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SPATIAL PATTERN OF ACCUMULATION AT TAYLOR DOME DURING THE LAST GLACIAL INCEPTION: STRATIGRAPHIC CONSTRAINTS FROM TAYLOR GLACIER

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Abstract. A new ice core retrieved from the Taylor Glacier blue ice area contains ice and air spanning the Marine Isotope Stage (MIS) 5/4 transition (74 to 65 ka), a period of global cooling and glacial inception. Dating the ice and air bubbles in the new ice core reveals an ice age-gas age difference (Δage) approaching 10 ka during MIS 4, implying very low accumulation at the Taylor Glacier accumulation zone on the northern flank of Taylor Dome. A revised chronology for the Taylor Dome ice core (80 to 55 ka), situated to the south of the Taylor Glacier accumulation zone, shows that Δage did not exceed 2.5 ka at that location. The difference in Δage between the new Taylor Glacier ice core and the Taylor Dome ice core implies a spatial gradient in snow accumulation across Taylor Dome that intensified during the last glacial inception and through MIS 4.

1 Introduction

Trapped air in ice cores provides a unique and direct paleoarchive of the Earth's past atmospheric composition. Paleo-atmospheric reconstructions of trace gas species, and particularly their isotopic composition, have created a demand for large-volume glacial ice core samples. Blue ice areas, where a combination of glacier flow and high ablation rates bring old ice layers near the surface, offer relatively easy access to large samples and can supplement traditional ice core paleoclimate archives (Bintanja, 1999; Sinisalo and Moore, 2010). As opposed to traditional ice coring where the age of ice and air bubbles always increases with depth, blue ice areas often have complex depth-age and distance-age relationships disrupted by folding and thinning of stratigraphic layers (e.g., Petrenko et al., 2006). Taking full advantage of blue ice areas requires precise age control and critical examination of the glaciological context in which they form.

Effective techniques for dating ablation zone ice include matching of globally well-mixed atmospheric trace gas records (e.g. CH_4, CO_2, $\delta^{18}O_{atm}$, N_2O) and correlation of glaciochemical records (e.g. $\delta^{18}O_{ice}$, Ca^{2+}, insoluble particles) to existing ice core records with precise chronologies (Bauska et al., 2016; Schilt et al., 2014; Petrenko et al., 2008; Schaefer et al., 2009; Baggenstos et al., 2017; Petrenko et al., 2016; Aarons et al., 2017). Other useful techniques include $^{40}Ar_{atm}$ dating (Bender et al., 2008; Higgins et al., 2015), and radiometric ^{81}Kr dating (Buizert et al., 2014). Correlation of gas and glaciochemical records has the advantage of high measurement precision, low sample volume needs, and portability of instrumentation, meaning that measurements can be made in the field with fast access to age information. $^{40}Ar_{atm}$ and ^{81}Kr require complex laboratory work and are not yet as precise, but they have the advantage of providing absolute age information that is independent of preexisting ice core chronologies and may extend beyond the age range of existing records.

A number of blue ice areas have provided useful paleoclimate archives including Pakitsoq, Greenland for the Younger Dryas-Preboreal transition (Petrenko et al., 2006; Petrenko et al., 2009; Schaefer et al., 2009; Schaefer et al., 2006), Allan Hills, Victoria Land, Antarctica for ice 90-250 ka and > 1 Ma (Spaulding et al., 2013; Higgins et al., 2015), Mt. Moulton, Antarctica for the last interglacial (Korotkikh et al., 2011), and Taylor Glacier, McMurdo Dry Valleys, Antarctica, for ice spanning the last glacial termination and MIS 3 (Bauska et al., 2016; Schilt et al., 2014; Baggenstos et al., 2017; Petrenko et al., 2017). Of these margin sites, Taylor Glacier is particularly well suited for paleoclimate reconstructions because of excellent record preservation, large age span, and relative age continuity of available ice (Buizert et al., 2014; Baggenstos, 2015; Baggenstos et al., 2017). Furthermore, the proximity of the Taylor Dome ice core site to the probable deposition site for Taylor Glacier ice provides a useful point of comparison for the downstream blue ice area records (Figure 1).

This study expands the Taylor Glacier blue ice area archive by developing ice and gas chronologies spanning the MIS 5/4 transition (74-65 ka), a period of global cooling and glacial inception. In 2015 a new ice core was retrieved approximately 1 km down-glacier from the “Main Transect,” the across-flow transect containing ice from Termination 1 through MIS 3 (Baggenstos et al., 2017) (Figure 1). This paper describes (1) dating the new ice core via value-matching or correlation of CH_4, $\delta^{18}O_{atm}$, dust, and $\delta^{18}O_{ice}$ to preexisting records, and (2) the description of a new MIS 4 paleoarchive, previously thought to be largely absent from Taylor Glacier. In order to investigate how the new Taylor Glacier chronology fits into the larger context of the glaciological history at Taylor Dome, new measurements of CH_4 and CO_2 from the Taylor Dome ice core are used to revise the Taylor Dome chronology across the MIS 5/4 transition. We

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conclude with inferences about the climate history of Taylor Dome that are implied by the differences in the ice age-gas age difference (Δage = ice age – gas age) between the two sites.

2 Field site and analytical methods

Taylor Glacier is an outlet glacier of the East Antarctic Ice Sheet located in the McMurdo Dry Valleys (Figure 1). The Taylor Glacier catchment is situated on the north flank of Taylor Dome and receives 3-5 cm ice accumulation annually in present-day climate conditions (Kavanaugh et al., 2009a; Morse et al., 1999). The glacier ablation zone flows ~ 80 km through Taylor Valley at a rate of ~ 10 m a^{-1} and terminates near Lake Bonney, approximately 30 km from the Ross Sea (Kavanaugh et al., 2009b; Aciego et al., 2007). The close proximity to McMurdo Station provides excellent logistical access to the site, which makes Taylor Glacier an ideal natural laboratory (Fountain et al., 2014; Petrenko et al., 2017; Baggenstos et al., 2017; Marchant et al., 1994; Aarons et al., 2017).

A combination of relatively high sublimation rates (~ 10 cm a^{-1}) and relatively slow flow (~ 10 m a^{-1}) results in an ~ 80 km ablation zone where ancient ice with a large range of ages is exposed at the surface of Taylor Glacier. An along-flow transect of water stable isotopes from just below the equilibrium line to the terminus of the glacier revealed ice from the last glacial period in several sporadic intervals (Aciego et al., 2007); the sporadic nature of the occurrences was later shown to be an artifact of sampling nearly parallel to isochrones such that they were occasionally crossed (Baggenstos et al., 2017). More recent across-flow profiles dated with gases revealed ice that varies continuously in age from the Holocene to the last ice age (Schilt et al., 2014; Bauska et al., 2016; Baggenstos et al., 2017), with ice of last interglacial or older age found near the terminus of the glacier (Baggenstos et al., 2017; Buizert et al., 2014). The most utilized archive to date is a 500 m section (called the 'Main Transect') oriented perpendicularly to isochrones across a syncline/anticline pair containing ice spanning ~50 ka before present (BP) to the mid Holocene (7 ka). Ice stratigraphy in the Main Transect dips approximately vertically so that it is possible to obtain large quantities of ice of the same age by drilling vertical or near-vertical ice cores. Ice containing the full MIS 5/4 transition was formerly considered to be missing from the record, but we show here that a new ice core contains an intact record with ice dating from 77.5-63.3 ka that contains air dating from 74.7-57.1 ka.

In the 2013-2014 field season an exploratory core was drilled vertically using a "PICO" hand auger 380 m south ("-380 m" by convention) of a benchmark position along the Main Transect (Figure 1). The core contained air with CH_4 and CO_2 trends similar to Dansgaard-Oeschger event 16/17 and late MIS 4, but it did not contain the MIS 5/4 transition. In the 2014-2015 field season a second exploratory core was drilled vertically using the "PICO" hand auger approximately 1 km down glacier from the Main Transect (77.7591° S, 161.7380° E) where older air bubbles might be nearer to the surface. Preliminary CH_4 measurements in discrete 10 cm x 2 cm x 2 cm ice samples showed CH_4 variations similar to those at Dansgaard-Oeschger event 19 (72.3-69.8 ka, ~ 40 ppb CH_4 increase) (Figure 2), suggesting the ice contained the MIS 5/4 transition. A second exploratory core was obtained directly adjacent using the blue ice drill (BID), a 24 cm diameter shallow coring device designed for retrieving large volume ice samples suitable for trace gas and isotope work (Kuhl et al., 2014). A portion of the core spanning 9-17 m was sampled for laboratory analyses of CH_4 and CO_2, and these analyses confirmed that the exploratory cores contained the MIS 5/4 transition in the gas phase. In the 2015-2016 field season a third core was drilled directly adjacent to the previous boreholes using the BID, and portions of the new core spanning 0-9 m and 17-19.8 m were sampled for laboratory analyses of CO_2 and CH_4 at Oregon State University (OSU) and $\delta^{18}O_{atm}$ and $\delta^{15}N$-N_2 at the Scripps Institution of Oceanography (SIO). The entire new ice core (0-19.8 m) was sampled for continuous flow analyses of CH_4 and insoluble particles in the field and continuous CH_4, major ions and trace elements, $\delta^{18}O_{ice}$, and insoluble particles in the laboratory at the Desert Research Institute (DRI). Ice core samples for all analyses were cut with a band saw on the glacier, stored in chest freezers at < -20˚ C in camp, and flown to McMurdo Station within 2 weeks of retrieval, where they were stored at < -20˚ C. Storage temperature remained at < -20˚ C for the remainder of their shipment to the USA and subsequent storage in the laboratories.

The temporary laboratory constructed at the Taylor Glacier field camp permitted continuous measurements of CH_4 and particle count on ice core samples within days of drilling and recovery. CH_4 concentration was measured using a Picarro laser spectrometer coupled to a custom continuous gas extraction line with a de-bubbler apparatus similar to that described in Rhodes et al. (2013). The continuous CH_4 data were calibrated by measuring standard air tanks of known CH_4 concentration that were introduced into a stream of gas-free water to simulate a bubble/ liquid mixture similar to the melt stream from ice core samples. The tests suggested a ~ 5% loss of CH_4 due to dissolution in the melt stream, though the exact value changed with CH_4 concentration. We adjusted the continuous CH_4 data upwards by 5% to account for the solubility effect, which resulted in good agreement with other Antarctic CH_4 records (Schilt et al., 2010). Insoluble particle abundance was also measured continuously in the field using an Abakus particle counter coupled to the continuous melt-water stream. In order to obtain preliminary/ exploratory gas age information and verify the continuous CH_4 data, discrete ice core samples were also measured for CH_4 concentration in the field using a Shimadzu gas chromatograph coupled to a custom melt-refreeze extraction line, a manual version of the automated system used at OSU (Mitchell et al., 2011; Mitchell et al., 2013).

Laboratory analyses on recovered samples included discrete CH_4, CO_2, $\delta^{15}N$-N_2, and $\delta^{18}O_{atm}$, and continuous CH_4, $\delta^{18}O_{ice}$, major ion and elemental chemistry, and insoluble particle counts. Continuous chemistry, dust, $\delta^{18}O_{ice}$, and CH_4 measurements were made at DRI by melting 3.5 x 3.5 cm longitudinal samples of ice and routing the melt stream to in-line instruments (McConnell, 2002; Maselli et al., 2013). Insoluble particles were measured using an Abakus particle counter, water isotopes using a Picarro laser spectrometer (Maselli et al., 2013), and CH_4 using a Picarro laser spectrometer coupled to the melt stream similar to the system used in the field (Rhodes et al., 2013). Continuous CH_4 data measured at DRI were calibrated with standards similar to the procedure in the field, resulting in an upward adjustment of 8% to account for dissolution in the melt stream. Discrete CH_4 and CO_2 measurements were made at OSU. CH_4 was measured using an Agilent gas chromatograph equipped with a flame ionization detector coupled to a custom melt-refreeze extraction system (Mitchell et al., 2011), and CO_2 was measured on an Agilent gas chromatograph equipped with a Ni catalyst and a flame ionization detector coupled to a custom dry extraction "cheese grater" system for carbon isotopic analyses (Bauska et al., 2014). Stable isotopes of N_2 and O_2 were measured at SIO using a Thermo Delta V mass spectrometer coupled to a custom gas extraction system (Severinghaus et al., 1998; Petrenko et al., 2006). For the purposes of developing a chronology for the MIS 5/4 transition, the three ice cores (one PICO core and two BID cores) are hereafter treated as one ice core record (unified depth and age scales), which is justified given the close proximity of the boreholes (< 2 m spacing at surface) and the minimal depth uncertainty between the cores (< 10 cm).

Thermal expansion and contraction causes abundant cracks in the surface ice of Taylor Glacier. The cracks rarely penetrate below 4 m and have never been observed deeper than 7 m (Baggenstos et al., 2017). We avoided analyses of ice with visible fractures. Though we report shallow data < 4 m depth for completeness, we caution that gas data from 0-4 m may be affected by contamination via cracking. The interpretations that follow do not depend on data taken from 0-4 m.

Discrete measurements of CH_4 and CO_2 were made at OSU on archived Taylor Dome samples following similar procedures described above. Taylor Dome CH_4 samples were measured with the same custom melt-refreeze extraction system as Taylor Glacier samples (Mitchell et al., 2011). Taylor Dome CO_2 measurements were made on small samples (~ 10 g, 1.5 cm^3) using a dry extraction needle crusher system (Ahn et al., 2009).

3 Results and discussion

3.1 Age model

Gas age and ice age models for the new Taylor Glacier ice core were constructed by matching variations in the CH_4, $\delta^{18}O_{atm}$, insoluble particle count, and $\delta^{18}O_{ice}$ to preexisting ice core records synchronized to the Antarctic Ice Core Chronology (AICC) 2012 (Veres et al., 2013; Bazin et al., 2013) (Figure 2). This approach is valid for the gas age scale because CH_4 and $^{18}O_{atm}$ are globally well mixed (Blunier et al., 2007; Blunier and Brook, 2001), and it is valid for the ice age scale because to first order the temporal patterns of dust content and temperature in Antarctic ice are highly correlated at point locations across the continent (Mulvaney et al., 2000; Schupbach et al., 2013). Variations in CH_4 were tied to the EPICA Dronning Maud Land (EDML) CH_4 record on AICC 2012 (Schilt et al., 2010). The $\delta^{18}O_{atm}$ record was tied to North Greenland Ice Coring Project (NGRIP) $\delta^{18}O_{atm}$ record on AICC 2012 (Landais et al., 2007). Insoluble particle counts were tied to the EDC dust record on AICC 2012 (Lambert et al., 2008). One tie point matches $\delta^{18}O_{ice}$ variability to EDC $\delta^{18}O_{ice}$ on AICC 2012 (Jouzel et al., 2007) where dust variability is minimal (Figure 2). Tie points linking ages to depths were manually assigned (Figure 2, Tables 1-2), and ages between the tie points were interpolated linearly. We did not explicitly account for errors associated with using linear interpolation between tie points, though we note that interpolation with a cubic spline did not improve the fit to the reference record. The differences between the linear and cubic spline interpolation methods were minimal and within the age range assigned to tie points. Tie points were not assigned to the end points of our records unless there was clearly a feature to match, therefore the age models are extrapolated from the closest pair of tie points for the intervals 0-0.31 m and 16.62-19.8m for the ice age scale and 0-1.74 m for the gas age scale.

The new Taylor Glacier ice core accurately records the atmospheric history spanning 74.7-59.7 ka including the ~ 40 ppm CO_2 decrease at the MIS 5/4 transition and the ~ 30 ppm CO_2 increase near the MIS 4/3 transition (Figure 3). CO_2 measurements were not used to tie to AICC 2012, and therefore the agreement with preexisting CO_2 measurements on the AICC 2012 chronology (Bereiter et al., 2015) supports our choice of tie points for the gas age scale. The CO_2 offset between Taylor Glacier and the composite record during the MIS 4/3 rise (Figure 3) could be due to a bias in our age model toward younger ages, however CO_2 offsets between ice cores are observed (Luthi et al., 2008), and since we cannot reject the possibility that the offsets are real we refrain from value-matching the CO_2 rise. The resemblance of $\delta^{18}O_{atm}$ to the NGRIP $\delta^{18}O_{atm}$ record younger than 72 ka supports our gas age scale since tie points younger than 72 ka were picked only from the CH_4 record. This is particularly important because CH_4 variability is small in portions of the new ice core record (especially < 70 ka), limiting tie point selection. The choices of tie points for constructing the ice age scale are supported by the close resemblance of the Taylor Glacier nss-Ca^{2+} to EDC nss-Ca^{2+} (Lambert et al., 2012) on AICC 2012 and the Taylor Glacier $\delta^{18}O_{ice}$ records to EDC and EDML $\delta^{18}O_{ice}$ (Jouzel et al., 2007; EPICA Community Members, 2010) on AICC 2012 for intervals younger than 75.75 ka (Figure 3). Taylor Glacier $\delta^{18}O_{ice}$ has more variability than other Antarctic records, most likely recording local-scale changes in temperature and precipitation (Baggenstos, 2015). We note that large features seen in other Antarctic stable isotope records are present (e.g. Antarctica Isotope Maximum (AIM) 19, AIM 20, and MIS 4) and support our choice of tie points for the ice age scale (Figure 3).

Though this is the first time a complete record of the MIS 4 has been found at Taylor Glacier, the -380 m reconnaissance data from the 2013-2014 field season (location in Figure 1) suggest late MIS 4 ice exists on the Main Transect. A gas age scale was constructed for this core by value matching CH_4 records to AICC 2012 reference records similar to the strategy described above. The CH_4 measurements suggest the ice contains air spanning the MIS 4/3 transition and late MIS 4, which is supported by the existence of unique features in CO_2 (~30 ppm rise ~64 ka) and $\delta^{18}O_{atm}$ (excursion ~64 ka) (Figure 3). Although the existence of MIS 4 ice on the Main Transect does not prove the ice at the MIS 5/4 BID site came from the same deposition site as the ice contained in the Main Transect, it is highly suggestive of this continuity. The fact that $\delta^{15}N\text{-}N_2$, a proxy for firn thickness, is similarly low in the -380 m core as in the MIS 5/4 BID core is suggestive that the ice cores originated from similar firn (Figure 3). Regarding stratigraphic continuity it is important to note that geologic evidence from Taylor Valley suggests that Taylor Glacier has not changed dramatically in terms of its extent or its thickness in the last ~ 2.2 Ma and that Taylor Dome remained a peripheral dome of the East Antarctic Ice Sheet during the last ice age (Marchant et al., 1994; Brook et al., 1993). Though this does not necessitate that the ice at the MIS 5/4 drill site came from the same deposition site as the ice in the Main Transect, it does suggest that on the larger scale Taylor Glacier unlikely experienced dramatic changes in the source of the paleoarchive.

One clear observation from the new ice core is that the ice from MIS 4 is very thin; indeed the entire MIS 4 period appears to be contained in ~ 6 m of ice (Figure 2). This is in contrast to ice from the last glacial maximum, which is found at the surface of Taylor Glacier in two thicker (> 10 m) outcrops that dip approximately vertically and strike along the glacier longitudinally (Baggenstos et al., 2017; Aciego et al., 2007). Thin ice helps explain why the MIS 4 interval has been relatively difficult to find at Taylor Glacier. The implications of thin layers for the accumulation history are discussed in more detail below.

3.2 Analytical and age model uncertainties

Laboratory measurements of CH_4 and insoluble particles at DRI replicated the field measurements and supported the original data acquired in the 2014-2015 and 2015-2016 field seasons and at OSU (Figure 2). The mismatch between field and laboratory CH_4 in the top 0-4 m of the 2015-2016 core likely is due to contamination from resealed cracks in surface glacier ice. We prefer to interpret the 0-4 m section of the 2015-2016 field data as uncontaminated because the CH_4 variability matches that of Dansgaard-Oeschger event 16/17 closely, though the disagreement with the laboratory analysis makes it impossible to rule out that both records are affected. Our interpretations do not depend on data from the uppermost 4 m.

There are two types of uncertainty associated with the gas and ice age models constructed for the new cores: (1) absolute age uncertainty that is propagated from the reference age scale (AICC 2012), and (2) uncertainties from the selection of tie points related to the choice of features to tie, the sampling resolution, and the measurement error. While there is some ambiguity in matching features in CH_4 and insoluble particle records visually, particularly when the magnitude of changes is small, our choice of features for tie points are suitable because independent data (e.g., CO_2, $\delta^{18}O_{atm}$ younger than 73 ka, nss-Ca^{2+}, and $\delta^{18}O_{ice}$ younger than 75.75 ka) also match preexisting ice core data on AICC 2012. To estimate the relative age uncertainty introduced from (2), we assigned an error range to each individual tie point by surveying the value-matched or correlated data and conservatively estimating the maximum and minimum possible age, taking into consideration the sampling resolution and analytical errors of the reference record and the new data. Smoothing in the continuous CH_4 data due to mixing of the sample stream in the instrumentation did not affect the magnitude of CH_4 features that we used to tie to the reference record, but it likely added a small amount of error to the depth registry. The depth error was estimated by observing the depth offset in features resolved by the continuous versus discrete CH_4 measurements. The largest depth offset was at the onset of the Dansgaard-Oeschger event 19 CH_4 rise at ~ 16.0 m depth (Figure 2): there is a 10 cm offset between the continuous field CH_4 and the discrete laboratory CH_4, and a 20 cm offset between the continuous laboratory CH_4 and the discrete laboratory CH_4. 20 cm depth uncertainty equates to, conservatively, 300 years on the gas age scale near the onset of Dansgaard-Oeschger event 19. This error was propagated into the Δage calculations that are discussed below. Lastly, smoothing of the atmospheric signal in the firn column prior to bubble trapping may affect the timing and magnitude of peaks in our records, but we note that it likely does not affect tie point selection when matching to features in EDML because these features are similarly smoothed. Analytical noise in the continuous records contributed negligible uncertainty to the age models. The absolute age uncertainty in the reference timescale (AICC 2012) is 4 ka for ice age and 6 ka for gas age (Veres et al., 2013). By nature these errors are inherited by the Taylor Glacier 5/4 chronology, but we note that the relative age uncertainty is much smaller (Table 1, Table 2).

3.3 ΔAge and comparison to Taylor Dome

Gas is trapped in air bubbles in firn at polar sites 50-120 m below the surface, thus ice core air is younger than the ice matrix that encloses it (Schwander and Stauffer, 1984). The difference between ice age and gas age, Δage, depends on temperature and accumulation rate with the latter having the stronger control (Herron and Langway, 1980). Δage ranges from 100-3000 years in polar ice cores under modern conditions (Schwander and Stauffer, 1984) with high accumulation sites having smaller Δage on the order of hundreds of years (e.g., Buizert et al., 2015). Extrema in Δage up to 6500 years (Vostok) and 12,000 years (Taylor Dome) have been documented at low accumulation sites at the last glacial maximum (Baggenstos et al., 2018, in review; Veres et al., 2013; Bender et al., 2006).

Δage was calculated for the new Taylor Glacier ice core by subtracting the gas age at a given depth from the independently determined ice age at the same depth (Δage = ice age – gas age). Uncertainty for Δage was determined from the error range reported for individual tie points (Table 1, Table 2) ± 300 years to account for depth offsets that resulted from smoothing of the continuous gas data (described above). Maximum and minimum Δages were calculated by subtracting the oldest gas age scale (interpolation between oldest tie points) from the youngest ice age scale (interpolation between youngest tie points) and vice versa. Δage in the new core approaches ~10 ka during MIS 4 (Figure 3), which exceeds Δage for typical modern polar ice core sites even where ice accumulates very slowly. This finding is unprecedented in ice from Taylor Glacier as Δage in ice from the Main Transect does not exceed ~ 3 ka throughout MIS 3 back to 50 ka (Baggenstos et al. 2018, in review). The implication of high Δage is that precipitation in the Taylor Glacier accumulation zone was near zero, or the effect of wind scouring was large enough to reduce the net accumulation. The $\delta^{15}N\text{-}N_2$ enclosed in ice core air bubbles is controlled by gravitational fractionation in the firn column, and to first order it is an indicator of firn thickness (Sowers et al., 1992). Our results indicate that as Δage increased at the onset of MIS 4, the $\delta^{15}N\text{-}N_2$ progressively decreased

(Figure 3), which is consistent with thinning of the firn column in response to decreased net accumulation. In principle one could use the Δage and the $\delta^{15}N\text{-}N_2$ to compute the accumulation history at the deposition site, but we refrain from doing so here because the large magnitude of Δage implies accumulation rates that are well below the calibration range for typical firn densification models (Herron and Langway, 1980).

To investigate the Taylor Glacier Δage record in the context of the glaciological history of Taylor Dome, we present new Taylor Dome gas and ice age scales (and Δage) spanning the MIS 5/4 and MIS 4/3 transitions (Figure 4). The new Taylor Dome gas age scale is based on new measurements of CH_4 as well as previously published measurements of CH_4 made at OSU (Brook et al., 2000) that were tied to AICC 2012 by matching variations to EDML (Schilt et al., 2010). Likewise, the new Taylor Dome ice age scale comes from matching features in the Taylor Dome Ca^{2+} record (Mayewski et al., 1996) to the EDC dust record (Lambert et al., 2008). All tie points were chosen manually (Table 3 and Table 4). Uncertainties in the age scales were treated in the same manner described for the Taylor Glacier MIS 5/4 ice core, i.e. maximum and minimum ages were assigned to each tie point considering the analytical precision and sampling resolution of the Taylor Dome measurements and reference datasets (Table 3 and Table 4). Maximum and minimum Δages were determined from the error ranges assigned to individual tie points (similar to above). Note that a Δage of 0 or less is physically impossible, and minimum Δage <= 0 in Figure 4 is merely an artifact of estimating the error for individual tie points generously and without the physical constraint that ice age > gas age.

In contrast to Taylor Glacier, Δage at Taylor Dome does not rise above 2.5 ka throughout MIS 4 (Figure 4). The implication of the relatively "normal" Δage is that accumulation at Taylor Dome did not dramatically change at the onset of the last glacial period or throughout MIS 4 as Taylor Glacier did. Comparing the depth-age relationships in the new Taylor Glacier core versus the Taylor Dome ice core highlights the difference in accumulation between the two sites. Taylor Glacier age increases more steeply with depth during MIS 4 relative to the intervals before and after (Figure 3), while Taylor Dome age increases approximately monotonically with depth throughout the entire 80-55 ka interval (Figure 4). A caveat is that the shapes of the depth-age curves could be due to differential thinning of layers (differential thinning between Taylor Dome and Taylor Glacier ice as well as differential thinning within the Taylor Glacier ice core, i.e. in MIS 4 ice versus MIS 5 or MIS 3). We prefer the explanation that accumulation controls the shape of the depth-age curves in both ice cores because it is consistent with Δage and $\delta^{15}N\text{-}N_2$.

The key to understanding the difference between the two records might be that Taylor Glacier ice is sourced from a site located to the north of the Taylor Dome deposition site (Figure 1). The large difference between the inferred paleo-accumulation rates at Taylor Glacier versus Taylor Dome therefore implies a dramatic gradient in precipitation (or wind scouring) between the two locations. This implication is perhaps not surprising because the observed modern accumulation gradient is in the same direction, with accumulation decreasing going from south (Taylor Dome accumulation zone) to north (Taylor Glacier accumulation zone) (Morse et al., 1999). As moisture delivery to Taylor Dome primarily occurs during storms that penetrate the Transantarctic Mountains south of the Royal Society Range and reach Taylor Dome from the south (Morse et al., 1998), the modern-day accumulation rate gradient decreases from the Taylor Dome accumulation zone in the south to the Taylor Glacier accumulation zone to the north. The Taylor Glacier accumulation zone is effectively situated on the lee side of Taylor Dome with respect to the delivery of moisture (Morse et al., 1999) (Figure 1).

It is thought that this accumulation rate gradient across Taylor Dome (and hence between Taylor Dome and the Taylor Glacier accumulation zone) may have varied in the past. Morse et al. (1998) used modern accumulation data, a calculated flow field, and an age scale determined by correlation of isotope and chemical data to the Vostok ice core to calculate the accumulation rate history for the Taylor Dome ice core. By mapping the age scale to the radar stratigraphy of the region Morse et al. (1998) also calculated the accumulation rate history for a virtual ice core situated ~7 km to the north of the Taylor Dome drill site. The inferred accumulation histories revealed strong horizontal accumulation gradients in the past including (1) extremely low accumulation during the last glacial maximum at Taylor Dome (thin layers), (2) relatively high accumulation at the northern virtual ice core site during the last glacial maximum (thicker layers), and (3) the opposite accumulation gradient (decreasing from south to north) for ice older than 60 ka. The possibility that different layer thicknesses were a result of differential flow was rejected because deeper layers did not show the same effect (Morse et al., 1998). The spatial pattern of accumulation on Taylor Dome during the last glacial maximum was confirmed by independent age determinations on Taylor Glacier and Taylor Dome ice with Taylor Glacier last glacial maximum Δage = ~ 3000 years and Taylor Dome last glacial maximum Δage = ~12,000 years (Baggenstos et al., 2018, in prep.; Baggenstos, 2015). Therefore two independent lines of evidence support the notion that accumulation practically ceased at Taylor Dome during the extreme aridity of the last glacial maximum. It is thought that this resulted from a shift in the trajectory of storm systems in response to the extension of grounded ice far into the Ross Sea (Morse et al., 1998).

Our observations of Taylor Glacier ice from MIS 4 combined with our revisions to the Taylor Dome age scale contribute a new piece of information to the glaciology history at Taylor Dome. The evidence suggests that the modern accumulation gradient did not reverse during MIS 4 as it did during the last glacial maximum. If indeed ice sheets extended far enough into the Ross Sea during the last glacial maximum to alter the atmospheric circulation patterns that delivered moisture to Taylor Dome (e.g., Morse et al., 1998), the implication would be that they did not do so during MIS 4. This interpretation seems at odds, however, with evidence that the Southern Hemisphere experienced full glacial conditions during MIS 4 (e.g., Schaefer et al., 2015; Barker and Diz, 2014). A possible explanation is that the sea level minimum at MIS 4 was 25 m higher than during the last glacial maximum (Shakun et al., 2015; Siddall et al., 2003; Cutler et al., 2003), which limited how far the East Antarctic Ice Sheet could extend into the Ross

Embayment. Though we do not offer quantitative evidence to support this explanation, we note that it is consistent with (1) data suggesting the maximum Ross Ice Shelf extent occurred during the last glacial termination (Hall et al., 2015; Denton and Hughes, 2000) and (2) the notion that grounding line position in the Ross Sea is set by the interplay between marine forcing (basal melting) and accumulation on the Antarctic ice sheets.

A second hypothesis arises from the notion that broad differences in regional atmospheric dynamics could have occurred during MIS 4 versus MIS 2 without invoking the extent of the Ross Ice Shelf as a mechanism for disrupting the atmospheric circulation. The Amundsen Sea Low, a low-pressure center that influences the Ross Sea and Amundsen Sea sectors of Antarctica, responds strongly to changes in tropical climate (Raphael et al., 2016; Turner et al., 2013) and exhibits cyclonic behavior that likely controls the path of storms that enter the Ross Embayment and ultimately reach Taylor Dome, as alluded to by Morse et al. (1998) and explored by Bertler et al., (2006). A plausible scenario is that the Amundsen Sea Low intensified and/ or shifted westward during MIS 4 relative to MIS 2, resulting in strong meridional flow across Taylor Dome from the south and thus maintaining a strong south-to-north decreasing accumulation gradient. The ultimate cause of broad differences in the strength and/or position of the Amundsen Sea Low during MIS 4 versus MIS 2 (without invoking ice extent in the Ross Sea) is difficult to pinpoint, but presumably differences in the Amundsen Sea Low might arise as a result of atmospheric teleconnections driven by different mean global climate states (e.g. Northern Hemisphere MIS 4 glaciation was weaker than MIS 2).

4 Conclusions

We obtained the first ice core from the Taylor Glacier blue ice area that contains air with ages spanning the MIS 5/4 transition and the MIS 4/3 transition (74.7-57.7 ka). The ice core also contains ice spanning the MIS 5/4 transition (77.5-63.3 ka). Δage in the core approaches 10,000 years during MIS 4 implying extremely arid conditions with virtually zero net accumulation at the site of deposition. South of the deposition site, the Taylor Dome ice core exhibits lower Δage (1000-2000 years) during the same interval. This implies a steep accumulation gradient across Taylor Dome with precipitation decreasing toward the north and/or extreme wind scouring affecting the northern flank. The direction of the gradient suggests that the trajectory of storms was south-to-north during MIS 4 and was not disrupted by Antarctic ice protruding into the Ross Sea or by changes in the strength and/or position of the Amundsen Sea Low.

Data will be made available through the US Antarctic Program Data Center and the National Center for Environmental Information.

Author contribution

JAM made measurements at OSU on Taylor Glacier samples, developed chronologies, and prepared the manuscript; JAM, EJB, and JRM made measurements in the field; TKB made measurements at OSU on the -380 m Taylor Glacier core; SB and SM made measurements at OSU on Taylor Dome samples; SS made measurements on all new Taylor Glacier samples at SIO except the -380 m core, which were made by DB; JRM made measurements on Taylor Glacier samples at DRI; all authors provided valuable feedback and made helpful contributions to writing the manuscript.

The authors declare no conflicts of interest.

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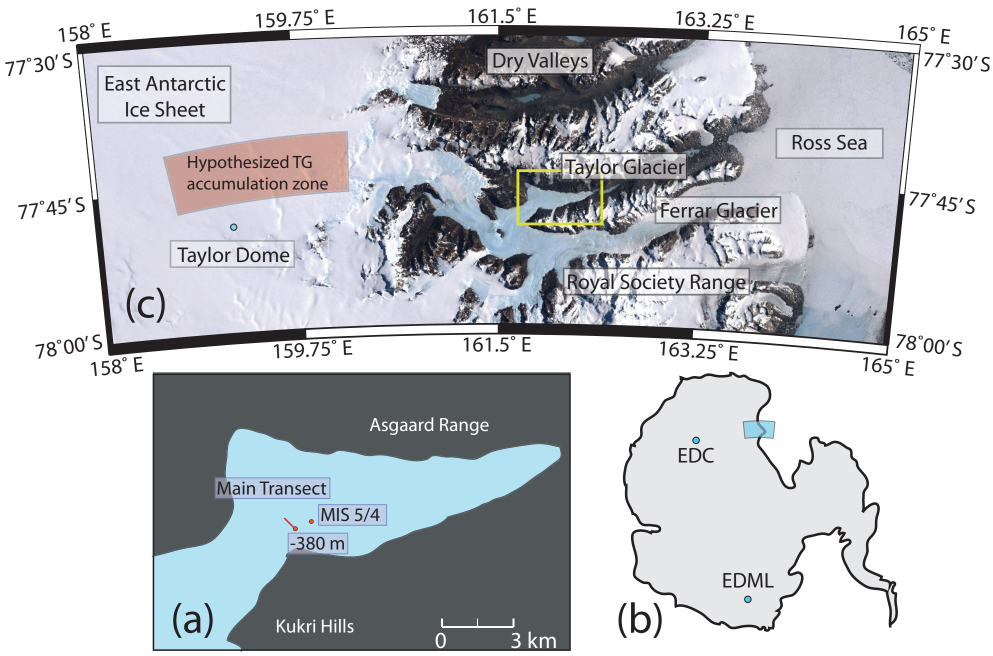

Figure 1 – (a) Simplified map of Taylor Glacier showing main transect (red line) containing ice spanning the Holocene-MIS3 time period and drill sites discussed in the text (red dots). (b) The locations of Taylor Glacier and other ice core sites in this text are indicated with blue dots on the continent outline (EDC = EPICA Dome C, EDML = EPICA Dronning Maud Land). (c) Landsat imagery of Taylor Valley is courtesy of USGS (Bindschadler et al., 2008).

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-53
Manuscript under review for journal Clim. Past
Discussion started: 17 May 2018

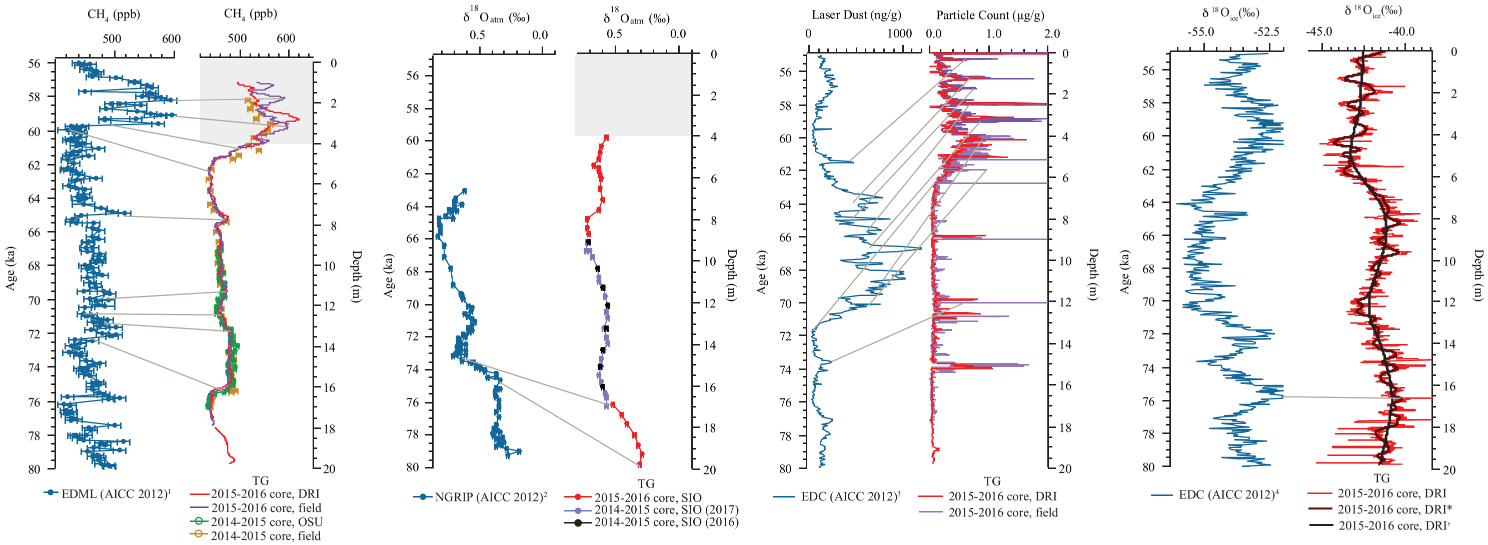

Figure 2 - Records used to synchronize Taylor Glacier 5/4 gas age and ice age scales to other ice core records on AICC 2012. Tie points are indicated by gray lines. The legends on the figure indicate the ice core from which samples were cut and the laboratory where new measurements were made (TG = Taylor Glacier, EDML = EPICA Dronning Maud Land, EDC = EPICA Dome C, and NGRIP = North Greenland Ice Coring Project; DRI = Desert Research Institute, OSU = Oregon State University, SIO = Scripps Institution of Oceanography). Data sources are indicated with superscripts: (1) Schilt et al. (2010), (2) Landais et al. (2007), (3) Lambert et al. (2008), (4) Jouzel et al. (2007). Shading of the top 4m of the gas data marks depths where abundant cracks are observed on the glacier surface (see text). Resealed cracks in the 2015-2016 core CH_4 record are likely the reason for the discrepancies between the two continuous CH_4 records above 3.5 m. CH_4 is missing from the lowest portion of the 2015-2016 field data set because of technical problems with the melter system.
* and † indicate smoothing with 500-point and 5000-point Loess algorithms, respectively.

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-53
Manuscript under review for journal Clim. Past
Discussion started: 17 May 2018

Table 1 – Tie points relating Taylor Glacier depth to gas age on the AICC 2012 timescale. Gray shading indicates tie points < 4 m depth where abundant cracks in shallow ice may cause contamination of the gas records. Ice phase parameters (e.g. dust) are likely unaffected by surface cracks. Error is expressed as range of maximum and minimum ages on AICC 2012. "DO" refers to Dansgaard-Oeschger event.

Depth (m)	Gas Age (ka)	Parameter	Age Range (ka)	Description
1.74	58.21	CH_4	57.98-58.41	Peak during DO 16/17
3.15	59.1	CH_4	58.9-59.3	Peak during DO 16/17
4.19	59.66	CH_4	59.6-59.7	Midpoint initial DO 16/17 rise
5.4	59.94	CH_4	59.71-60.78	Low point before DO 16/17 rise
7.79	64.90	CH_4	64.6-65.26	Peak during DO 18
11.24	69.92	CH_4	69.5-70.36	Small peak between DO 19 and DO 18
12.43	70.62	CH_4	70.37-70.93	Low point after DO 19
13.25	71.21	CH_4	70.94-71.42	End of DO 19
16.2	72.27	CH_4	72.1-72.45	Midpoint initial DO 19 rise
16.95	73.52	$\delta^{18}O_{atm}$	73.1-73.65	Inflection point (see Figure 2)
19.8	74.65	$\delta^{18}O_{atm}$	74.1-75.94	Inflection point (see Figure 2)

Table 2 - Tie points relating Taylor Glacier depth to ice age on the AICC 2012 timescale. Ice phase parameters (dust and $\delta^{18}O_{ice}$) are likely unaffected by surface cracks. Error is expressed as range of maximum and minimum ages on AICC 2012. "AIM" refers to Antarctic Isotope Maximum event, "MIS" refers to Marine Isotope Stage.

Depth (m)	Ice Age (ka)	Parameter	Age Range (ka)	Description
0.31	61.47	Particles	61.4-61.6	Peak near end of MIS 4
1.26	63.93	Particles	63.22-64.48	Peak during MIS 4
1.71	64.9	Particles	64.8-64.97	Peak during MIS 4
2.51	65.57	Particles	65.2-65.89	Peak during MIS 4
3.24	66.73	Particles	66.31-66.94	Peak during MIS 4
4.19	68.6	Particles	67.86-69.6	Peak during MIS 4
5.65	70.11	Particles	69.71-71.13	Peak during MIS 4
6.3	71.64	Particles	71.4-72.64	Low point before MIS 4
12.05	73.58	Particles	73.27-74.18	Small peak before MIS 4
16.62	75.75	$\delta^{18}O_{ice}$	75.28-76.08	Peak during AIM 20

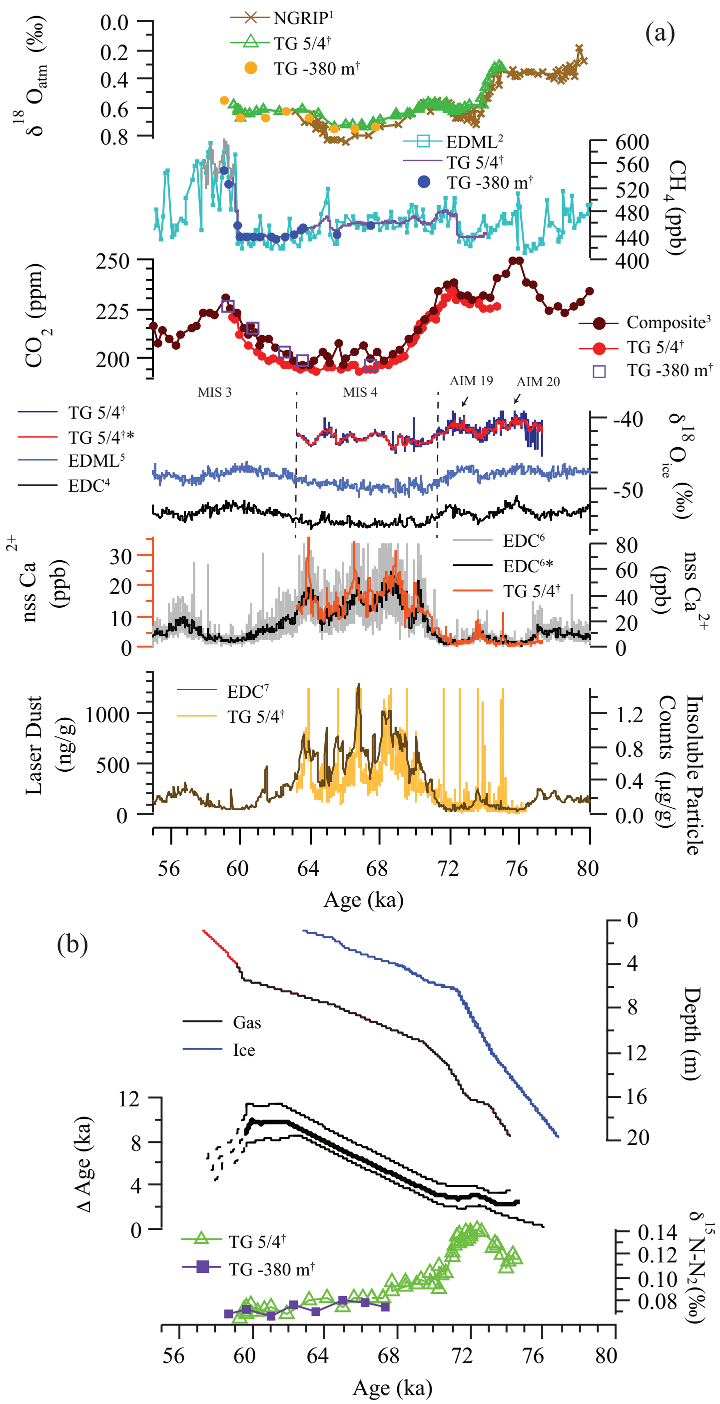
(a)
NGRIP[1]
TG 5/4[†]
TG -380 m[†]
δ18 Oatm (‰)
0.0
0.2
0.4
0.6
0.8
EDML[2]
TG 5/4[†]
TG -380 m[†]
CH4 (ppb)
600
560
520
480
440
400
CO2 (ppm)
250
225
200
Composite[3]
TG 5/4[†]
TG -380 m[†]
MIS 3
MIS 4
AIM 19
AIM 20
TG 5/4[†]
TG 5/4[†]*
EDML[5]
EDC[4]
δ18Oice (‰)
-40
-50
nss Ca2+ (ppb)
30
20
10
0
EDC[6]
EDC[6]*
TG 5/4[†]
80
60
40
20
0
Laser Dust (ng/g)
1000
500
0
EDC[7]
TG 5/4[†]
Insoluble Particle Counts (µg/g)
1.2
0.8
0.4
0.0
56
60
64
68
72
76
80
Age (ka)
(b)
Gas
Ice
Depth (m)
0
4
8
12
16
20
Δ Age (ka)
12
8
4
0
TG 5/4[†]
TG -380 m[†]
δ15 N-N2 (‰)
0.14
0.12
0.10
0.08
56
60
64
68
72
76
80
Age (ka)

Figure 3 – (A) Measurements of trace gases, stable isotopes (ice and O_2), insoluble particles, and nss-Ca^{2+} from the Taylor Glacier ice core on new gas and ice age scales synchronized with AICC 2012. CH_4 data from < 4 m depth could be contaminated by surface cracks and are colored gray. Ice cores are labeled as follows: NGRIP = North Greenland Ice Coring Project, TG = Taylor Glacier (5/4 BID core and -380 m main transect PICO core), EDML = EPICA Dronning Maud Land, EDC = EPICA Dome C. Composite CO_2 includes measurements from EDC, EDML, and Talos Dome. Data sources are indicated with superscripts: (1) (Landais et al., 2007), (2) (Schilt et al., 2010), (3) (Bereiter et al., 2015), (4) (Jouzel et al., 2007), (5) (EPICA Community Members, 2010), (6) (Lambert et al., 2012), (7) (Lambert et al., 2008). † indicates this study, * indicates smoothing with 500-point Loess algorithm. MIS 5/4 and MIS 4/3 transitions are marked at the midpoint in the stable isotope transitions with dotted lines, and Antarctic Isotope Maxima (AIM) 19 and 20 are labeled for chronological reference. (B) Ice age and gas age vs. depth models were constructed from tie points in Figure 2, Table 1, and Table 2, and the gas age model for ice < 4 m depth is colored red. Calculated Δage (= ice age – gas age) and $\delta^{15}N$-N_2 are plotted on the gas age scale. Maximum and minimum Δage were determined based on the uncertainty estimation described in the text.

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-53
Manuscript under review for journal Clim. Past
Discussion started: 17 May 2018

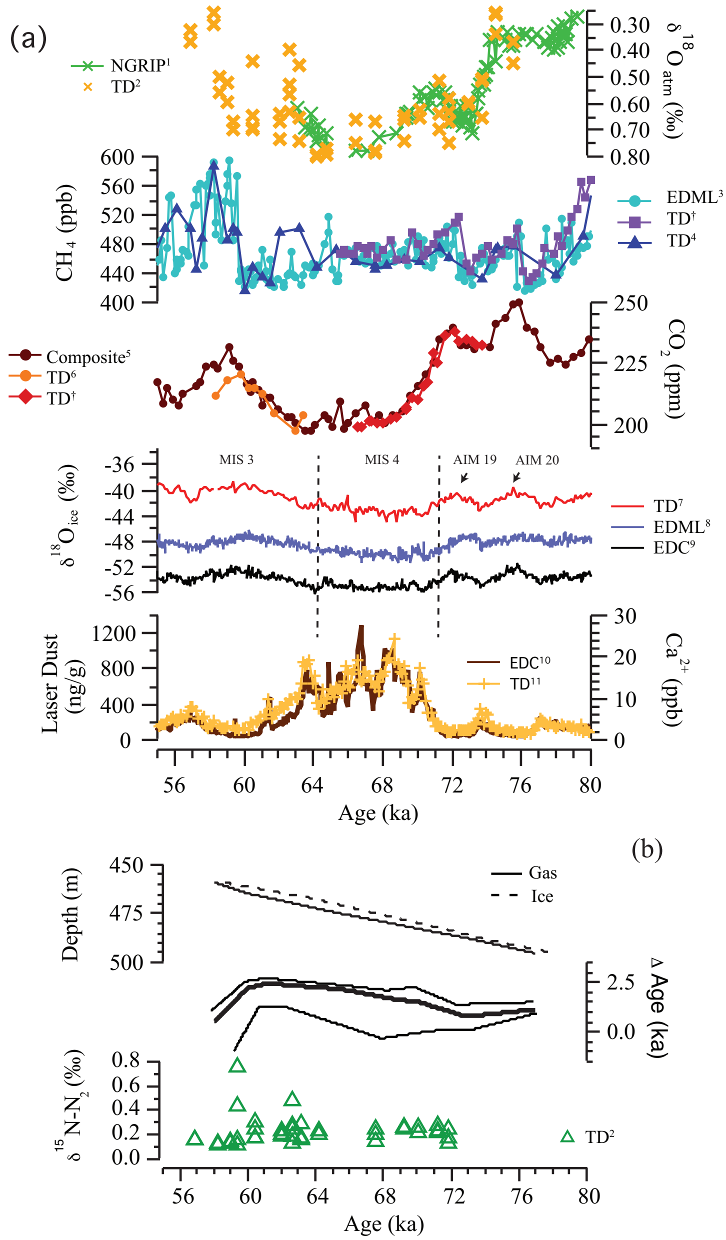

Figure 4 - (A) Measurements of trace gases, stable isotopes (of ice and O_2), and nss-Ca^{2+} from the Taylor Dome ice core on new gas and ice age scales synchronized with AICC 2012. Ice cores are labeled as follows: NGRIP = North Greenland Ice Coring Project, TD = Taylor Dome, EDML = EPICA Dronning Maud Land, EDC = EPICA Dome C. Composite CO_2 includes measurements from EDC, EDML, and Talos Dome. Data sources are indicated with superscripts: (1) (Landais et al., 2007), (2) (Sucher, 1997),

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-53
Manuscript under review for journal Clim. Past
Discussion started: 17 May 2018

(3) (Schilt et al., 2010), (4) (Brook et al., 2000) (5) (Bereiter et al., 2015), (6) (Indermuhle et al., 2000), (7) (Steig et al., 2000), (8) (EPICA Community Members, 2010), (9) (Jouzel et al., 2007), (10) (Lambert et al., 2008), (11) (Mayewski et al., 1996), † indicates this study. (B) Ice age and gas age vs. depth models were constructed from tie points in Table 3 and Table 4. Calculated Δage (= ice age – gas age) and $\delta^{15}N-N_2$ are on the gas age scale. Maximum and minimum Δage were determined based on the error estimation described in the text. The three $\delta^{15}N$ points > 0.4 ‰ are likely artifacts due to a known issue with water in the mass spectrometer and should be disregarded.

Table 3 – Tie points relating Taylor Dome depth to gas age on the AICC 2012 timescale.

Depth (m)	Gas Age (ka)	Parameter	Age Range (ka)	Description
459.4	58.2	CH_4	58.0-59.3	DO 16/17
464.6	60	CH_4	59.85-60.7	Midpoint DO16/17 rise
474.95	65.5	CH_4	65.46-67.9	Value match before DO 18
487.83	73.1	CH_4	72.6-73.6	Low point before DO 19 rise
493.5	76.05	CH_4	75.8-76.2	Low point before DO 20 rise

Table 4 - Tie points relating Taylor Dome depth to ice age on the AICC 2012 timescale.

Depth (m)	Ice Age (ka)	Parameter	Age Range (ka)	Description
456.3	56.89	Ca^{2+}	56.4-57.25	Small peak after MIS 4
466.8	63.61	Ca^{2+}	63.5-63.75	Peak near end of MIS 4
479.9	70.11	Ca^{2+}	70.05-70.3	Peak at beginning of MIS 4
482.85	71.65	Ca^{2+}	71.5-72.1	Low point before MIS 4
487.3	73.59	Ca^{2+}	73.5-73.68	Small peak before MIS 4
493.5	77.1	Ca^{2+}	76.96-77.28	Small peak before MIS 4