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Ice core nitrogen isotopes archive dramatic changes in West Antarctic Ice Sheet thinning

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Summary

We show how measurements of nitrogen isotopes in Antarctic ice core records can be used to show dramatic thinning of an ice sheet during ice mass changes in the Holocene. Combining such measurements with proxies for ice sheet elevation could be a powerful tool for constraining the history of ice dynamics at sites which are sensitive to rapid changes, and could contribute to constraining ice sheet models.

Abstract

The behaviour of ice sheets during ice mass loss is currently not well constrained and is a major limiting factor in accurate predictions of ice sheet behaviour in our warming climate. Proxies from ice cores can record the history of ice mass loss at exceptional temporal resolution and unrivalled chronological accuracy. A recent record of Total Air Content (TAC) and ice core chemistry from Skytrain Ice Rise resolved a 450 m drop in ice sheet elevation at the site in the Weddell Sea Sector of the Antarctic Ice Sheet 8,000 years ago, an event which occurred over just 200 years. The event is thought to represent an ungrounding and removal of the buttressing effect on the ice sheet in the region. However, proxy records for ice elevation, TAC, can show unexpected signals which indicates an imperfect understanding of how such gas records are captured in ice cores during rapid changes in ice sheet conditions, inhibiting expansion of such studies to other sites. Here we use ice core nitrogen isotope measurements to elucidate the dynamic evolution of the firn column, where such gas records are gradually trapped, during the 8 ka rapid ice mass loss. The horizontal divergence imparted on the ice rise during the event dramatically thinned the firn column to the extent that dynamic thinning of the firn is the dominating factor in how nitrogen isotopes are captured. As a result, the recorded signal of nitrogen isotopes directly opposes the signal predicted by current firn models which do not include such ice dynamics, suggesting that it is a critical factor to include in firn modelling studies of sites susceptible to rapid ice mass changes. Our findings allow us to tightly constrain where reliable elevation signals, not disrupted by changing ice dynamics, are available in ice core records. Moreover, our study demonstrates that the combination of TAC and nitrogen isotopes can be a powerful tool in constraining ice sheet dynamics at a site, thus helping to inform the physics of ice sheet models.

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1 Introduction

Uncertainty in ice sheet processes is identified as one of the major limiting factors in accurately predicting future sea level rise under current emissions pathways (Pörtner et al., 2022). Under all current scenarios, the West Antarctic Ice Sheet (WAIS) is shown to be one of the most decisive climate tipping elements due to its high sensitivity to temperature increases and subsequent effects on sea level (Rosser et al., 2024). It is thus critical that we improve our understanding of both the timing of, and mechanisms behind, ice mass loss in this region. An effective way to do this is to obtain high resolution records of past ice sheet behaviour, which can be used to inform the models that predict future ice mass changes.

Ice cores provide exceptional records of past ice sheet behaviour, capturing direct samples of the ice properties and the atmosphere at the time the ice formed. A recent study from an ice core drilled at Skytrain Ice Rise (SIR) (Grieman et al., 2024) (Fig. 1) combined multiple ice-core climate proxies to elucidate ice sheet changes in the Weddell Sea region throughout the Holocene deglaciation. The study observed a rapid decline in ice mass at the ice core site approximately 8,000 years ago (8 ka), with a 450 m reduction in ice sheet elevation over just 200 years, imposed on a background of more gradual ice mass decline. The event was followed by substantial ice shelf retreat in front of the ice rise. The proposed mechanism behind such a rapid ice mass loss was that ungrounding of the ice sheet at the ice/ocean margin, with ocean water encroaching underneath the ice sheet. The sudden loss of the buttressing effect of the grounded ice that would otherwise have constrained outward flow of the ice sheet drove a rapid thinning upstream of the grounding line and Skytrain Ice Rise experienced a drop in elevation. This is the first time such a rapid, centennial scale ice-loss event has been so well resolved in a direct climate record, and it raises important questions as to the potential for such future events to occur in other regions where ice currently grounded on retrograde slopes – most notably the Amundsen Sea region and Thwaites Glacier. We would thus look to repeat such studies in other ice core records throughout the region and indeed more widely through the ice sheet to help improve the spatial and temporal resolution of our picture of such rapid ice mass loss. However, a key record used to reconstruct the past elevation of the ice sheet in the study, the Total Air Content (TAC) of ice core samples, showed a complex oscillating signal throughout the period of rapid ice mass loss (Fig. 1) which cannot be directly attributed to elevation change (Grieman et al., 2024) but is a real signal recorded in the ice well above the threshold of our high-accuracy TAC method (Nehrbas-Ahles et al., 2022). An improved understanding of the parameters affecting the TAC signal, and more widely the capture of gases in ice core samples during rapid ice sheet changes, is required before the study can be expanded.

One underexplored process is the effect of ice sheet thinning on gas record preservation. In the case of TAC, physical properties of the firn column (the upper snow layers where compaction from snow to ice is in process and has not fully isolated the air bubbles from the overlying surface air) such as temperature and pore volume (the space available between snow grains in the firn column) affect the total amount of gas captured (Martinerie et al., 1992). Changes in the firnification processes thus have the potential to greatly impact TAC and other gas record capture. Thinning, or horizontal divergence, is often ignored in firn

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studies and infrequently discussed as a possible driver of variability in gas-phase proxies, with the notable exception of thinning changing the firn temperature gradient at South Pole (Morgan et al., 2022). This stems from the fact that most ice cores are drilled into some of the thickest areas of the ice sheet (> 3,000 meters depth) and thus thinning in the firn (the uppermost 50 to 100 meters) is relatively minor. In contrast, SIR is only 650 meters thick with a firn column of at least 50 meters. Additionally, as SIR is frozen to the bed, the ice flow in the lowermost hundred meters or so is very slow and thus most of the thinning occurs in a relatively short column of the uppermost ice. Furthermore, we typically drill ice cores on thick, stable domes or divides that do not record any major flow disturbances or changes in ice thickness. Even a record like WAIS Divide, an ice core drilled in central West Antarctica, has probably only experienced modest changes in elevation during the last deglaciation, on the order of few hundred meters, which is relativity minor compared to total ice thickness (~10% of a total of ~3,450 meters). In contrast, SIR is currently 650 meters thick but may have been up to 1,300 meters thick prior to the rapid ice loss at 8 ka. The ice thinned by up to 650 meters (most likely value being 450 meters) (Grieman et al., 2024), meaning that potentially the whole column thinned by up to 50% within just a few hundred years.

Secondarily, accumulation-induced thinning driven simply by the vertical motion of ice is relatively minor at most sites. For example, a typical core in East Antarctica might have an accumulation rate of 0.05 m a^{-1} over a thickness of 3,000 meters, which gives a whole column horizontal divergence of ~$2e^{-5}$ a^{-1}, where horizontal divergence is approximately equal to accumulation divided by ice thickness (see Equation 3). Meanwhile, SIR, with modest accumulation at 0.14 m a^{-1} and ice thickness of only 650 meters, experiences nearly an order of magnitude faster rates of thinning (~$2e^{-4}$ a^{-1}).

In this study we use nitrogen isotopes to determine the changing properties of the firn column during rapid loss of ice sheet elevation at SIR. The ratio between nitrogen isotopes ^{15}N and ^{14}N, expressed herein as $\delta^{15}N$, is constant in the atmosphere over the timescales we consider here, and so any change in the ratio is due to fractionation processes in the firn column (Severinghaus et al., 2003). These may be preferential gravitational settling of the heavy isotope, telling us the thickness of the firn column, or preference of the heavier isotope toward cold temperatures, which tells us about the temperature fluctuations within the firn column. We combine these measurements with firn modelling techniques to show how $\delta^{15}N$ can tell us about dramatic changes in ice sheet thickness. We also identify potential missing processes in our current understanding of the firnification process at the ice core site. We conclude by proposing the mechanisms behind the disrupted TAC gas archive in Skytrain ice core and add to the picture of the processes occurring in the ice sheet at SIR during rapid ice mass loss.

2 Methods

Skytrain Ice Core Sampling

The 651 m Skytrain ice core was drilled at Skytrain Ice Rise during the field season 2018-2019 (Mulvaney et al., 2021). Samples for nitrogen isotope analysis were selected based on the previously developed ST22 age scale (Hoffmann et al., 2022;

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Mulvaney et al., 2023). To align with previously published TAC data, sample ages are presented on the ST22-WD2014 version of the gas age scale, where age alignment has been optimised to the WD2014 age scale. Sampling in this study covers the period of disrupted TAC signal around the 8 ka elevation change as well as a period of relative TAC stability on either side. A total of 60 samples were taken between 352.0 – 403.35 m, representing an age range of 5.84 – 8.54 ka, and giving an average age resolution of 46 yrs. Samples of 5 cm length were taken from a pre-cut ice strip of 3.2 x 3.2 cm, from which the previously measured TAC samples had also been taken. Samples for nitrogen isotopes were taken proximally (or as close to, dependent on features such as cracks) to where TAC samples had been taken to allow for close replication. Samples were prepared in the -25°C cold laboratories at the British Antarctic Survey, Cambridge, UK, and transported to the analytical laboratory in Paris, France, in insulated boxes and using specialist cold chain shipping which retains sample temperature at -25°C.

Nitrogen Isotope Analysis

Nitrogen isotopes, alongside argon isotopes and the ratio of O_2/N_2, were measured at LSCE, Paris. After removing 2-3 mm of the exterior part of the ice samples, air was extracted from the ice samples using a semi-automatic melt - refreeze line. Three duplicate samples can be processed each day together with two samples of outside air used for daily calibration. In short, the samples are placed into glass vessels which are evacuated before the ice is melted, enabling air to escape from the bubbles. The melt water is then refrozen, and the extracted air is cryogenically trapped in tubes filled with silica gel and immersed in liquid nitrogen. After 3 hours at 30°C, allowing air desorption from the silica gel, the air is introduced into the bellows of an isotopic ratio mass spectrometer (Thermo® Delta Q). The isotopic and elemental measurements are performed by dual inlet, i.e. by successive introduction of a small amount of the sample and the measurements standard (dry air without CO_2). Two sequences of 16 dual inlet measurements are performed, usually leading to a 1-sigma uncertainty of 0.007 ‰ and 0.6 ‰ respectively for $\delta^{15}N$ and $\delta O_2/N_2$. For the Skytrain samples, the values for the 1-sigma uncertainty were larger (0.14 ‰ for $\delta^{15}N$ and 1.8 ‰ for O_2/N_2) suggesting variability at short spatial scale in this record. Although less precise than with other techniques using purification of the gas (Servettaz et al., 2022), $\delta^{40}Ar$ can also be measured with this configuration of the Delta Q mass spectrometer. There was a 1-sigma uncertainty of 0.06 ‰ for $\delta^{40}Ar$ on this series of measurements.

Final values of $\delta^{15}N$ and $\delta^{40}Ar$ preserved in the ice core are products of both thermal and gravitation fractionation within the firn column. Following Severinghaus et al. (2003) the difference in mass dependent gravitation fractionation between the two, which is four times greater for $\delta^{40}Ar$, can be used to isolate the thermal component of the signal, N excess.

Equation 1

$$N_{excess} = \delta^{15}N - (\delta^{40}Ar/4)$$

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A negative N excess value implies that the top of the firn column was colder than the base, and a positive N excess implies the top of the firn column was warmer than the base. Using the thermal sensitivities of N (ΩN, 0.0145 ‰°C $^{-1}$) and Ar (ΩAr, 0.036 ‰°C $^{-1}$) we can deduce the temperature difference in the firn, ΔT.

Equation 2

$$\Delta T = \frac{N_{excess}}{\Omega_N - (\Omega_{Ar}/4)}$$

Sample Gas Fractionation

Loss of gases from ice core samples can cause distortion of the captured gas records. Gas fractionation processes can occur during bubble formation or due to post-coring factors (Bender et al., 1995). Smaller gas molecules can more easily diffuse out of the ice compared to larger molecules, thus gas fractionation can be indicated using the ratio of O_2, the smaller molecule, to N_2, the larger molecule in the ice core samples. The record of O_2/N_2 for Skytrain shows no change above the background variability of the data in the period measured (Supplement Figure 2).

Community Firn Model

We employed the Community Firn Model (CFM) (Stevens et al., 2020) as a heuristic guide to understand the processes driving the $\delta^{15}N$ variability we observe, as well as a quantitative method to explore possible histories of temperature, accumulation and ice sheet thinning that reconcile our $\delta^{15}N$ data. The CFM is an open-source firn model designed to simulate the evolution of physical firn properties such as temperature, density, porosity, and associated firn air parameters including profiles of $\delta^{15}N$ and $\delta^{40}Ar$ (thus N excess is modelled). Here we present results that were run exclusively in the standard physics setup which enables a transient evolution of the Herron and Langway (1980) empirical model ("HLdynamic") with ice conductivity based on Calonne et al. (2019)

Additionally, we use the recently developed horizontal divergence scheme in the CFM (Horlings et al., 2021) whereby a parcel (in a Lagrangian framework) is first compressed due to densification and then further thinned due to a prescribed horizontal divergence rate. In our case, we impose a total horizontal divergence rate (a^{-1}). To calculate the total horizontal divergence, we sum the divergence imparted from accumulation a (m a^{-1}) and rate of change in ice sheet thickness $\dot{H}$ (m a^{-1}):

Equation 3

$$\dot{\epsilon}_h = \frac{a}{H} + \frac{\dot{H}}{H}$$

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By dividing the vertical velocity induced by both accumulation and change in ice sheet thickness by the ice sheet thickness itself (H) we are assuming that ice is incompressible, and more importantly that the vertical strain is uniform in the ice column. The uniform strain is an oversimplification, but a conservative one. If the ice sheet is frozen to the bed, as is the case with SIR, the vertical velocity slows dramatically near the base of the ice sheet. Typically, this is at least one hundred meters off the bed and thus the effective value of H one might consider to calculate horizontal divergence is some fraction of the true thickness. A more accurate method using a Lliboutry vertical profile (Lliboutry, 1979) is employed in our 1-D borehole model, but to first order our approximation is sufficient for our heuristic purposes.

Another crucial assumption of our model is that the material properties of the firn do not change with the imposed thinning. For example, there is no further change in density nor any feedback into the densification rate itself such as strain-induced softening (Oraschewski and Grinsted, 2022) – a set of assumptions that may require further study. The net effect of enhanced horizontal divergence is a shoaling of the close-off depth, as has been shown to be important in fast-flowing ice regimes, not unlike SIR during a rapid thinning event.

To drive the CFM in all the heuristic experiments (Fig. 2), we use the stable water isotopes records to first derive a plausible surface temperature history of the site using an isotope-to-temperature conversion of 0.8 per mil per deg C with a modern temperature (last 250 years) of -25°C. To roughly estimate an accumulation history we then use a temperature-dependent accumulation rate conversion of 0.005 m ice equivalent per deg C (about 3.3% per deg C) with a modern accumulation of 0.15 m ice equivalent. This choice of sensitivity places the accumulation rate increase at 8 ka between the prior and posterior histories from the Skytrain chronology (Supplementary Figure 5). Additionally, this sensitivity is within bounds but at the lower end of model- and data-based constraints on the Antarctic-wide accumulation-to-temperature relationship (Nicola et al., 2023)

As a first pass constraining a possible thinning history, we extracted the ice thickness history at SIR from a single experiment with the Parallel Ice Sheet Model (PISM) model and calculated the thinning-induced divergence rate. The particular transient experiment comes from the deglacial scenario presented in Kingslake et al. (2018) which indicated a widespread retreat of the grounding line starting around 12,500 years before present that extended further inland than the present-day grounding line before readvancing in the early Holocene. The absolute timing, rate of change and magnitude of this response in the model have been shown to be dependent on model boundary conditions and parameterization - in particular model resolution and bed topography (Albrecht et al., 2020b, a). For consistency with previous work (Grieman et al., 2024) we use this particular model and align the elevation drop with the initial rise in water isotopes at 8 ka by shifting the modelled time forward by 4,500 years. We stress that his model run is only a guide to the possible divergence rates and that the detailed history of WAIS retreat remains highly under constrained from models alone.

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Smoothing Splines

Smoothed splines of datasets are generated using the methods presented in King et al. (2024). Briefly, the method applies a random sampling with replacement bootstrap over 10,000 iterations with the smoothing function generating a spline and uncertainty bands based on the smoothing parameter. The parameter is tuned to the time-resolution and length of the input data such that the spline produced is at half height of a generic cosine function, which is a good balance point between preserving signals in the record while not being overly influenced by record variability. Spline parameters used for each dataset can be found in Supplement Table 1.

3 Results and Discussion

Modelling drivers of $\delta^{15}N$ change

As a first step, we use the CFM to break down the possible drivers of $\delta^{15}N$ change at SIR into constituent parts in a series of factorial experiments. These experiments should not be considered perfect reconstructions of individual factors as the forcings (temperature, accumulation and thinning) are not known *a priori*, but rather illustrations to guide us. First, holding all other variables stable, we change surface temperature (Fig. 2, Scenario 1), increasing it by about 4°C which roughly reflects the lapse-rate impact of the reconstructed decrease in elevation at 8 ka. The result is an initial increase in $\delta^{15}N$ as a strong temperature gradient is briefly established in the firn and the thermal fractionation dominates, followed by a shift toward slightly lower values as the firn densification adjusts to the warmer temperature and the close-off depth shoals. In the second experiment, Scenario 2, we change only accumulation, increasing it as would be expected from an ice core site experiencing warmer, more moist, more coastal conditions. Here the close-off depth increases along-side the $\delta^{15}N$. In the third experiment, Scenario 3, we combine both temperature and accumulation and see how competing effects of temperature and accumulation on close-off depth largely cancel each out and the thermal effect (the peak in $\delta^{15}N$) dominates the signal. At the same time, the bubble close-off depth becomes slightly shallower, from ~58 m to ~52 m. The result is a predicted peak at ~8.0 ka, with increases in both $\delta^{15}N$ and N excess (Supplement Fig. 2) of ~0.04 ‰ and ~0.02 ‰ respectively, which decay away by ~7.8 ka.

This suggests that all else being equal, we would expect to see a peak in $\delta^{15}N$ across the 8 ka event. However, as we will see, this is not the case.

To explore a new scenario, in the fourth experiment (Scenario 4) we model just changes in horizontal divergence as modelled in the PISM simulation (see methods) combined with a small, constant divergence induced by the relatively high accumulation in a short ice column. The increased divergence causes the close-off depth to shoal and the $\delta^{15}N$ decreases strongly as the

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gravitational effect dominates the signal. We thus have a competing effect from thinning that could potentially drive the $\delta^{15}N$ signal.

Comparing $\delta^{15}N$ model predictions and measured data

We now compare our predictions to the measured data (Fig. 3). Comparing $\delta^{15}N$, where each of our temperature and accumulation scenarios predict a peak in values, we observe a similar small initial peak, from a spline-based value of 0.20 ± 0.01 ‰ at 8.4 ka to 0.22 ± 0.006 ‰ at 8.1 ka. However, this is followed by a large decrease in $\delta^{15}N$ to a minimum of 0.13 ± 0.008 at ~7.4 ka. The minimum is reached approximately 500 years after the initiation of ice mass changes at SIR, with a slow recovery in values lasting until ~ 6.6 ka with values of 0.22 ± 0.007 ‰, and with an apparent slow reduction and 're-stabilisation' of values to 0.19 ± 0.007 ‰ by ~ 6 ka. This indicates that after an initial as-predicted reaction to increasing temperature and accumulation at the site as elevation lowered, the horizontal divergence factor takes over with a striking dominating effect on the firn signal of $\delta^{15}N$. The dynamic ice changes at SIR appear to last up to a duration of 1,500 years following the start of the initial rapid 200-year event of ice elevation loss as observed in Grieman et al. (2024).

Predicted values of N excess are also contradicted by the measured data. Again, a small increase in N excess is predicted in all scenarios at the initiation of ice mass change 8 ka, returning to stable values shortly thereafter. Despite a large scattering, our results suggest that values first increased to a spline-based value of -0.02 ± 0.004 ‰ at ~ 8 ka from -0.03 ± 0.004 ‰ at ~ 8.4 ka, and then reduced to as low as -0.04 ± 0.004 ‰ at ~ 7.5 ka. Measured N excess data shows that values remain negative throughout, with a reduction towards more negative values occurring throughout the same period as the reduced $\delta^{15}N$.

Comparing both $\delta^{15}N$ and N excess to the TAC signal (Fig. 3), the disruption to the signals, with lowering of values and recovery, spans the full duration of the oscillating TAC signal, with a minimum duration of ~1,500 years.

Optimising model-data agreement

So far we have considered the importance of individual factors in explaining our nitrogen isotope records. We now attempt to 'tune' the model output to the best fit for our measured $\delta^{15}N$ and explore some plausible scenarios that may best explain our measured record (Fig. 4). The most realistic starting point from our factorial experiments is a combination of Scenarios 3 and 4, including the changes in temperature, accumulation rate and horizontal divergence. While this combination comes close to explaining our $\delta^{5}N$ record, it predicts absolute values of $\delta^{15}N$ which are slightly higher than the measured data both preceding and during the drop in $\delta^{15}N$, and a drop and recovery in $\delta^{15}N$ values which is slightly shorter in duration than suggested by the measured data (Fig. 4, 'Combined Scenario').

One possibility to align absolute values of the $\delta^{15}N$ is to consider a stronger, two-phase increase in accumulation following the water isotope increase. Grieman et al. (2024) argued that delays in the Na increase relative to the water isotope increase

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reflects that thinning preceded ice shelf breakup. The proposed breakup phase centres around 7.5 ka, which aligns with an increase in $\delta^{15}N$ not captured in our idealized scenario. Following ice shelf breakup Skytrain Ice Rise would be approximately 270 km closer to local sources of moisture, which could have increased accumulation. In the optimized scenario we include a second increase in accumulation after 7.5 ka which drives a stronger, sharper increase in $\delta^{15}N$ as the thinning returns to steady-state. This larger increase in accumulation before and after the jump with an effective accumulation-to-sensitivity of approximately 6% also improves the $\delta^{15}N$ match before and after the jump – which are nearly equal in the data.

Additionally, our idealized scenario assumes uniform strain throughout the ice column whereas, in reality, thinning rates will be higher in the upper sections. To better fit the shape of the drop in the measured $\delta^{15}N$, we require the firn column to be thinned for a longer duration than that suggested by the current model and with a marginally higher divergence rate. Although this is a subjective process, we increase the duration over which the horizontal divergence is acting on the firn in the model and increase the divergence rate to within a reasonable fit of the measured data to give a suggestion of the magnitude of change required. This is not intended to be quantitative but does suggest that the ice thinning at SIR in the PISM model may be underestimated in both duration and magnitude. Further quantification would require extracting the thinning rates from a 3D thermo-mechanical ice sheet model, but in principle this demonstrates that ice core nitrogen isotopes can inform the physics of the ice sheet models.

N excess as a temperature signal at Skytrain

Is our N excess record a signal of firn column temperature? If we take the N excess as a true indication of firn column temperature, then our data rather surprisingly suggests that the top of the firn column cooled relative to the base of the firn column, ΔT, by up to -4 °C (Supplement Fig. 1). Given the observed rise in site temperature and accumulation rate following surface lowering of the ice sheet, this is unexpected. The pre-existing gradient of warming down the borehole at SIR (shown on Supplementary Fig. 2) comes from the geothermal gradient of the ice at the site (Mulvaney et al., 2021). An increasingly negative N excess signal would require a relative cooling of the surface air at the site or a relative warming of the base of the firn column. In the case of the former, we already know that the surface elevation lowered and surface temperatures subsequently increased. A possible mechanism for warming the base of the firn column exists where thinning of the ice sheet occurs at a site where a geothermal gradient warms the base of the ice sheet upwards, or where the geothermal heat flux itself increases. The latter we rule out over the timescales and magnitude of temperature change required here. Considering the former, at the Skytrain ice core site, the measured borehole temperature profile shows an increase in temperature down through the depth of the ice sheet due to the geothermal gradient, from a modern surface temperature of – 26°C to a basal temperature of - 15°C, a -11°C change over the 654 m ice thickness. Though a potential mechanism to warm the base of the firn column, this would be combined with warming surface temperatures, reducing the temperature gradient in the firn column. While the required temperature gradients for our N excess data seem unlikely in these scenarios, we briefly test these assumptions

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employing a 1D borehole thermal model (see Supplement). Given the known physical properties at the site, the model confirms that an inversion of temperature gradient to more negative values at the top of the firn column did not occur (Supplement Fig. 2).

We did not use the most optimised methodology for measurement of $\delta^{40}Ar$ on these samples as the main target was $\delta^{15}N$. This introduces a limit on how far we can interpret the $\delta^{40}Ar$ and as such the N excess signals, alongside the higher 1-sigma uncertainty of the samples suggesting short term variability in the Skytrain record.

Comparison to other ice core records

A similar example in terms of magnitude and duration of the nitrogen isotope records observed in Skytrain is presented in the literature, in the Siple Dome ice core (Severinghaus et al., 2003). Siple Dome sits at the interface between the Ross Ice Shelf and WAIS and is similar to Skytrain Ice Rise in location, between ice shelf and ice sheet, in background climatic conditions in the Holocene, and previous geomorphological evidence of large-scale and rapid loss of ice mass in the Ross Sea region during the Holocene (Pittard et al., 2022; Spector et al., 2017).

At approximately 15 ka, $\delta^{15}N$ (Fig. 6) drops rapidly to near zero at Siple Dome. The effect of any thinning in the firn column at Siple Dome must be even greater than at Skytrain, as the $\delta^{15}N$ record suggests that gravitational fractionation, and therefore diffusive column height, reduced to near zero. Alternatively, there is potential for a process which enhances the effect of the thinning firn column on the isotope records, for example cracking of the ice exposing gases deeper in the firn column to modern air.

Does ice sheet thinning explain the Skytrain TAC signal?

We now revisit how this new understanding of physical firn column changes can help with our interpretation of the TAC record observed in the Skytrain ice core. Our isotope records show that the TAC record is disrupted throughout the same time interval that the firn column is being affected by dynamic changes in firn column thickness. This extends beyond the actual period of change in elevation of the ice sheet at the ice core site. A reliable elevation record from TAC is thus only available where physical firn column processes are also stable. Based on this study, we define this period of disruption for the Skytrain ice core record as between ~ 8.2 ka, before the initial small upward inflection which corresponds to the beginning of the elevation change, and ~6.5 ka, where the $\delta^{15}N$ data values re-stabilise and align with model predictions not including horizontal divergence, suggesting stabilisation of firnification processes at the site. This supports the decision of Grieman et al (Grieman et al., 2024) to compare only the stable values from 9.5-8.5 ka (before the disruption) and those from 6.6 to 5.0 ka (after the disruption) to assess the net change in elevation.

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The specifics behind the oscillating signal of TAC during dynamic thinning of the firn column are not explained by our isotope data. With temperature change at the site well constrained, we must consider the other major influence on TAC, pore volume, to explain TAC variability. The nitrogen isotope record presents a consistent drop and then recovery of values over the period of ~ 1.5 kyr, without the oscillations of the TAC record, indicating that the impact on the TAC signal of the thinning of the firn column is not a simple, linear response to a single factor that could be driven by the dynamic thinning, for example an artificial decrease in pore volume driven by mechanical deformation of the snow grain structure.

Pore volume has been shown to be controlled by a complex interplay between the gas and physical ice properties of a firn column at each ice core site based on varying rates of temperature change, accumulation rate and densification profiles. However the fine scale controls on TAC are currently under-studied. Epifanio et al. (2023) observed a strong correlation between accumulation rate and TAC at the low accumulation South Pole ice core site. They propose that snow grain metamorphism is behind this link, with low accumulation rate allowing grains to grow proportionally larger as they remain on or close-to the snow surface for longer, as well as growing towards more spherical shapes that promote higher gas diffusivity and lower TAC. This agrees with Gregory et al. (2014), who found that low accumulation sites in Antarctica close-off at lower open porosity with higher gas diffusivity, compared to higher accumulation sites with finer grain sizes. They suggest that layering in the firn column may also control TAC changes, with layers capturing relic microstructures controlled by accumulation at the time that layer was at the snow surface, which could be a mechanism to control TAC variations over short timescales. Contrastingly, in a central Greenland core, Eicher et al. (2016) found that higher accumulation may lower TAC. With TAC being controlled at the point of bubble close-off, higher accumulation would increase the load on the snow surface and increase densification rates, inhibiting formation of spherical grains and reducing pore volume. This effect could alter the TAC signal for several hundreds of years following the accumulation increase. None of these sites match the physical ice properties and meteorological conditions of the Skytrain ice core. However, these examples do show how strongly TAC may be affected by differing controls on pore volume within a firn column, with such changes being plausible over a rapid ice mass reduction with dynamic firn column changes.

The oscillating TAC at Skytrain is likely to be a complex interplay of some or all of the above processes as the ice elevation loss and dynamic thinning cause disequilibrium of the firnification process. Future work is planned for grain-scale analysis of Skytrain ice core samples throughout the Holocene TAC record which may help to elucidate the microstructure changes occurring during the oscillation. We suggest that paired measurements of high-accuracy TAC and inert gas isotopes could be a powerful tool for constraining the history of ice dynamics at ice core sites – particularly at those sites that are sensitive to rapid changes in ice sheet configurations. Neither proxy stands on their own as a perfect archive of ice sheet thickness, with one proxy being obscured or over printed by other processes that are, at least partially, constrained by the other.

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4. Conclusions

Nitrogen isotope measurements in Skytrain ice core identify a period of dramatic firn column thinning during a rapid ice elevation loss at about 8 ka, a process which apparently disrupts the capture of the TAC signal due to the disequilibrium of the firnification process. As ice mass decreased in the Weddell sector of the WAIS through the Holocene deglaciation, ungrounding of the ice at the ice margin and removal of the buttressing effect resulted in horizontal divergence in the ice at Skytrain Ice Rise, thinning the firn column. Such thinning significantly reduces the gravitational fractionation of nitrogen isotopes in the firn column, dominating the physical factors that influence the isotope signal (temperature, accumulation rate) and resulting in a drop in $\delta^{15}N$ values (Fig. 6). As far as we are aware from existing literature, this is the first time such a mechanism has been proposed using nitrogen isotope analysis in ice cores. A similar feature is present in the existing Siple Dome ice core nitrogen isotope record at 15 ka, hinting at the possibility that the same mechanism is at play in other coastal ice rises/domes at different times during the last deglaciation.

We previously had two proxies for ice sheet elevation, water isotopes and TAC, neither of which are perfect but have worked together in a "belts and braces" approach. Now we have a third in the form of $\delta^{15}N$, which reflects the rate of thinning, and thus can use a "belts, braces and buttons" approach when identifying past periods of rapid ice sheet destabilisation. Where de-stabilisation of the firnification process exists, the large magnitude oscillating TAC record measured in Skytrain ice core is not a true elevation signal. However, the nitrogen isotope record can be used to precisely identify the disrupted portion of the TAC record, helping to resolve the true elevation signal. Nitrogen isotopes are thus important to measure in future studies where TAC is being applied, particularly in regions such as coastal ice-rises where more rapid changes in ice mass are possible. TAC is still a powerful tool for relative elevation change estimates over rapid ice mass changes where disrupted records can be precisely identified and avoided, and indeed the combination with nitrogen isotopes opens the potential to constrain dynamic ice changes, subsequently informing model physics. Future work is planned for ice grain microstructure analysis to further investigate causes of the oscillations in the TAC signal, which is likely driven by an interplay of controls affecting pore volume in the firn column during bubble close-off.

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Data Availability

Data published in this manuscript will be uploaded to the PANGEA data repository on acceptance of the manuscript.

Author Contributions

A.C.F.K: Project concept, sample preparation, data interpretation, wrote manuscript, revised manuscript. T.K.B: data interpretation, wrote manuscript, revised manuscript, funded sample analysis. A.L: Sample analysis, data interpretation, revised manuscript. C.M: Data interpretation, revised manuscript. E.W. Collected and supplied samples, revised manuscript.

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Competing Interests

At least one of the (co-)authors is a member of the editorial board of Climate of the Past.

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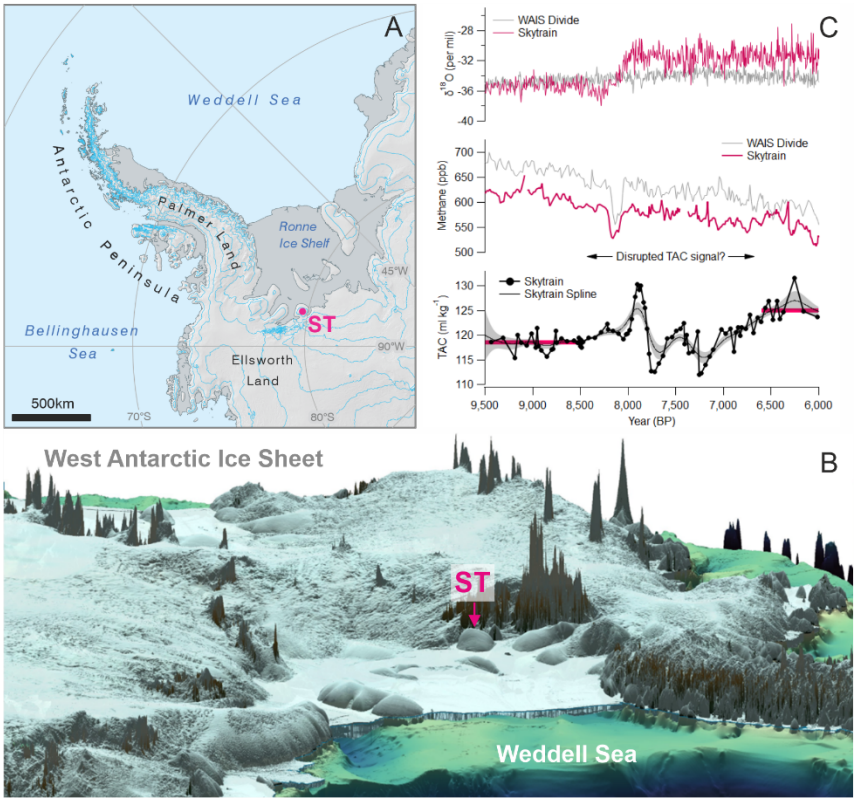

Figure 1: Location map of Skytrain Ice Rise (panel A, 'ST') and shown in a 3D topographic context (panel B, Greene et al., 2017; Morlighem et al., 2020) with ST sitting at the interface between the floating Ronne Ice Shelf and the outward flowing continental ice sheet of West Antarctica. Panel C highlights the elevation loss event, over ~ 200 years at ~8 ka, observed in the Skytrain ice core records, with a significant jump in water isotopes caused by ice elevation loss and subsequent temperature increase at the site (Grieman et al., 2024). Comparatively, records from the central WAIS, indicated by the WAIS Divide ice core record (Fudge et al., 2013), remain relatively stable. The TAC record from Skytrain, which is expected to indicate elevation at SIR during the ice mass change, shows a complex oscillating signal after 8 ka which is too great to be an elevation signal, and does not re-stabilise until significantly later, ~6.5 ka. Also shown are the CH_4 record from Skytrain and WAIS Divide (Rhodes et al., 2015; Buizert et al., 2015).

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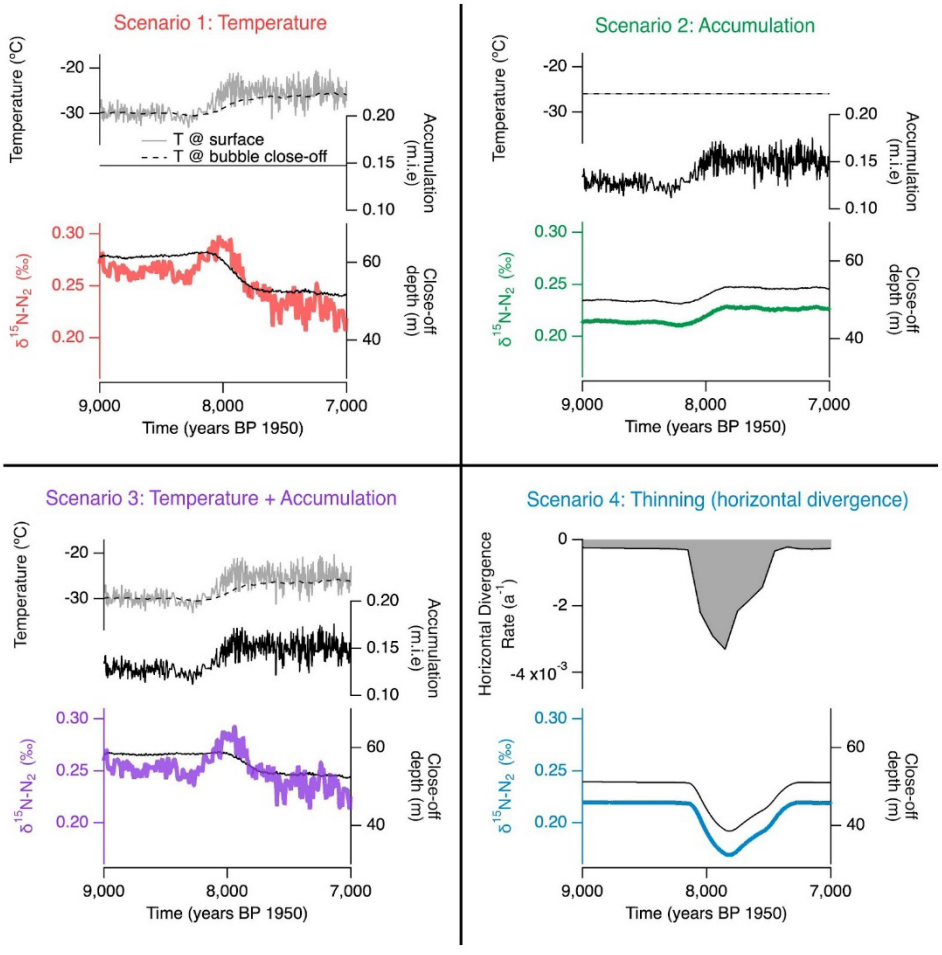

Figure 2: Factorial Experiments using the CFM to disentangle the potential drivers of $\delta^{15}N$ variability at SIR. Panels show changes in temperature-only (red), accumulation-only (green) and a combination of temperature and accumulation (purple) with the two forcings of surface temperature (light grey) and accumulation (solid black). Also shown in these panels are the predicted temperature at bubble close-off (dashed black), the close-off depth (solid black) and the $\delta^{15}N$ (coloured coded to the given experiment). Panel 4 shows the prediction using just the horizontal divergence calculated from PISM plus constant accumulation rate (filled in grey).

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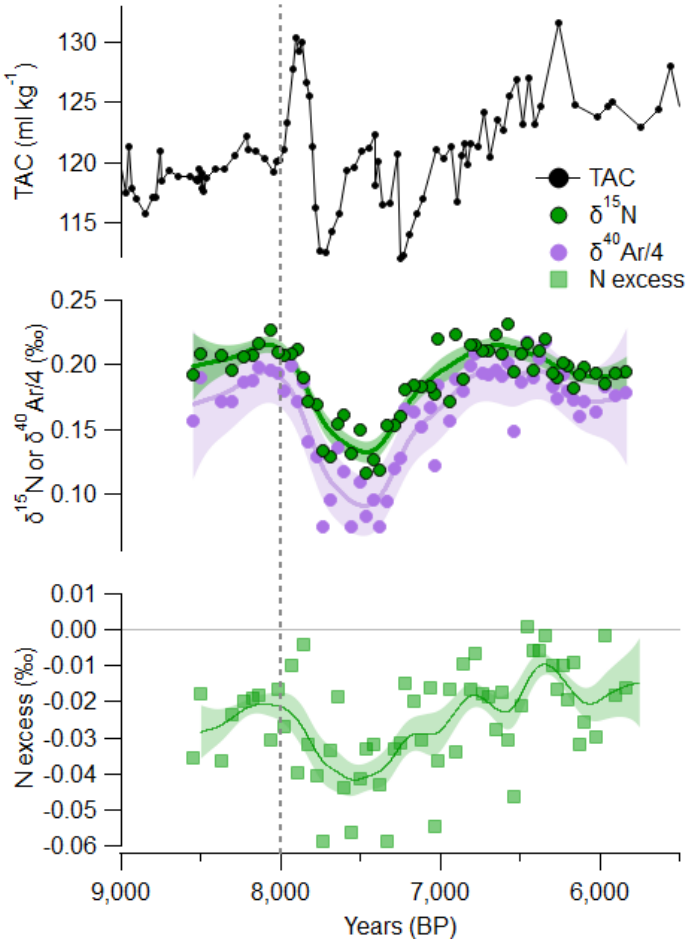

Figure 3: Values of $\delta^{15}N$ and $\delta^{40}Ar$ from the Skytrain ice core (middle panel) throughout the rapid elevation change at the site ~ 8 ka (dashed line), plotted against the previously published TAC data (top panel) (Grieman et al., 2024). Smoothing splines are also presented (see methods), with uncertainty bands becoming large at the ends of the dataset due to a lack of constraining data points beyond here. Also shown is the calculated N excess.

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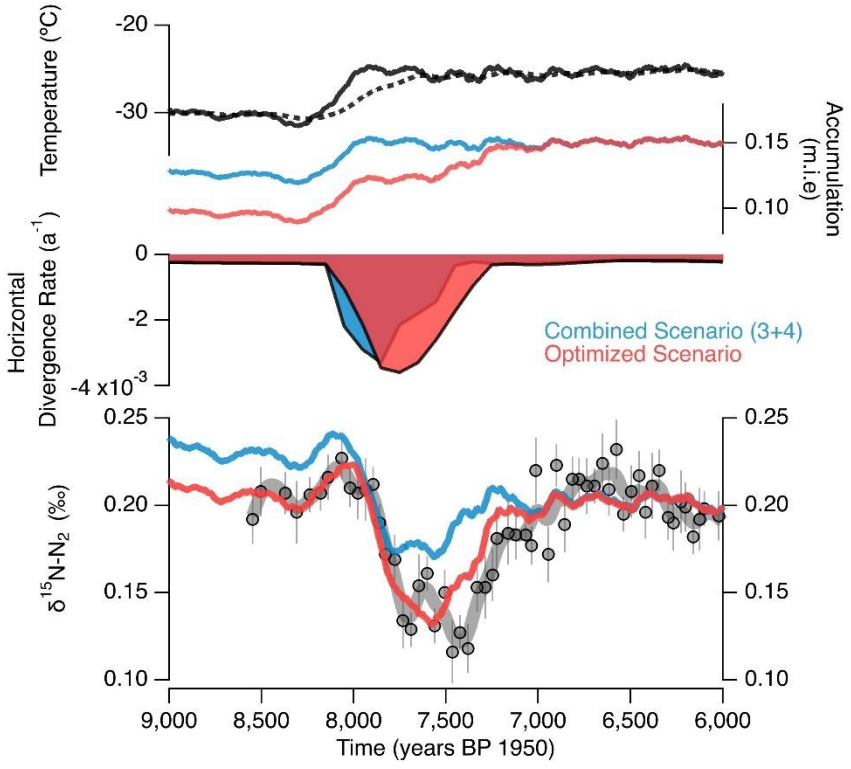

Figure 4: Optimising the model parameters to best fit data, where accumulation and horizontal divergence rates are adjusted so that the model output of the absolute values of $\delta^{15}N$ and duration of the reduction in $\delta^{15}N$ more closely match the measured data ('Optimised scenario', lower panel).

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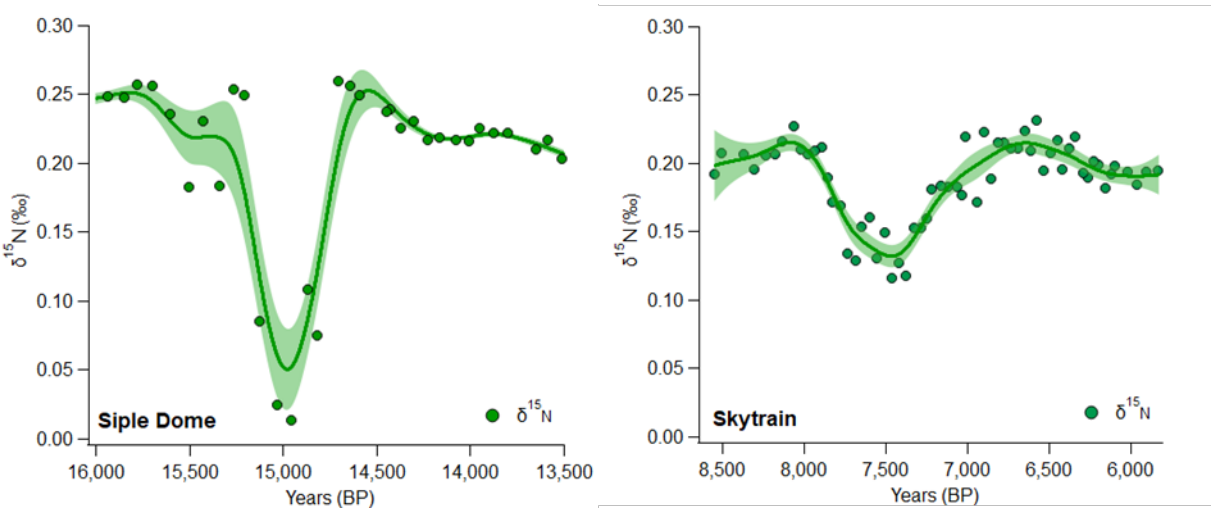

Figure 5: Comparison of $\delta^{15}N$ from the Siple Dome (left) (Severinghaus et al., 2003, 2009) and Skytrain (right) ice cores, highlighting the substantial drop in $\delta^{15}N$ in both records lasting over timescales of ~ 1000 years.

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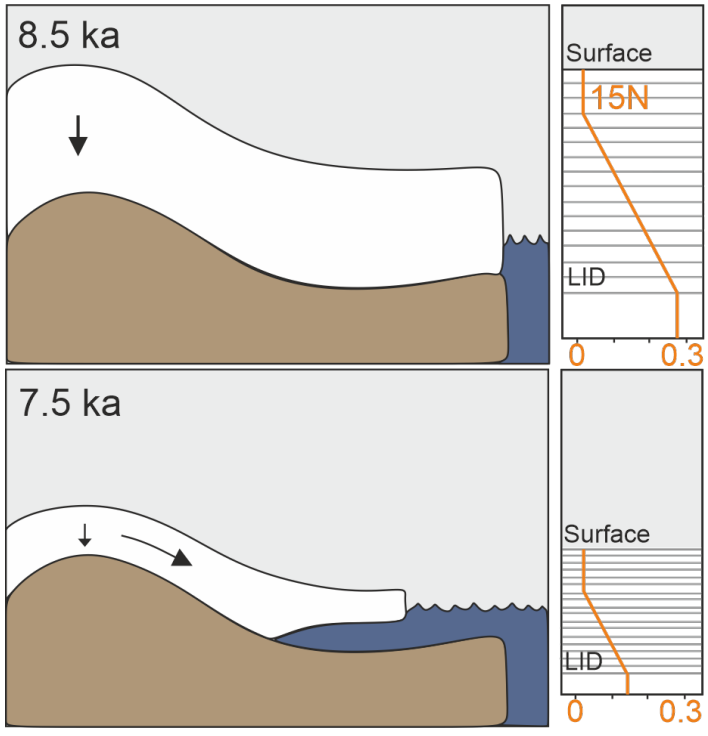

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550 **Figure 6: Schematic of the physical ice changes at Skytrain Ice Rise throughout the 8 ka elevation change alongside the**
551 **effects on the $\delta^{15}N$ values shown as profiles through the respective firn column for each scenario of ice thickness. Where**
552 **ice dynamics are stable at 8.5 ka, $\delta^{15}N$ increases down the firn column from the ice surface to bubble lock-in depth**
553 **(LID) due to gravitational fractionation. Where ice thickness is reduced and layers dynamically thinned due to**
554 **horizontal divergence at 7.5 ka, there is less gravitation fractionation through the thinned firn-column, resulting in**
555 **lower values of captured $\delta^{15}N$ at bubble LID. Values of $\delta^{15}N$ shown here are indicative only.**

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