transect names for the four selected profiles are: A: CLX/MKB2n/R52a; B: CLX/MKB2o/R64b; C: CLX/MKB2o/R73a; D: CLX/MKB2o/R82a.

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Previous work identified and traced eight continuous englacial horizons across the survey region and assigned their ages using nearby ice-core and borehole age–depth constraints, yielding dated horizons between 4.9 and 87.9 ka (L1–L8 in Table 1) (Singh et al., 2023). To extend the temporal coverage of the dated stratigraphy, we also extended the 161.9 ka horizon by Sanderson et al. (2024) into the survey region (L9 in Table 1). Together, these dated horizons provide the observational basis
 80 for reconstructing accumulation-rate evolution from the late Holocene through approximately 30 kyr before the Last Interglacial period (Fig. 2).

Among the nine dated horizons considered in this study, the youngest horizon (L1; 4.9 ka) is used to estimate the contemporary surface-accumulation field across the survey region, as described in Sect. 3. The remaining horizons provide constraints on the temporal evolution of accumulation, as described in Sect. 4. However, because L3 is only present in the
 85 downstream part of the survey region and cannot be traced continuously upstream, it is excluded from the flowband model experiments, which mainly focus on the upstream part of the survey region.

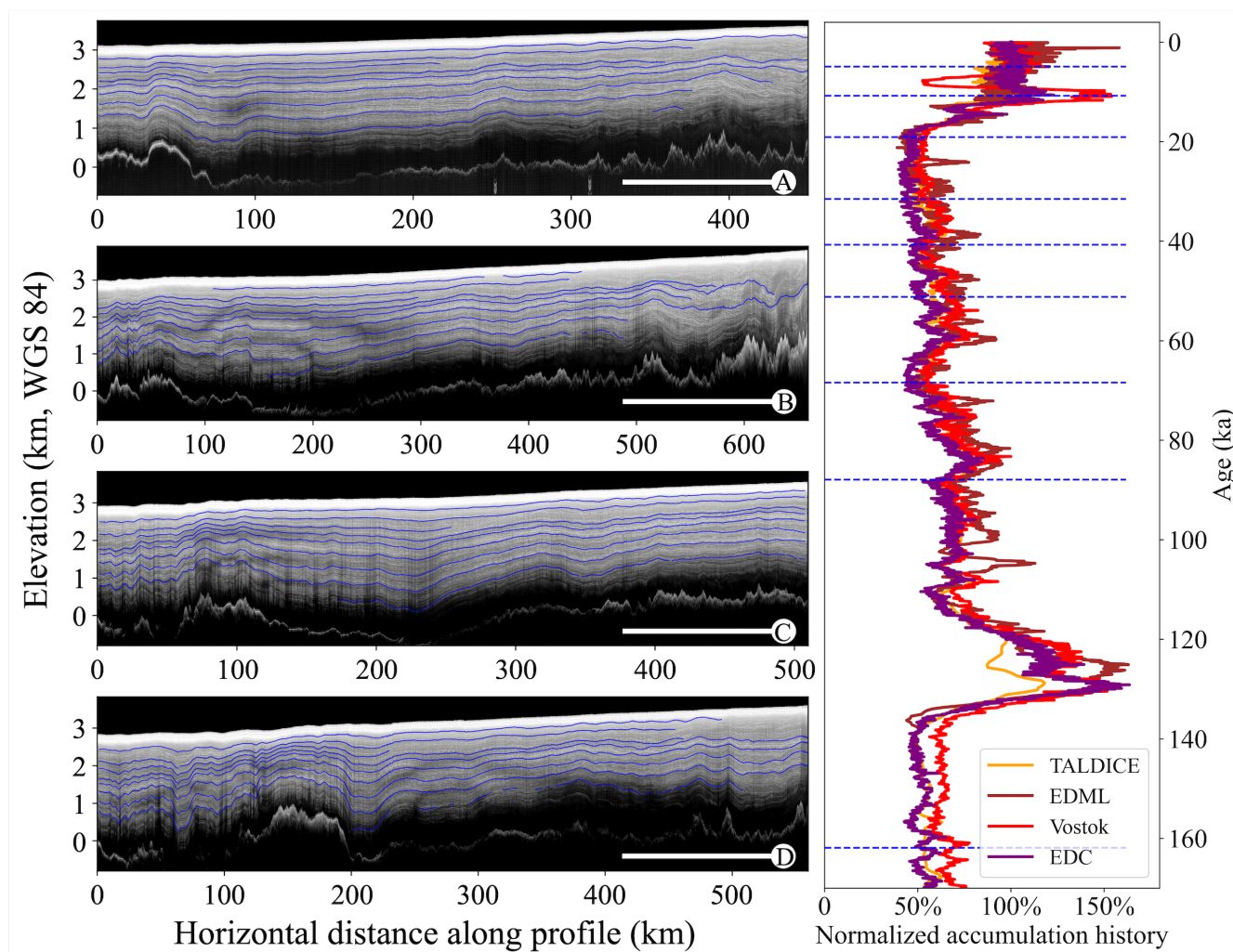


Figure 2. Englacial radiostratigraphy with age constraints. Left: Radargrams from the four selected radar profiles, with traced englacial stratigraphy shown in blue. Profile locations are shown in Fig. 1. Right: Normalized accumulation histories from four East Antarctic ice cores (Bouchet et al., 2023). Blue dashed lines mark the ages of the nine dated horizons considered in this study. TALDICE: Talos Dome Ice Core; EDML: European Project for Ice Coring in Antarctica (EPICA) ice core from Dronning Maud Land; Vostok: Vostok Ice Core; EDC: EPICA ice core from Dome C.

3. Estimation of contemporary accumulation rate

3.1 Inferring contemporary accumulation using a 1-D model

We use the youngest available dated horizon (L1; 4.9 ka) to estimate the average surface accumulation rate across the study region over the past 4.9 kyr. We use this estimate as the contemporary accumulation-rate forcing in the temporal-variability experiments presented in Sect. 4. Although this approach does not resolve shorter-term accumulation variability over the past 4.9 kyr, the 4.9 ka horizon is the youngest dated horizon available in the survey region, and accumulation changes over the

late Holocene are expected to be relatively small compared with glacial–interglacial variations. This approximation therefore provides a reasonable first-order estimate of the contemporary spatial accumulation pattern.

We calculate average accumulation over the past 4.9 kyr using a one-dimensional flow model and therefore neglect horizontal advection. This approximation is appropriate for most of the survey area because ice flow velocities are relatively low, typically on the order of meters per year (Rignot et al., 2017). Accurate estimation of accumulation from englacial stratigraphy requires accounting for firn density, which influences both radar-derived horizon depth and the conversion to ice-equivalent accumulation. Because direct firn-density observations within the survey region are limited to the South Pole, we estimate firn density profiles using the Herron and Langway (1980) firn densification model. We further account for vertical thinning due to ice flow by assuming a linear vertical velocity profile following Nye (1963). The density-profile calculation requires initial estimates of accumulation and surface temperature. These are assigned at each radar location as functions of surface elevation, referenced to approximate South Pole values. Accumulation is assumed to decrease with elevation at a rate of $7.1 \times 10^{-2} \text{ m a}^{-1} \text{ km}^{-1}$, and temperature is assumed to decrease by 1°C km^{-1} .

For each location, we begin with an initial firn density profile defined using a surface density of 350 kg m^{-3} . This profile is used to determine the depth of the 4.9 ka horizon and the local ice thickness. A thinning correction is then calculated. The horizon depth, density profile, and thinning correction are combined to estimate the accumulation rate. The updated accumulation rate is subsequently used to recompute the firn density profile, while surface density and temperature are held fixed. Iteration continues until the change in accumulation rate between successive steps is less than 0.001 m a^{-1} . Final results are not highly sensitive to initial estimates, and convergence is typically reached within three iterations.

3.2 Average accumulation for the past 4.9 kyr

Using the 4.9 ka horizon, we estimate the contemporary surface accumulation field across the southern flank of Dome A (Fig. 3). This radar-derived accumulation field shows a clear regional gradient along the Dome A–South Pole corridor. The lowest accumulation rates, approximately 2 cm yr^{-1} , occur in the upstream part of the survey region near the southern flank of Dome A. Accumulation increases progressively downstream, reaching approximately 11 cm yr^{-1} near the South Pole region. This result represents the first observation-informed accumulation constraint for this region, filling an important data gap and providing a spatially resolved forcing field for subsequent ice-flow and age–depth modeling.

Across most of the study area, the spatial pattern of the radar-derived accumulation field agrees well with the surface mass balance provided by RACMO2.4 (van Dalum et al., 2024) (Fig. 3). Both products show low accumulation near Dome A and increasing accumulation toward the South Pole. In the upstream region, the difference between the two fields is generally small, typically on the order of a few mm yr^{-1} , or approximately 10% of the local accumulation rate. This indicates that the 1-D radar-derived estimate captures the first-order accumulation pattern in areas where ice flow is relatively simple. Larger mismatches occur above the Recovery Subglacial Highlands and grid south of the South Pole point. These areas are characterized by extreme subglacial topographic relief (Young et al., 2025a), a large-scale change in ice-flow direction (as



demonstrated by the ice-surface elevation contours in Fig. 3), accelerated ice flow (Rignot et al., 2017), and likely changes in subglacial hydro-geological conditions (Kerr et al., 2026). Such complexity likely violates the assumptions of the 1-D accumulation model, which does not account for horizontal advection, complex flow reorganization, or localized deformation associated with rugged bed topography. We therefore interpret these larger mismatches as reflecting limitations of the simplified 1-D framework in dynamically complex regions, rather than a regional disagreement between the radar-derived accumulation field and RACMO.

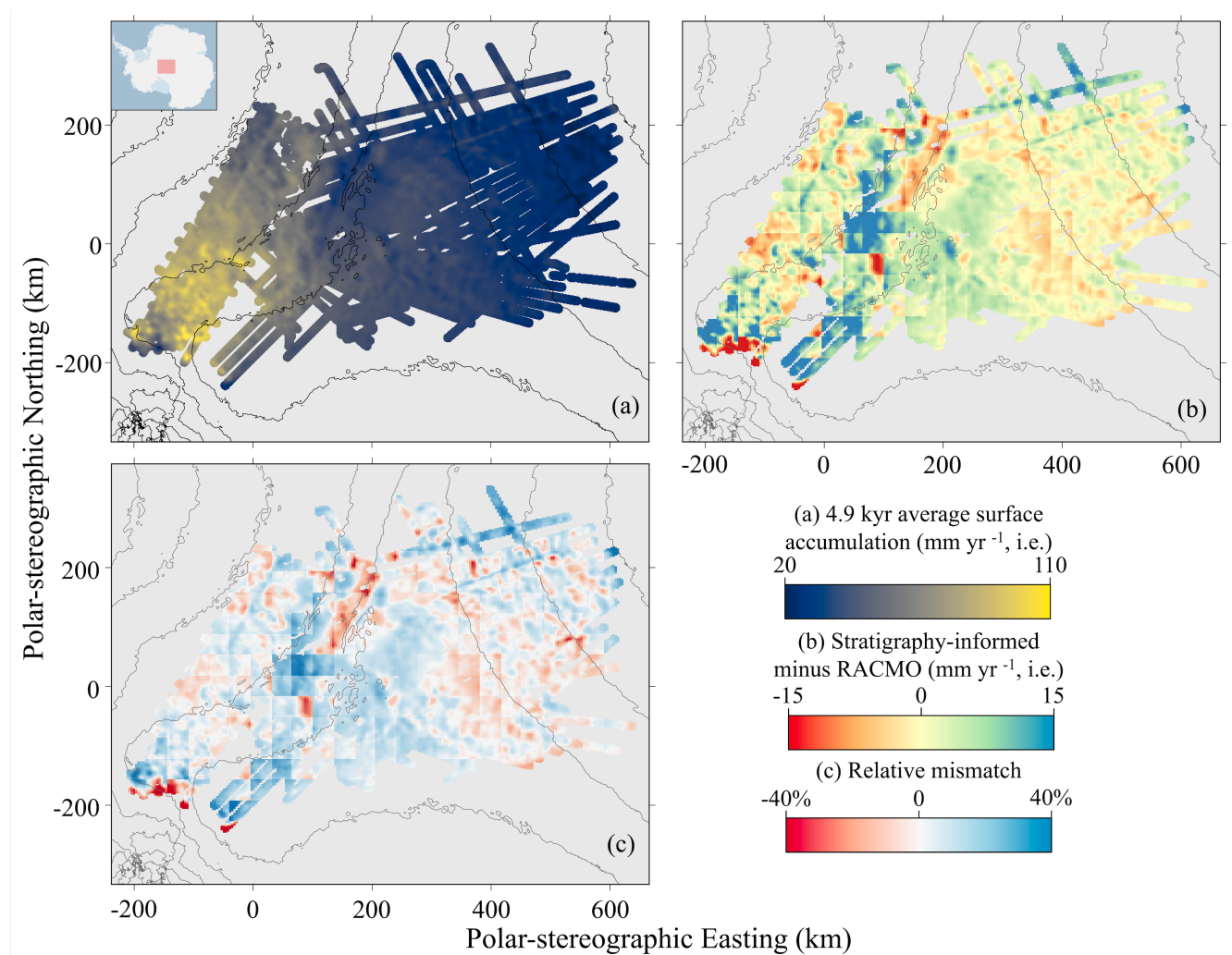


Figure 3. Stratigraphy-informed contemporary accumulation field and comparison with RACMO2.4 (van Dalum et al., 2024). (a) Average surface accumulation rate over the past 4.9 kyr inferred from the youngest dated internal reflection horizon. (b) Difference between the stratigraphy-informed accumulation estimate and RACMO2.4 surface mass balance. (c) Relative mismatch, defined as the difference in panel (b) normalized by the stratigraphy-informed accumulation in panel (a). Surface-elevation contours are shown in the background.



4. Temporal variation of accumulation rate for the past 162 kyr

145 In this study, we evaluate the extent to which the temporal variation in surface accumulation derived from the EPICA Dome
 C (EDC) ice core (Bouchet et al., 2023; EPICA community members, 2004; Jouzel et al., 2007) is representative of the
 southern flank of Dome A. Where it is not representative, we investigate the first-order scaling required to improve
 agreement between the modeled isochrones and the observed stratigraphy. We choose the EDC record as a reference because
 it provides a long, well-established accumulation history from the East Antarctic interior. Comparing the EDC accumulation
 150 history with the radiostratigraphic record from the southern flank of Dome A allows us to evaluate whether accumulation
 changes inferred at EDC are representative of another interior East Antarctic sector, and to assess the degree of spatial
 variability in East Antarctic accumulation history.

4.1 Inferring SMB history using a 2.5-D flowband model

We use a 2.5-D flowband model to investigate how the long-term temporal evolution of surface accumulation rate across the
 155 southern flank of Dome A can affect the shapes and depths of englacial horizons. The model follows the framework of
 Koutnik and Waddington (2012), and has been applied to test hypotheses about ice-sheet history elsewhere in Antarctica
 (e.g., Koutnik et al., 2016; Yan et al., 2025). The model represents a two-dimensional cross section of the ice sheet oriented
 along a flowline from the ice surface to the bed, with an additional half dimension that accounts for transverse strain-rate
 effects along the flow direction; this is therefore considered a flowband model.

160 Given the longer timescales analyzed and the flank-flow regime of the study region, accounting for 2-D flow is necessary for
 the interpretation of deeper horizons. Although the NSF COLDEX airborne survey terminates approximately 300 km from
 Dome A, the model domain extends upstream to the dome. This extended domain is needed because we model ice-flow and
 stratigraphic evolution over glacial-cycle timescales, during which ice parcels that make up layers observed downstream may
 have originated hundreds of kilometers upstream. Extending the domain to the approximate divide also simplifies a model
 165 boundary condition because at the dome the upstream boundary is a zero-flux boundary.

Under prescribed boundary conditions, the model can dynamically solve for the englacial velocity field from the momentum
 balance using the shallow-ice approximation (SIA), where only bed-parallel shear is retained (Cuffey and Paterson, 2010).
 The model calculates the time-varying velocity field and then tracks englacial particles over time from the surface to depth.
 The end points of numerous particle paths for ages that match the observed horizon ages are used to define the modeled
 170 englacial stratigraphy, which can then be compared with radar-observed englacial stratigraphy to assess model performance.
 For each model run, we quantify model performance using the root-mean-square (RMS) mismatch between modeled and
 observed horizon depths. The RMS mismatch is calculated separately for each dated horizon along each profile, providing a
 first-order measure of how well a given accumulation history reproduces the observed age–depth structure. Lower RMS
 values indicate better agreement between the modeled stratigraphy using a given prescribed accumulation history and the
 175 observed stratigraphy.



We perform model experiments along four radar profiles across the survey region (Fig. 1). These profiles were selected to cover the main portion of the COLDEX survey area while remaining sufficiently separated from one another to sample regional-scale variability. Conducting the modeling experiments along four profiles, rather than a single profile, allows us to test whether the inferred SMB history reflects a regional pattern rather than a profile-specific result. The analysis is restricted to the approximately 300 km-long upstream portion of each profile (Fig. 4), where ice flow is relatively slow, horizons are relatively continuous, and SIA assumptions are most appropriate. Downstream regions near the Recovery Subglacial Highlands and South Pole Basin are excluded because they are characterized by rapid basal unit thickness changes, stronger subglacial topographic relief, a greater likelihood of widespread subglacial water, and increasingly complex flow conditions that are less well represented by a 2.5-D SIA flowband model and the available data (Kerr et al., 2026; Young et al., 2025a).

4.1.1 Surface and basal boundary conditions

Within the radar survey area, surface and bed topography are derived from the COLDEX radar data. Outside the radar coverage, these boundary conditions are taken from Bedmap3 (Pritchard et al., 2025). The contemporary accumulation-rate field inferred from the 1-D analysis described above is used as the present-day accumulation forcing within the COLDEX survey area. Upstream of the survey area, the accumulation field is extended using RACMO2.4 output (van Dalum et al., 2024). Where localized surface-scour zones have been observed (Das et al., 2013; Fudge et al., 2026), these features are incorporated into the SMB forcing as zero accumulation zones. Surface temperature is prescribed from RACMO2.4 (van Dalum et al., 2024), and geothermal heat flux is prescribed from Shen et al. (2020). The resulting temperature field is used to calculate spatially variable ice viscosity following an Arrhenius relationship. We acknowledge, however, that geothermal heat flux, and therefore the modeled ice-temperature field, remains relatively poorly constrained. We use the Shen et al. (2020) estimate because it is empirically constrained, incorporates a recent high-resolution Antarctic seismic model, provides uncertainty estimates, and has a smoothing length scale of approximately 100 km, which is appropriate for characterizing regional-scale heat-flux variability. We do not directly interpret the modeled ice-temperature field in this study. Although modeled ice temperature influences the simulated ice-flow velocity through its effect on viscosity, the modeled surface velocities generally agree with MEaSUREs annual velocity observations within their uncertainty (Rignot et al., 2017) and this is the primary data comparison available so we do not explicitly explore the sensitivity of our model to prescribed heat flux.

4.1.2 Assumptions about ice surface elevation history

The model domain covers a limited portion of the ice sheet, and therefore its transient evolution would require assumptions about boundary fluxes that allow the domain to evolve consistently within the larger ice sheet (Koutnik and Waddington, 2012). This is achieved by prescribing an additional dynamic flux at the model-domain boundaries, which means that the surface elevation and divide (Dome A in this case) position can change over time in the model. However, the actual surface elevation, dome position, and ice-flux history in this region, and across East Antarctica, are poorly constrained over the past



hundreds of thousands of years by direct observations. Constraints primarily come from models that may or may not be constrained by ice-core data and/or glacial geology information, and these studies find that the East Antarctic interior is expected to vary over the last glacial-interglacial cycle by only a few percent of the ice thickness (e.g., Mackintosh et al., 2014; Parrenin et al., 2007; Rand et al., 2025).

We therefore choose to fix the ice-sheet geometry at the modern configuration over the past 162 kyr in our flowband model. The surface mass balance history and the ice-thickness history can trade off against each other when modeling englacial stratigraphy, where similar horizon depth may be achieved by higher accumulation with less thinning or lower accumulation with more thinning. Disentangling the influence of climate and ice-flow imprints on englacial stratigraphy is a challenge common to all models that use englacial horizons to test hypotheses about ice-sheet and climate histories. Since we are investigating the surface mass balance, we fix the ice-sheet geometry, but fixing the modeled ice-sheet geometry while the SMB is changing in time is a structural assumption in our flowband model and we must carefully consider if this adds structural uncertainty. We discuss this in Sect. 5.

4.2 Base run: flowband model with unmodified EDC accumulation history

We first construct an EDC “scaling curve” by normalizing the EDC accumulation history by its contemporary accumulation rate (Fig. 2). This dimensionless scaling curve describes relative accumulation change through time. Multiplying the EDC scaling curve by the contemporary accumulation rate produces an initial time-varying accumulation history for the survey region with the modern pattern scaled over time by the EDC record. The unmodified EDC-scaled accumulation history is used as the “base run” in our modeling experiment, and the resulting modeled englacial stratigraphy is compared with the radar observation to provide a first-order test of whether an EDC-like accumulation history is transferable to the southern flank of Dome A.

The base run reproduces some aspects of the observed stratigraphy but does not provide a consistent fit across all dated horizons (Fig. 4). The mismatch pattern varies systematically with horizon age:

- For horizons between the present and the Last Glacial Maximum (LGM), the modeled and observed horizon depths are in relatively good agreement. This result is expected because the contemporary accumulation-rate field used for model forcing is derived from the 4.9 ka horizon, and accumulation changes over the late Holocene are likely small compared with glacial–interglacial-scale variations. This also means that the multi-millennial averaged accumulation-rate pattern has remained relatively stable over this time period.
- Horizons between the LGM and approximately 87.9 ka show substantially larger mismatches between the modeled and observed horizons. In this interval, the modeled horizons are shallower than the observed horizons, indicating that the unmodified EDC scaling curve underestimates the cumulative accumulation required to place these horizons at their observed depths.



- The 161.9 ka horizon shows a smaller mismatch, suggesting that the total accumulation integrated from the present to 161.9 ka is broadly comparable to that inferred from the unmodified EDC-scaled history, even though the exact distribution of accumulation through time may differ.

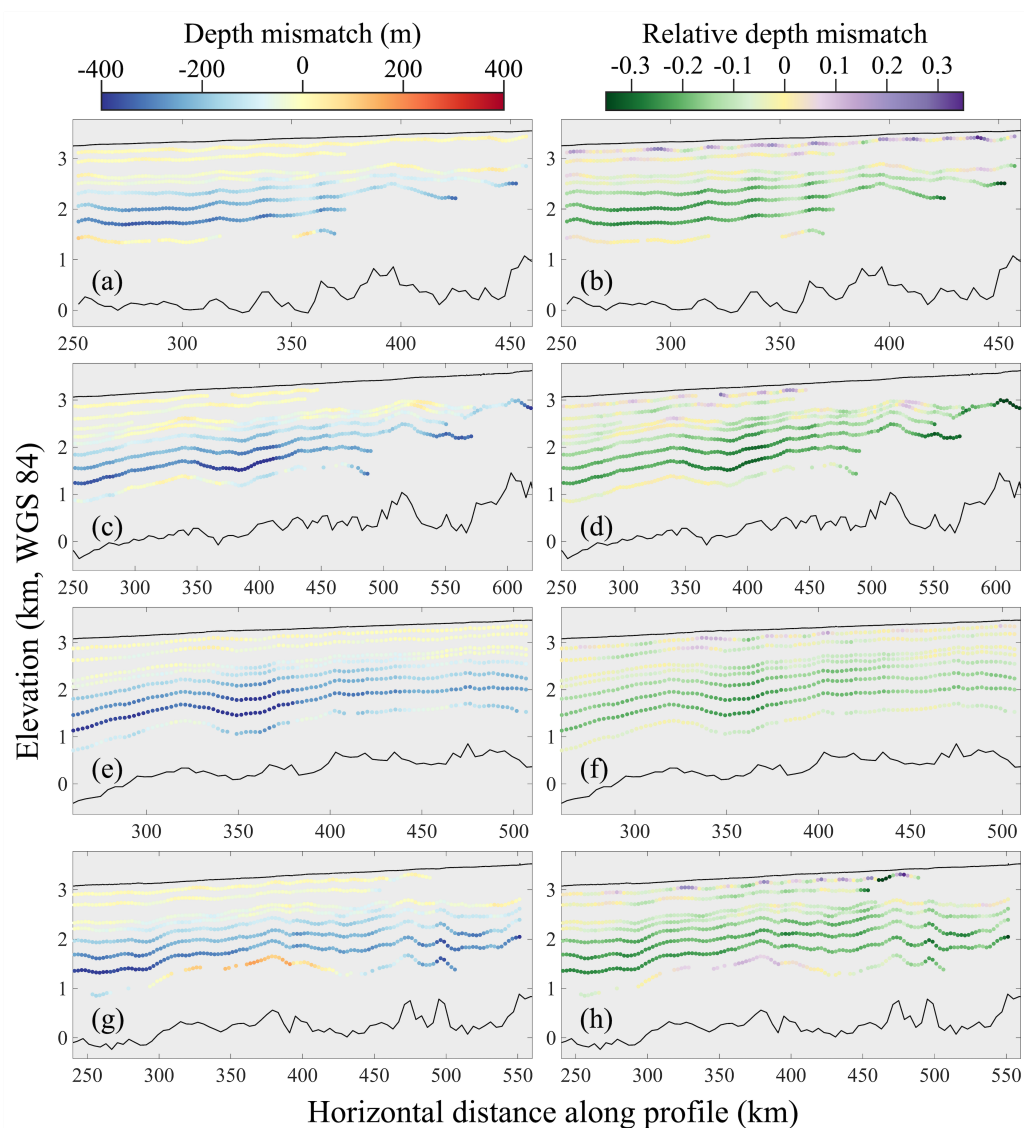


Figure 4. Depth mismatch between modeled and radar-observed englacial horizons when the flowband model is forced with the unmodified EDC-derived accumulation history. The panel pairs show results for the four selected profiles in Fig. 1 and Fig. 2: (a, b) profile A, (c, d) profile B, (e, f) profile C, and (g, h) profile D. Absolute depth mismatch (model depth minus observation depth) is shown in panels (a, c, e, g), and relative mismatch, normalized by observed horizon depth, is shown in panels (b, d, f, h). The ice surface and bed are shown in black, and englacial horizons are colored by absolute depth mismatch or relative depth mismatch.

Together, these results indicate that the EDC accumulation history is not entirely representative of this interior region of Antarctica over the past approximately 162 kyr. The mismatch between modeled and observed stratigraphy is not well



250 explained by a single uniform offset in accumulation magnitude because some horizons that bracket certain age intervals can fit better than others. Instead, the pattern of mismatch implies that the difference between the EDC-derived history and the accumulation history required by the observed stratigraphy is time dependent.

4.3 Searching for temporal variations in accumulation consistent with observed englacial stratigraphy

255 To constrain the accumulation history that best reproduces the observed englacial stratigraphy, we introduce time-dependent perturbations to the EDC scaling curve and use the resulting modified curves to construct accumulation forcing for separate model experiments. The EDC scaling curve is divided into time intervals bounded by dated horizons, with each interval beginning and ending at the age of a dated horizon (L1, L2 and L4–L9, Table 1). For each interval, we apply a set of prescribed percentage modifications to the original EDC scaling curve and evaluate the model fit using the mismatch for the horizon marking the end of that interval. For instance, a 110% modification increases the original EDC scaling curve by 10%
 260 within the selected interval. The adjusted scaling curve is then multiplied by the modern accumulation rate and pattern inferred from the 4.9 ka horizon to prescribe the spatial and temporal accumulation history for that interval. As described above, the unmodified EDC scaling likely underestimates accumulation after the Last Interglacial and overestimates accumulation before it. We therefore primarily apply percentage modifications greater than 100% to intervals younger than the Last Interglacial and percentage modifications less than 100% to older intervals.

265 We perform the perturbation experiment sequentially to account for the cumulative influence of accumulation history on horizon depth. Each age interval is bounded by dated horizons, and the perturbation for that interval is evaluated from the model-minus-observation depth RMS mismatch of the horizon marking its older boundary. After identifying the best-fitting perturbation for the youngest modeled interval, we hold that perturbation fixed and proceed stepwise to older intervals. This strategy provides first-order accumulation adjustments for each interval while accounting for the effect of younger
 270 accumulation changes on older horizons.

The results of the perturbation experiments are broadly consistent across the four modeled profiles and are summarized in Fig. 5. In this figure, each panel shows one of the four modeled profiles, with individual curves representing the RMS depth mismatch for the dated horizon that bounds each accumulation-scaling interval. The best-fitting perturbations show a consistent temporal pattern across four profiles: accumulation rates are approximately 5%–33% higher than EDC-derived
 275 values between 10.9 and 40.8 ka, 30%–98% higher between 40.8 and 87.9 ka, and 18%–38% lower between 87.9 and 161.9 ka. Applying these perturbations improves the agreement between modeled and observed englacial stratigraphy, as shown in Fig. 6.

We evaluate the sensitivity of the preferred accumulation scaling to two sources of uncertainty: (1) age uncertainty in the dated horizons and (2) structural uncertainty associated with the fixed-geometry assumption (Table 1). For each horizon, we
 280 repeat the modeling experiment using the upper and lower bounds of its age uncertainty range. We also estimate the uncertainty introduced by prescribing a fixed modern ice-sheet geometry, as discussed in Sect. 5.1. Together, these



uncertainties define the tolerance used to evaluate model fit. Perturbation scenarios with RMS mismatches within this tolerance are considered indistinguishable from the nominal best-fitting case. We therefore interpret the accepted perturbation range, rather than only the single minimum-RMS solution, as the plausible range of accumulation histories that are consistent with the data.

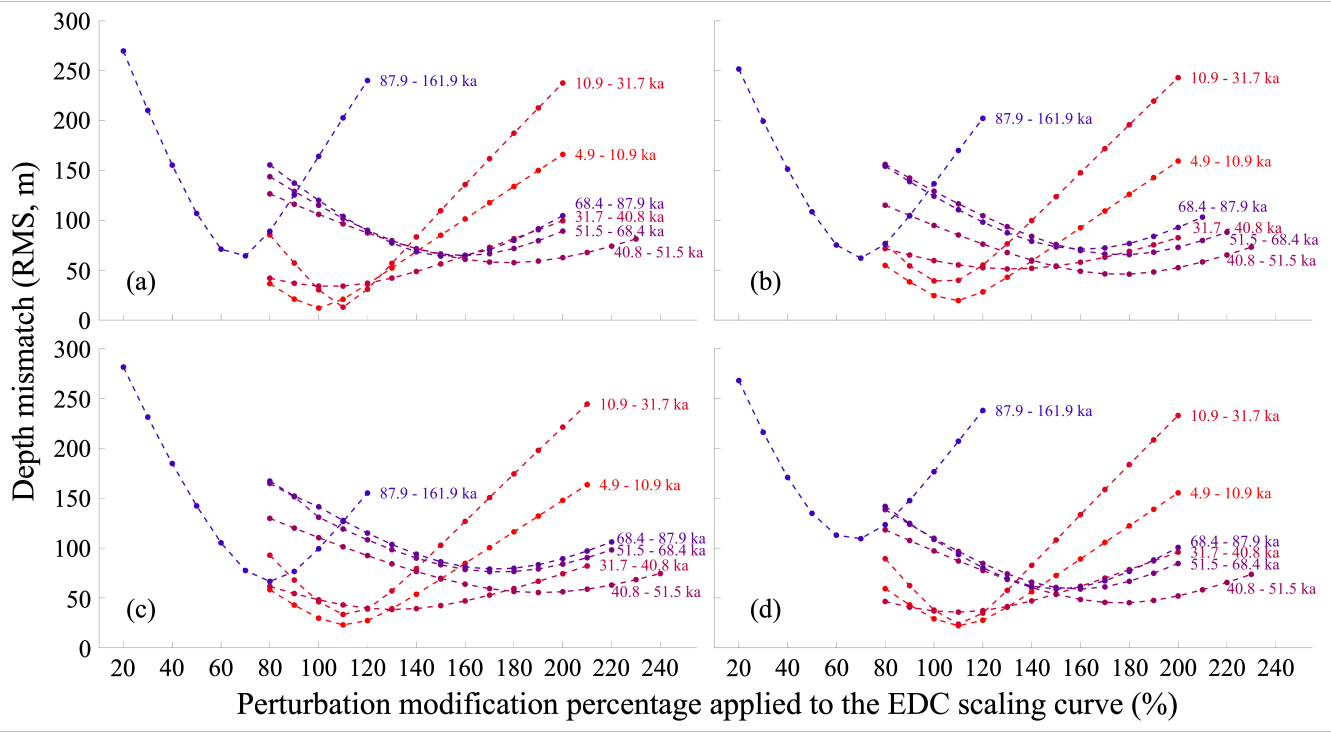


Figure 5. RMS depth mismatch for each modeled horizon as a function of the perturbation applied to the EDC-derived accumulation scaling curve. Results are shown for the four selected profiles in Fig. 1 and Fig. 2. Each curve represents the mismatch for one dated horizon used to evaluate the accumulation scaling for the corresponding time interval.

The consistency across the four selected profiles (Fig. 5) indicates that the inferred deviations from the EDC-derived accumulation history are not artifacts of making inferences from one individual radar transect, but instead reflect a regional-scale signal across the southern flank of Dome A. We therefore average the four profile-specific accepted perturbation ranges to define the regional mean accumulation history shown in Fig. 7; the corresponding upper and lower bounds of the perturbation range are listed in Table 1. These results show that the EDC-derived accumulation history is a useful reference, but that its temporal evolution cannot be transferred directly to the southern flank of Dome A without regional modification.

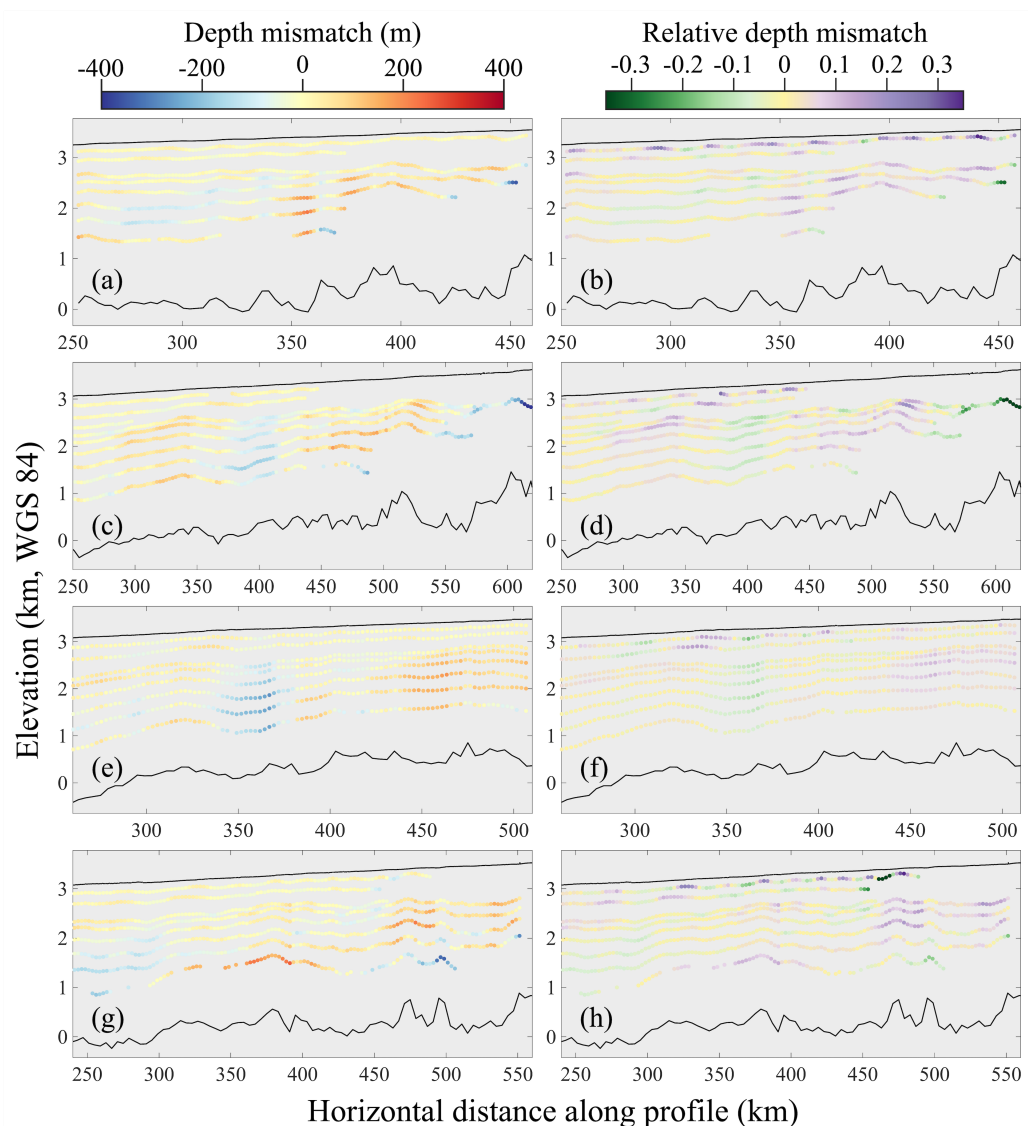


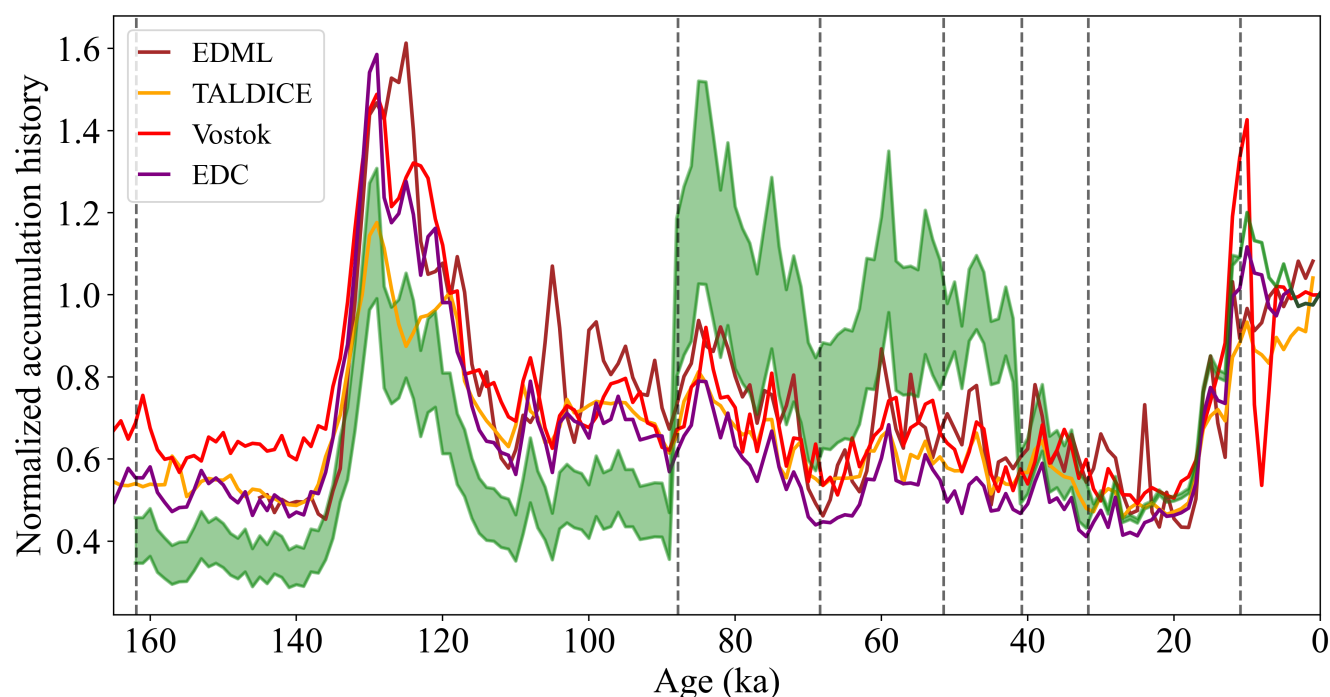
Figure 6. Depth mismatch between modeled and radar-observed englacial horizons when the flowband model is forced with the nominal best-fit accumulation history. The panel pairs show results for the four selected profiles in Fig. 1 and Fig. 2: (a, b) profile A, (c, d) profile B, (e, f) profile C, and (g, h) profile D. Absolute depth mismatch (model depth minus observation depth) is shown in panels (a, c, e, g), and relative mismatch, normalized by observed horizon depth, is shown in panels (b, d, f, h). The ice surface and bed are shown in black, and englacial horizons are colored by absolute depth mismatch or relative depth mismatch.



Horizon name	L1	L2	L3	L4	L5	L6	L7	L8	L9
Age assignment (ka)	4.89	10.85	19.14	31.65	40.77	51.46	68.44	87.88	161.9
Age uncertainty (kyr)	0.107	0.445	2.041	0.569	0.770	0.617	4.212	0.740	6.760
Depth sensitivity to age uncertainty (RMS, m)	NI	5	NI	2	2	2	15	20	12
Non-dimensional depth sensitivity to surface elevation history (RMS)	NI	1.5%	NI	2.7%	2.4%	2.5%	1.9%	2%	2.6%
Depth sensitivity to surface elevation history (RMS, m)	NI	5.1	NI	17.8	18.6	24.2	23.7	31.2	48.5
Average lower bound of the accepted perturbation range	NI	107.5%	NI	107.5%	105%	165%	140%	130%	62.5%
Average upper bound of the accepted perturbation range	NI	107.5%	NI	110%	132.5%	197.5%	197.5%	192.5%	82.5%

Table 1. Age assignments and uncertainty estimate for the dated englacial horizons. Ages and associated uncertainties for L1–L8 are from Singh et al. (2023) and will be described in detail in a companion manuscript currently under review; the age and uncertainty for L9 are from Sanderson et al. (2024). The table also reports the sensitivity of modeled horizon depths to age uncertainty and to the assumption of fixed modern ice-sheet geometry, together with the profile-averaged lower and upper bounds of the accepted accumulation perturbation for each time interval. For each interval, this perturbation is applied to the normalized EDC temporal accumulation curve, which is then multiplied by the contemporary accumulation rate along each profile to define the time-varying accumulation forcing. NI: horizons not included in the flowband-model experiments.

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315 **Figure 7. Reconstructed normalized accumulation history for the southern flank of Dome A compared with normalized accumulation histories from four East Antarctic ice cores (Bouchet et al., 2023). The green envelope shows the profile-averaged accepted perturbation range constrained by the dated englacial horizons (gray dash lines) and flowband-model experiments. TALDICE: Talos Dome Ice Core; EDML: European Project for Ice Coring in Antarctica (EPICA) ice core from Dronning Maud Land; Vostok: Vostok Ice Core; EDC: EPICA ice core from Dome C.**

320 5. Discussion

5.1 Structural uncertainties in the flowband model

As introduced in Sect. 4.1.2, fixing the modeled ice-sheet geometry while the SMB is changing in time is a structural assumption in our flowband model, because if the ice-sheet geometry is unchanged when the accumulation rate is changing then the dynamic flux of the ice sheet must change to conserve mass. Since we do not know the dynamic-flux history to
 325 prescribe in the model, here we calculate the added structural uncertainty to our model experiments from this assumption. Similar fixed-geometry approaches have been used in previous interior Antarctic ice-flow modeling studies, including by Chung et al. (2023, 2025), Parrenin et al. (2025), and Parrenin and Hindmarsh (2007). These are kinematic modeling approaches, and are considered “pseudo-steady” models that keep ice geometry and the prescribed velocity-shape function fixed, while allowing accumulation magnitude, and therefore velocity magnitude, to vary through time. In such models, the
 330 velocity field is commonly constructed from balance flux, a prescribed vertical velocity-shape function, and incompressibility; in flow-tube or 2.5-D geometries, lateral divergence is also fixed in time. This formulation assumes that



velocity magnitude responds instantaneously to changes in accumulation rate. It is computationally efficient for long-timescale simulations and has been shown to perform reasonably well near ice divides.

Our approach differs in that we use a dynamic flowband model, but the fixed-geometry assumption plays a similar role: the spatial structure of the velocity field is constrained by the prescribed geometry, while velocity magnitudes respond to the time-varying SMB forcing. We prescribe and fix the modern geometry because the surface-elevation history of the East Antarctic interior is poorly constrained, and existing reconstructions suggest that interior thickness changes over the past several hundred thousand years were relatively small, on the order of only a few percent of the ice thickness (e.g., Parrenin et al., 2007; Ritz et al., 2001). This choice reduces computational cost and limits the number of poorly constrained parameters in the model, which was important for our study even though it introduces additional structural uncertainty.

To estimate the structural uncertainty introduced by our fixed-geometry assumption, we conduct a set of sensitivity tests where we solve for an additional boundary flux term that allows the flowband model to conserve mass while the surface elevation can also change through time (see Koutnik and Waddington, 2012). The test constrains the boundary flux so that the modeled surface-elevation history is similar to the one inferred by Parrenin et al. (2007) for Dome C. This allows us to evaluate the influence of fixing the ice-sheet geometry by comparing to cases where the geometry could evolve and the modeled ice-sheet velocities fully conserved mass with this time-evolving surface.

We compare the resulting change in modeled horizon depth with the fixed-geometry case using non-dimensional horizon depth, defined relative to the local ice thickness, so that the metric is not biased by variations in ice thickness between these runs (Fig. 8; Table 1). The resulting non-dimensional horizon-depth differences are small for younger horizons, generally only a few percent, and increase slightly for older horizons. For each horizon, the non-dimensional depth difference RMS is then converted to an absolute depth uncertainty by multiplying by the average observed depth of that horizon (Table 1). This value provides an estimate of the structural uncertainty associated with prescribing fixed modern geometry. Combined with the depth uncertainty induced by horizon age uncertainty, this structural uncertainty defines the model-fit tolerance used to identify the accepted perturbation range for each time interval.

5.2 Regional climate variability across interior East Antarctica

A central result of this study is that the EDC-derived accumulation history does not fully reproduce the observed englacial stratigraphy at the southern flank of Dome A. Although the unmodified EDC scaling curve provides an adequate first-order fit for some time intervals, the best-fitting solutions require time-dependent modifications to the EDC-derived history. In particular, the model configuration that is most consistent with the observed englacial stratigraphy requires moderately higher accumulation than the EDC-scaled history through 40.8 ka, substantially higher between 40.8 and 87.9 ka, and lower between 87.9 and 161.9 ka. These departures indicate that the temporal evolution of accumulation at Dome C cannot be transferred directly to this sector of the East Antarctic interior. Although the broad glacial–interglacial pattern may be similar, the magnitude and timing of accumulation changes differ enough to produce meaningful changes in modeled



horizon depths. Regionally constrained accumulation histories provide observational benchmarks for future ice-sheet
 modeling studies to quantify how spatially variable paleoclimate forcing affects reconstructed ice-sheet geometry, flow
 evolution, and the preservation of old ice.

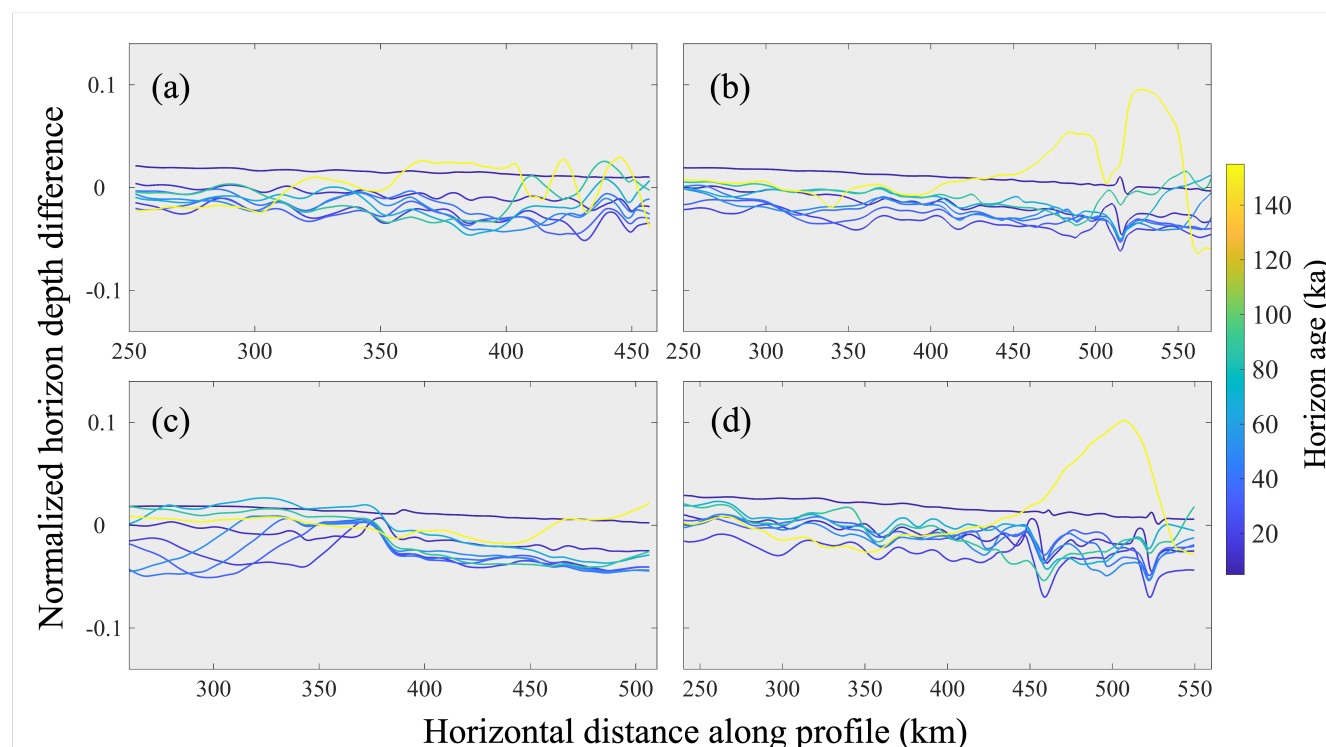


Figure 8. Effect of prescribing fixed modern ice-sheet geometry on modeled englacial horizon depths. Panels show normalized depth differences for all dated englacial horizons along each of the four selected profiles shown in Fig. 1 and Fig. 2. Depth differences are normalized by local ice thickness.

This result is consistent with existing evidence that Antarctic accumulation variability is regionally heterogeneous, even across the interior plateau. Thomas et al. (2017) found that snow-accumulation composites from the central Antarctic Plateau lack regional coherency over the past millennium. They interpreted this weak regional agreement as an indicator either that sparse ice-core records do not adequately represent broader accumulation variability or that regional climate model products
 do not fully capture the precipitation and post-depositional processes operating in the cold, dry interior. Although their study addresses centennial-to-millennial variability rather than glacial-cycle evolution, it provides a relevant modern analogue: accumulation histories from individual interior ice-core sites should not be assumed to represent broad sectors of East Antarctica without independent regional constraints.

Several physical mechanisms may contribute to such regional differences. Sector-specific moisture transport may be important. Dome C is influenced primarily by moisture from the Indian Ocean sector (Cavitt et al., 2018; Genthon et al., 2016; Scarchilli et al., 2011), whereas the southern flank of Dome A is farther inland, at higher elevation, and located in a



different geographic sector of East Antarctica. The Dome A region may therefore integrate a different mixture of moisture pathways. In addition, atmospheric rivers and other extreme moisture-transport events can produce highly localized accumulation anomalies in Antarctica (Baiman et al., 2023; MacLennan et al., 2023). Although these processes are best documented over modern observational timescales, they demonstrate that Antarctic precipitation is not spatially uniform and that accumulation variability can be sector-dependent.

Surface and ice-sheet geometry may further modulate these climatic differences. The southern flank of Dome A lies along a broad flow path from the Gamburtsev Mountains toward the South Pole, where surface slope, elevation, and bed-controlled ice-flow geometry differ substantially from those near Dome C. These differences can influence snowfall deposition through orographic effects, wind redistribution, and the interaction between surface topography and near-surface atmospheric flow. As a result, the accumulation history inferred from the southern flank of Dome A likely reflects both regional atmospheric forcing and the spatial redistribution of snowfall across the ice-sheet surface.

5.3 Englacial stratigraphy as a constraint on past ice-sheet and climate history

The limited regional representativeness of individual ice-core records motivates the use of spatially extensive constraints on past accumulation. Dated englacial radiostratigraphy provides such a constraint by propagating age information away from core sites and allowing core-derived accumulation histories to be tested across broader regions. Combined with ice-flow modeling, englacial radiostratigraphy can help refine regional age–depth structure and constrain time-varying accumulation, basal melting, and ice-flow history (e.g., Bodart et al., 2026; Holschuh et al., 2017; Leysinger Vieli et al., 2011; Ross and Siegert, 2020; Sutter et al., 2021; Waddington et al., 2007; Yan et al., 2025). These applications are central to the broader AntArchitecture objective of integrating Antarctic radiostratigraphy into models of past and future ice-sheet behavior (Bingham et al., 2025).

Recent model–data comparison studies have emphasized the value of englacial stratigraphy for testing paleo-ice-sheet simulations. Sutter et al. (2021) showed that ice-sheet models that reproduce present-day ice thickness and surface velocity can still misrepresent the internal architecture of the ice sheet, indicating that present-day surface and bed constraints alone are insufficient to evaluate evolution and that the internal layers provide valuable constraints. Bodart et al. (2026) extended this approach to off-divide regions of East Antarctica by comparing modeled and observed horizons, including a widespread approximately 91 ka horizon, and showed that paleo-climate forcing and model parameterization can produce substantially different modeled horizon geometries. Their results highlight both the potential and the difficulty of using horizons as constraints: horizons provide powerful tests of transient ice-sheet evolution, but the modeled horizons can be sensitive to uncertain forcing and model structure.

Our study builds on this framework, but with a complementary modeling strategy and scientific objective. Rather than evaluating continental-scale ice-sheet simulations against a few widespread horizons, we use a high-resolution regional flowband model constrained by along-flow radar profiles and multiple dated horizons spanning 4.9 to 161.9 ka. This



configuration allows us to test whether a prescribed reference accumulation history, derived from EDC, can reproduce the
 415 observed age–depth structure along the southern flank of Dome A. The use of multiple horizons is important because each
 horizon samples a different interval of the accumulation and ice-flow history. The combined stratigraphic sequence therefore
 provides stronger constraints than any single horizon alone.

The southern flank of Dome A is particularly well suited for this approach because the COLDEX survey geometry includes
 radar lines oriented close to the modern ice-flow direction. At the same time, this is a flank-flow setting rather than a divide
 420 setting. Ice parcels now located at mid-depth within the survey region may have originated hundreds of kilometers upstream
 over glacial-cycle timescales (Fig. 9). As a result, the observed stratigraphy integrates both temporal changes in
 accumulation and spatial variations along particle paths. This makes the englacial stratigraphy sensitive to regional SMB
 history, but it also means that its interpretation cannot be reduced to a purely local age–depth problem. This spatial
 integration is both an advantage and a source of non-uniqueness. In off-divide settings, temporal changes in SMB can trade
 425 off against spatial variations in accumulation, horizontal advection, vertical thinning, surface-elevation history, basal
 conditions, and uncertainties in horizon ages. For example, a given parcel depth could be produced by higher accumulation
 combined with stronger thinning, or by lower accumulation combined with weaker thinning. Similarly, an apparent temporal
 departure from the EDC-derived accumulation history could partly reflect differences in the upstream spatial accumulation
 pattern. These tradeoffs are common to all attempts to infer climate or ice-sheet history from englacial stratigraphy,
 430 especially for older and deeper horizons. For this reason, we do not interpret our perturbation experiments as a unique
 inversion for accumulation history. Instead, we use forward modeling to test a specific hypothesis: whether the normalized
 temporal accumulation scaling derived from EDC can explain the observed stratigraphy along the southern flank of Dome A
 when applied to a regionally constrained modern accumulation field.

These results also highlight the need to narrow the gap between increasingly detailed radiostratigraphic observations and the
 435 models used to interpret them. Radar surveys can map englacial stratigraphy with high spatial precision, but model
 interpretations remain limited by uncertainties in forcing and boundary conditions that can include accumulation forcing,
 englacial temperature, basal boundary conditions, surface-elevation history, and the spatial pattern of past SMB. High-
 resolution flowband models provide a useful intermediate framework: they retain the along-flow advection and local bed
 constraints needed to interpret flank stratigraphy while remaining computationally efficient enough for sensitivity testing
 440 over glacial-cycle timescales. Future progress will require combining dense, dated radiostratigraphy with high-resolution bed
 and surface datasets, improved regional climate reconstructions, and model frameworks capable of better separating
 temporal SMB changes from spatial accumulation gradients and ice-dynamic effects.

5.4 Limitations and future work

While this work has aided our understanding of SMB history on the flank of Dome A, this study has several limitations.
 445 First, age control remains sparse, particularly across the interval from 87.9 to 161.9 ka. For this work, this interval of more



than 70 kyr is treated as a single block of time with consistent scaling, which likely oversimplifies the true temporal structure of accumulation change; without additional dated horizons, there are no data available to better constrain this history using this approach. For example, the accumulation history before the Last Interglacial may have differed from that during or after the Last Interglacial, but the currently available dated horizons do not allow these possibilities to be resolved independently.

450 Additional dated horizons, either from future radar tracing, improved ice-core ties, or other chronologic constraints, would substantially improve the temporal resolution of the inferred accumulation history.

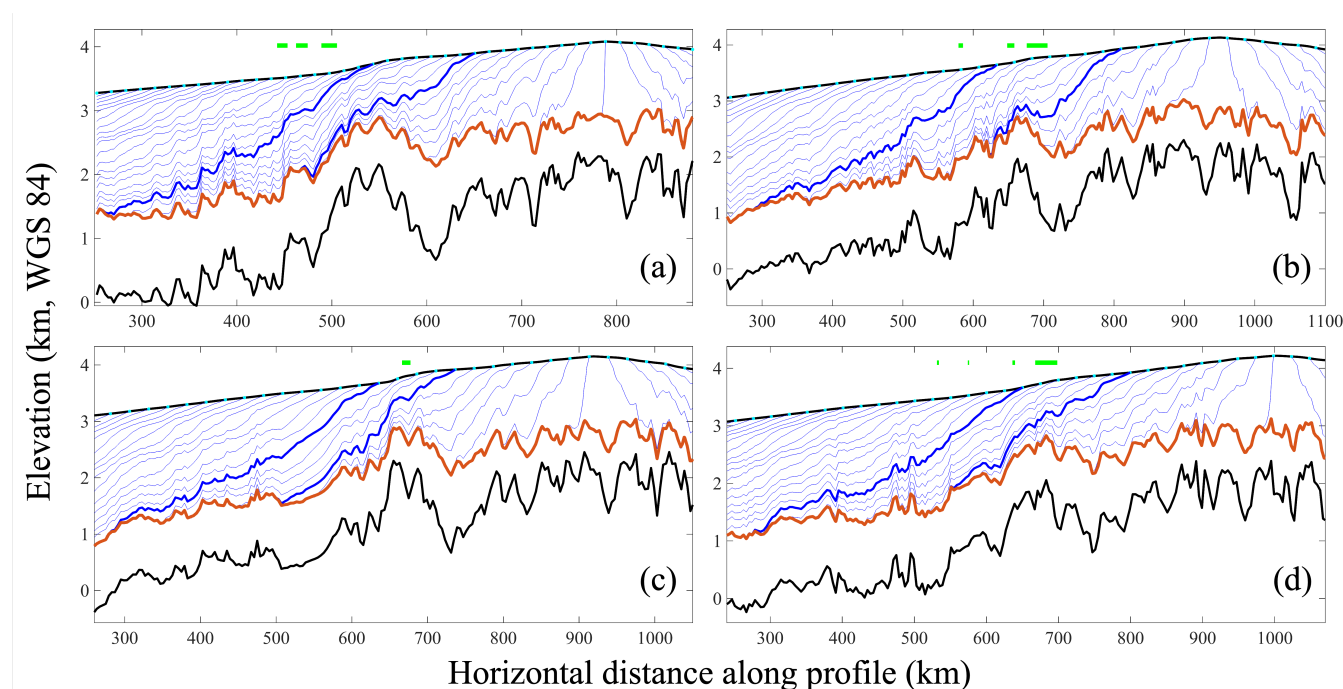


Figure 9. Modeled particle paths to the deepest dated horizon (L9 at 161.9 ka, shown in red). Thin blue lines show particle paths, and thick blue lines indicate paths to the edges of the profile segment used in the flowband modeling. The horizontal green bars mark the location of the surface-scour zone. The ice surface and bed are shown in black.

Second, our analysis assumes that the spatial pattern of surface accumulation has remained stable through time, such that only the magnitude of accumulation changes. This assumption is partly supported by prior work suggesting relative stability in the spatial accumulation pattern over portions of the survey region (Fudge et al., 2026). Nevertheless, changes in atmospheric circulation, moisture pathways, surface topography, or ice-sheet geometry could alter the spatial structure of accumulation through time. Such changes are not available as reliable reconstructions that can be prescribed in our modeling so are not captured in the present experiments. Spatially extensive, dated englacial stratigraphy can be used to test hypotheses about spatial and temporal variations in accumulation, and this work is a first step towards constraining temporal variations.



Finally, the modeling framework is based on a 2.5-D shallow-ice-approximation model with fixed flowband geometry. This approach is reasonable for evaluating first-order accumulation histories in slow-flowing interior ice, but it is less suitable for resolving local-scale processes or regions with complex flow. In particular, regions characterized by rugged subglacial topography, spatially variable basal units, and localized subglacial hydrologic activity. This includes the downstream portion of the NSF COLDEX airborne survey region that was excluded from our flowband-modeling experiments because the flow regime may depart substantially from SIA assumptions and therefore require higher-order or three-dimensional modeling approaches.

6. Conclusions

We use recently acquired NSF COLDEX englacial radiostratigraphy and numerical ice-flow modeling to reconstruct surface mass balance history across the southern flank of Dome A, East Antarctica. The youngest dated horizon, at 4.9 ka, provides the first observation-informed estimate of the contemporary accumulation averaged over the past 4.9 kyr across this region. The resulting accumulation field shows a strong regional gradient, with low accumulation near Dome A and progressively higher accumulation toward the South Pole.

We then combine englacial radiostratigraphy and a 2.5-D flowband model to test whether the normalized accumulation history inferred from the EDC ice core can reproduce the age–depth structure observed along the southern flank of Dome A. The unmodified EDC scaling produces substantial mismatch with the radar-observed stratigraphy, indicating that the EDC-derived accumulation history is not directly representative of accumulation across this sector of East Antarctica. To match the observed stratigraphy within the range of uncertainties, our model experiments require accumulation rates approximately 5%–33% higher than EDC-derived values between 10.9 and 40.8 ka, 30%–98% higher between 40.8 and 87.9 ka, and 18%–38% lower between 87.9 and 161.9 ka. These perturbations are broadly consistent across the four selected radar profiles, suggesting that the inferred deviations reflect a regional signal rather than a profile-specific artifact.

These results indicate that accumulation histories in the East Antarctic interior are spatially heterogeneous over glacial-cycle timescales. Although ice-core records provide essential high-resolution constraints on past climate and accumulation, individual core sites do not necessarily represent the temporal evolution of accumulation across distant sectors of the ice sheet. This has important implications for paleoclimate reconstruction, ice-sheet modeling, and old-ice exploration, because accumulation history directly affects thinning due to ice flow and the englacial age–depth structure; future work could evaluate this more specifically.

More broadly, this study demonstrates the value of dated radiostratigraphy for extending ice-core constraints beyond drilling sites. By combining ice-core chronologies, radar-derived englacial stratigraphy, and ice-flow modeling, regional accumulation histories can be evaluated against ice-sheet observations rather than assumed. Expanding dated radiostratigraphic coverage across East Antarctica will be essential for developing spatially resolved reconstructions of



495 Antarctic climate history and for improving boundary conditions used in long-timescale ice-flow and age–depth modeling, which is aligned with the community-defined priorities and progress of the AntArchitecture group (Bingham et al., 2025).

7. Data availability

The contemporary surface accumulation-rate dataset is available at <https://doi.org/10.5281/zenodo.21695835>. The dated horizon depths along the four selected flowband profiles are available at <https://doi.org/10.5281/zenodo.21695923>. The complete englacial stratigraphy dataset from the NSF COLDEX airborne radar survey will be released with a companion manuscript, currently under review, that focuses on mapping and describing the regional radiostratigraphy.

8. Author contribution

All authors contributed to the design of the field survey and the modeling exercise. Duncan Young and Shivangini Singh participated in field data acquisition. Englacial horizon tracing was led by Shivangini Singh and Shuai Yan. Age assignments and uncertainty estimate for L1–L8 are led by Shivangini Singh. Inversion of contemporary accumulation rate was led by T.J. Fudge. Flowband modeling was led by Shuai Yan and Michelle Koutnik. Shuai Yan led the preparation of the manuscript and figures, with contributions to manuscript writing and revision from all authors. All authors approved the final version of the paper.

9. Competing interests

510 At least one of the co-authors is a member of the editorial board of The Cryosphere.

10. Acknowledgements

This work was supported by the NSF Center for Oldest Ice Exploration, an NSF Science and Technology Center (NSF 2019719), as well as the G. Unger Vetlesen Foundation. We thank the NSF Office of Polar Programs, the NSF Office of Integrative Activities, University of Texas at Austin, University of Washington, and Oregon State University for financial, logistical, and administrative support, and the NSF Antarctic Infrastructure and Logistics Program, Kenn Borek Air, EarthScope and the Antarctic Support Contractor for logistical support. We thank the members of the NSF COLDEX airborne field team for their assistance with data acquisition. We thank S. Kempf, D. Buhl, and G. Ng for their assistance with data processing. We acknowledge the support of this work by Landmark Software and Services, a Halliburton Company. Maps in this manuscript were prepared using the QGIS platform, the Generic Mapping Tools (GMT, Wessel et al., 2019), and the Norwegian Polar Institute’s Quantarctica package. During manuscript preparation, the authors used ChatGPT (OpenAI) for limited language polishing; all content was subsequently reviewed and revised by the authors, who



take full responsibility for the final manuscript. This study is a contribution to the AntArchitecture Action Group of the Scientific Committee for Antarctic Research (SCAR).

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