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Evidence for substantial accumulation rate variability in Antarctica during the Holocene, through synchronization of CO_2 in the Taylor Dome, Dome C and DML ice cores

Eric Monnin[a,*], Eric J. Steig[b], Urs Siegenthaler[a], Kenji Kawamura[a], Jakob Schwander[a], Bernhard Stauffer[a], Thomas F. Stocker[a], David L. Morse[c], Jean-Marc Barnola[d], Blandine Bellier[d], Dominique Raynaud[d], Hubertus Fischer[e]

[a] *Climate and Environmental Physics, Physics Institute, University of Bern, Bern, Switzerland*
[b] *Quaternary Research Center and Department of Earth and Space Sciences, University of Washington, Seattle, WA, USA*
[c] *Institute for Geophysics, University of Texas, Austin, TX, USA*
[d] *CNRS Laboratiore de Glaciologie et de Géophysique de l'Environnement (LGGE), Grenoble, France*
[e] *Alfred-Wegener-Institut für Polar- und Meeresforschung, Bremerhaven, Germany*

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Abstract

High resolution records of atmospheric CO_2 concentration during the Holocene are obtained from the Dome Concordia and Dronning Maud Land (Antarctica) ice cores. These records confirm that the CO_2 concentration varied between 260 and 280 ppmv in the Holocene as measured in the Taylor Dome ice core. However, there are differences in the CO_2 records most likely caused by mismatches in timescales. Matching the Taylor Dome timescale to the Dome C timescale by synchronization of CO_2 indicates that the accumulation rate at Taylor Dome increased through the Holocene by a factor two and bears little resemblance to the stable isotope record used as a proxy for temperature. This result shows that different locations experienced substantially different accumulation changes, and casts doubt on the often-used assumption that accumulation rate scales with the saturation vapor pressure as a function of temperature, at least for coastal locations.

Keywords: ice core; CO_2; Dome C; Taylor Dome; timescale; accumulation rate

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1. Introduction

For the interpretation of information obtained from ice cores, an accurate timescale is a prerequisite. There exist many different approaches for dating ice cores, such as counting annual layers or modelling of ice flow. Another approach is to determine the age by comparing concentrations of trace gases that, due to their long atmospheric residence time, should be essentially identical in all cores. For some purposes, an absolute timescale may not be needed but reliable cross-dating between two records is sufficient. One successfully

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* Corresponding author. Tel.: +41-31-631-44-66; fax: +41-631-87-42.
E-mail address: monnin@climate.unibe.ch (E. Monnin).

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applied method is the matching of methane among Antarctic and Greenland ice cores [1,2]. Methane is well suited for timescale synchronization through the last glacial because it is globally well mixed and exhibits rapid and large changes. For the Holocene, methane synchronization between ice cores is less suitable because this is a time period where methane shows a limited number of significant sharp changes [3].

CO_2, which is also a well-mixed trace gas, shows variations during the Holocene with similar relative amplitudes and similar rates of change as methane but at different times [4,5]. CO_2 variations can therefore be used as an additional tool to synchronize timescales. In this paper, we use this method to synchronize the timescales of the Dome C, DML and the Taylor Dome ice cores from Antarctica, as high resolution CO_2 records of good quality measured in the same lab with the same procedure are available for each of these cores.

2. Measurements

Here we present records from the Dome C (75°06′ S, 123°21′ E) and DML (Dronning Maud Land, 75°00′ S, 00°04′ E), ice cores, both drilled in the framework of the "European Project for Ice Coring in Antarctica" (EPICA). We increased the resolution of the Dome C data published in Flückiger et al. [5] by measuring CO_2 on an additional 498 samples at 83 different depth intervals, between 99 and 416 m depth, covering the period from 0 to 11.2 ky BP (thousand years before present, where present is chosen as AD 1950). In the DML ice core, CO_2 measurements were performed on 144 samples at 24 different depth intervals, between 170 and 450 m depth, covering the period from 1 to 6 ky BP. The period form 0 to 1 ky BP is covered by the data presented in Siegenthaler et al. [6]. For each depth level, six samples were measured on a 60–100 mm length interval. The mean 1σ reproducibility of the CO_2 measurements is about 1 ppmv. The analytical method is described by Monnin et al. [7].

Measurements of CO_2 on Dome C were also done in Grenoble at LGGE with a lower resolution and a different analytical technique than in Bern. These measurements generally agree with the data measured in Bern but show a larger scatter, especially for the second part of the Holocene period. These measurements will be discussed elsewhere. As we compare the Dome C and DML CO_2 measurements with those of Taylor Dome, we focus only on the Dome C and DML measurements performed in Bern with the same analytical technique as those of Taylor Dome. In any case, the inclusion of the Grenoble set of measurements would not change the conclusions of this paper.

The Dome C CO_2 record (Fig. 1) shows a decrease from a mean value of 265 ppmv between 11.2 and 10.0 ky BP to a mean value of 260 ppmv between 8.5 and 6.5 ky BP. After 6.5 ky BP, the CO_2 concentration increases to the preindustrial value of 280 ppmv. This increase does not appear to occur continuously, but rather in steps of up to about 5 ppmv in one to two centuries. The DML CO_2 record agrees quite well with the Dome C values with the exception of slightly higher values in the last millennium. Although the reason for this 1–2 ppmv discrepancy is still unknown, the values from DML in the last millennium may be more reliable than those from Dome C due to the higher resolution and the higher accumulation rate at DML (64 kg m^{-2} $year^{-1}$ compared with 25 kg m^{-2} $year^{-1}$ for Dome C).

A comparison with the CO_2 record from the Taylor Dome ice core on the timescale used in Indermühle et

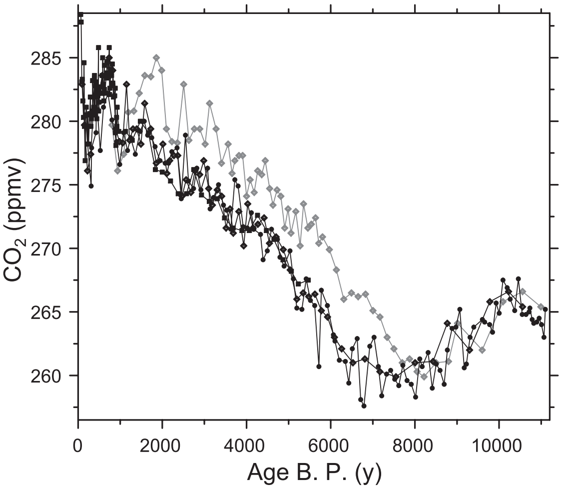

Fig. 1. CO_2 records over the Holocene. Squares: DML data. Dots: Dome C data. Diamonds: Taylor Dome data on the new timescale by matching the CO_2 records. Grey diamonds: Taylor Dome data on the timescale according to Brook et al. [20].

al. [4] shows that Taylor Dome CO_2 is about 6 ppmv higher than in Dome C between 7 and 5 ky BP. From 5 to 2 ky BP, the Taylor Dome record shows still higher CO_2 values than Dome C and DML, but by less than 5 ppmv.

3. Potential artefacts

One problem concerning the CO_2 measurements is the possibility of CO_2 enrichment by chemical reactions between impurities in the ice cores. The most likely sources are acid-carbonate reactions and the oxidation of organic compounds [8–10]. Generally, it is assumed that artefacts are more likely in relatively warm ice. Detailed high resolution measurements over a full 55 cm length of Dome C ice (mean annual surface temperature: $-54.5\,^{\circ}C$) showed that in the Holocene, the scattering of the CO_2 results in this core is slightly higher than the analytical reproducibility, indicating the existence of some artefacts caused by processes in the ice sheet or during the extraction procedure. However, these deviations are thought to be less than 1% [11]. The surface temperature of Taylor Dome is $-42\,^{\circ}C$, and the question arises whether the values of this core in the time interval 7.5 to 2 ky BP are higher due to an artefact or mismatches in the timescales. There are several arguments against elevated values due to artefacts:

- Neighboring samples of Taylor Dome samples show little scatter, which indicates generally very low artefacts.
- CO_2 values show a constant offset during several thousand years and not sporadic high values which are typical for artefacts.
- The Ca^{2+} concentration, which is an indicator for carbonate concentrations, over the time interval in question does not show anomalously high values [12].

Another argument supporting the hypothesis of an offset in the respective timescales is the shape of the stepwise increase of the CO_2 concentration. The CO_2 increase is often interrupted by plateaus at the same CO_2 levels in both records. The most evident example is the plateau around 266 ppmv recorded between 6 and 7 ky BP in the Taylor Dome ice core and between 5 and 6 ky BP in the Dome C ice core.

We conclude that an offset of the timescales is much more probable than an artefact causing too high CO_2 concentrations in the Taylor Dome ice core.

4. Chronologies

We are now interested in cross-dating both the gas and the ice timescales for the Dome C and Taylor Dome cores. For the Dome C ice core a timescale (*EDC1*) was constructed by Schwander et al. [13]. The absolute uncertainty of the timescale for the ice is estimated to ± 10 years back to 700 years and ± 200 years back to 10 ky BP. Back to 700 years, the timescale was matched with historically documented and other well-dated volcanic signals. Between 700 and 7100 years, the volcanic signals were matched to the Vostok GT4 timescale [14], which during this interval has been validated by comparison of ^{10}Be [15] with the tree ring record of ^{14}C. This comparison reveals an agreement of the Vostok GT4 timescale with the dendrochronology within ± 100 years (Raisbeck, personal communication). From 7.1 through 11.2 ky BP, a flow model was adjusted to fit the end of the Younger Dryas (YD).

At a given depth, the age of the air is younger than that of the surrounding ice. This time difference, due to the fact that air bubbles in the ice are formed at the bottom of the firn layer, is referred to as Δage. The depth at Dome C corresponding to the end of YD in the ice age was determined by comparing the Byrd and Dome C stable isotope records and identifying the YD in the Byrd ice core by using the methane record and the Byrd Δage value (see Schwander et al. [13] and references therein). The flow model was adjusted by assuming that accumulation scales with the saturation vapor pressure as a function of temperature (inferred from the deuterium content in the ice). Adjustments (13%) to this relationship were used to produce the best fit to both the Vostok GT4 comparison and the tie point associated with the end of the YD.

The value of Δage in Dome C is about 2000 years in the Holocene and has an estimated uncertainty of about 10%. The estimated error is therefore about 200 years for the ice age and 200 years for the Δage over the Holocene. An independent way to validate these error estimates is to compare the Dome C methane record of Flückiger et al. [5] with those of GRIP and GISP2 [3,16,17], two Greenland ice cores dated by counting annual layers. As already mentioned, the Holocene methane records show only a few prominent features. One of these is the methane decrease recorded in the GRIP ice core around 8.2 ky BP, associated with the δ^{18}O decrease. This methane decrease is strongly attenuated in the Dome C ice core due to the gradual enclosure process in the ice. However, a methane minimum can be recognized in the Dome C ice core a little later, indicating that the Dome C gas age timescale is probably younger than GRIP by about 25 ± 50 years at this event [18]. Another prominent feature is the Younger Dryas/Holocene transition with its sharp methane concentration change. In the Dome C ice core, the methane increase is recorded around 11.2 ky BP [7]. The same methane increase is recorded at 11.55 ky BP [17] in the GISP2 ice core and 11.6 ky BP in the GRIP ice core [16]. The Dome C gas age appears therefore to be about 350 years younger than the GRIP and GISP2 gas ages. This deviation is in the order of magnitude of the combined uncertainty of both 200 years for the ice age and Δage indicated by Schwander et al. [13].

No published timescale is available yet for the DML ice core. We construct a tentative timescale by adjusting the DML timescale to Dome C by comparing the records of electrical conductivity of both cores. To obtain a gas age timescale, we assume a constant Δage value of 825 years.

The Taylor Dome CO_2 record presented by Indermühle et al. [4] used a gas age timescale obtained by matching the Taylor Dome methane and $\delta^{18}O_{atm}$ record to its well-dated GISP2 counterpart [19]. A more recent version of the gas age timescale, presented in Brook et al. [20], results in even more pronounced differences between the CO_2 records of Taylor Dome and Dome C. Both timescales were done by visually matching common inflection points in the methane and $\delta^{18}O_{atm}$ records. Between these points, the timescale was derived by simple interpolation. For clarity, we refer in the discussion which follows only to the more recent gas age of Brook et al. [20] for the comparisons with our new timescale.

For the Taylor Dome ice age, the st9810 timescale from Steig et al. [12] is commonly used. This timescale was created independently from the Brook et al. [20] gas age timescale. For the Holocene, a 2-D finite element glacier flow model [21,22] was applied. The accumulation rate was assumed to be constant over the Holocene and adjusted to match a tie point associated with the end of the Younger Dryas. A key assumption for both the Taylor Dome [12] and Dome C [13] ice timescales is that the accumulation rate either did not change in the Holocene or changed as a simple function of temperature. As we will show, it does not appear that either of these assumptions is valid, and that both timescales may therefore need to be adjusted to obtain the best absolute dating. However, because the link of the Dome *C EDC1* timescale [13] to the Vostok GT4 timescale [14] is supported by the comparison with dendrochronology (i.e. ^{14}C) up to 7 ky, the Taylor Dome timescale in this time period probably has a greater uncertainty than the Dome C timescale. Therefore, for the purposes of obtaining the best relative dating, we have chosen to adjust the Taylor Dome record to obtain a match to the *EDC1* timescale [13] for Dome C.

5. Synchronization of the CO_2 records

We begin by adjusting the gas timescale for Taylor Dome to that of Dome C using CO_2. As the CO_2 record in the Holocene does not often show very distinct features but rather stepwise increases of a few ppmv, we used three different methods for the synchronization to test the consistency of the results. The first synchronization was done by matching the entire record visually. For the second synchronization, we visually matched control points at areas with prominent features and interpolated with a spline between these points. In the third synchronization, an automated wiggle matching procedure was used, which randomly varies the timescale and searches for maximum correlation. This program was slightly modified from that of Schwander et al. [23]; the match was optimized using a mix between maximum correlation and minimum deviation between the records. The two first methods have the disadvantage of being subjective; the third method is objective and reproducible. Despite this advantage, automated methods are not necessarily more accurate than visual methods [24]. Because it is difficult to evaluate which of these methods is the most reliable, we suggest to use the mean of all three. With this approach, we were able to increase the correlation coefficient of the Taylor Dome CO_2 record with the Dome C and DML records from $r=0.92$ for the Brook et al. [20] gas age to 0.98 for the CO_2 synchronized timescale. The resulting depth–gas age relationship is plotted in Fig. 2.

The automated wiggle-matching procedure provides an estimate of the uncertainty of the synchronization. A statistical evaluation using the scatter of the results with a correlation of $r>0.9$ over any window of 20 successive Taylor Dome CO_2 measurements indicates a mean uncertainty of about 200 years, increasing to 300 years at 10 ky BP [23] (see Fig. 2). An alternative estimate of the uncertainty is obtained from the degree of agreement between the three methods. The maximum deviation between the automated and visually matched methods, also plotted in Fig. 2, is in agreement with the statistical evaluation of the automated wiggle-matching, except for ages around 7 ky BP where differences are up to 450 years. On this basis, we estimate the uncertainty of the synchronization to be about 250 years from 0 to 6 ky BP, increasing to about 500 years for ages older than 6 ky BP.

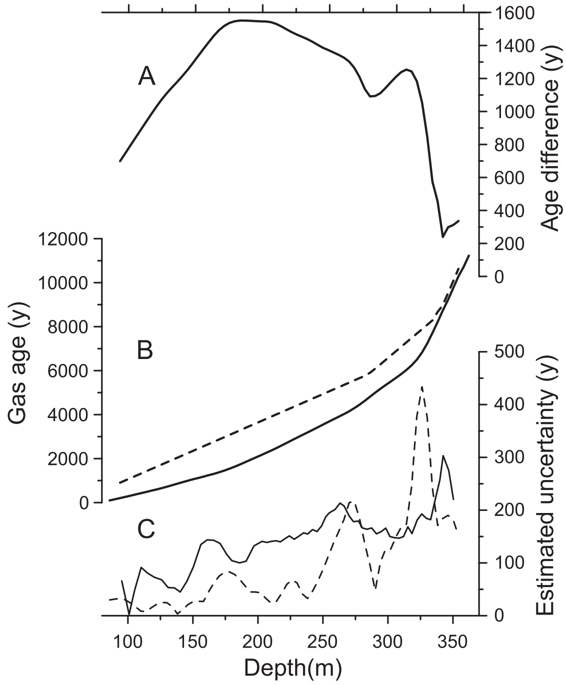

Fig. 2. (A) Age offset between the Taylor Dome timescale by Brook et al. [20] and this work. (B) Black line: depth–gas age relationship of the Taylor Dome ice core determined by synchronization with Dome C. Dashed line: depth–gas age relationship of the Brook et al. [20] timescale. (C) Uncertainty estimation of the synchronization. Black line: statistical evaluation considering all results with a correlation coefficient $r>0.90$ (see text). Dashed line: maximum difference between the automated and manual methods.

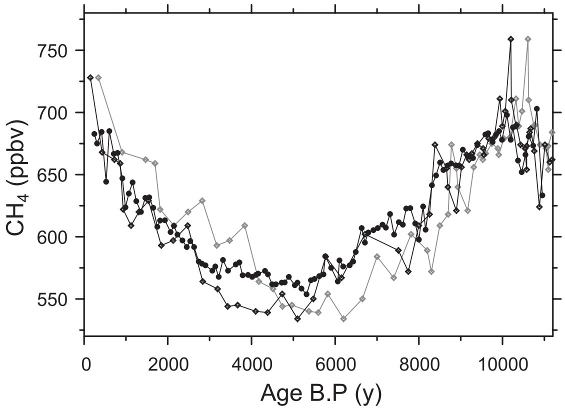

Fig. 3. Methane records over the Holocene. Dots: Dome C data. Diamonds: Taylor Dome data on the new timescale by matching the CO_2 records. Grey diamonds: Taylor Dome data on the timescale according to Brook et al. [20]. The methane data are from Flückiger et al. [5] and Brook et al. [20].

The age offset between the new CO_2 synchronized gas age for Taylor Dome and the Brook et al. [20] gas age increases from 800 years at a depth of about 100 m to over 1000 y between 120 and 330 m (corresponding to 7 ky BP on the new timescale), and decreases to values of about 300 years for the oldest part of the Holocene. The largest offset of 1550 years is observed at a depth of 190 m (see Fig. 2). The new timescale resulting from the CO_2 synchronization is therefore significantly younger for depths above 330 m corresponding to ages younger than 7 ky.

The Brook et al. [20] timescale was created using seven control points in the Holocene. Only one of these control points—at 5.9 ky (the rest are older than 8 ky), contributes significantly to the inconsistency between the timescales. This control point was set by comparing the Taylor Dome methane record with that of GISP2. Because real differences in methane concentrations may exist between the hemispheres, a comparison between Antarctic records is more reliable than a comparison of records from both hemispheres. The methane records of Dome C [5] and Taylor Dome are plotted in Fig. 3 for comparison. In particular, the Dome C Methane record does not suggest any particular feature around 6 ky that might be used to precisely assign a control point. Due to the shape and the coarse resolution of the methane curves, the ability to verify the accuracy of the synchronization is limited, but the methane records are certainly not in contradiction with the new CO_2 synchronized timescale. Although the synchronization was done by comparing only the CO_2 records, the correlation coefficient of methane is increased from $r = 0.80$ for the Brook et al. [20] timescale to $r = 0.92$ providing an independent check of the consistency of the synchronization. An enhanced resolution of the Taylor Dome methane record would be useful to further improve the precision of the synchronization, especially for the older part of the Holocene.

6. Ice timescale and accumulation rate calculations

To obtain an ice age timescale from the new gas ages for Taylor Dome, calculation of the Δage value is needed. Δage values can be calculated with a firn densification model, if the temperature and snow accumulation rate are known. Because snow accumulation rates are not known a priori, this poses a difficulty that is usually resolved by inferring accumulation rate from some other measurement. Here we use an alternative approach, which minimizes the mismatch between accumulation rates obtained from two different methods. The derivative of the gas age timescale is used to obtain an initial layer thickness profile, which is corrected for layer thinning (using flow models [21,22]) to obtain an initial accumulation rate estimate. This estimate is used to calculate Δage, using the Herron–Langway empirical densification model [25] with stable isotopes as the proxy for temperature. From this, an ice timescale is calculated directly by the addition gas age + Δage = ice age, and a new accumulation rate is obtained. An optimization routine, which is described in detail elsewhere (Steig, in preparation) is utilized to minimize the mismatch between the two accumulation rate estimates. Although this problem has no unique solution, we use a simple smoothness criterion (accumulation rate cannot vary more than 5% from point-to-point in 100 year increments) and allow for a mismatch of up to ± 200 years to obtain a set of normally distributed 100 solutions (standard deviation ± 180 years), and use the mean of these. As an additional constraint, we use the independent ice timescale of Hawley et al. [26] inferred from vertical strain rate measurements in the firn for the upper 130 m of the Taylor Dome core. The resulting accumulation rates, as well as Δage and ice age values are shown in Fig. 4.

Our calculations suggest that accumulation at Taylor Dome increased from a value of about 0.03 m ice equivalent per year between 8 and 11.5 ky BP to a mean value of about 0.06 m ice equivalent per year

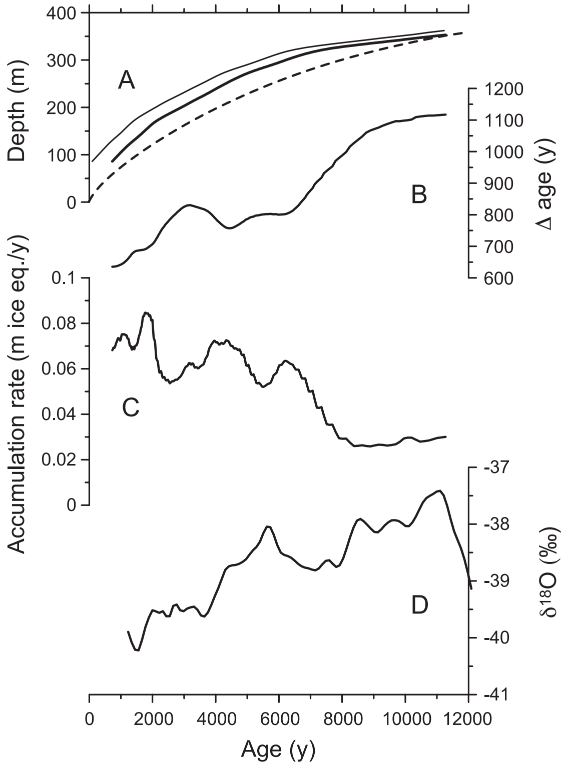

Fig. 4. (A) Depth–age relationship of thin line: Taylor Dome gas age determined by CO_2 synchronization with Dome C. Thick line: ice age calculated from the CO_2 synchronized gas age (see text). Dashed line: st9810 ice age according to Steig et al. [12]. (B) Calculated Δage values of the CO_2 synchronized timescale (see text). (C) Calculated accumulation rates at Taylor Dome according to the CO_2 synchronized timescale (see text). (D) Spline with a cut-off frequency of 750 years through the Taylor Dome oxygen isotope record as a proxy for local temperature [2,12].

from 6 to 2 ky BP. The record shows also smaller accumulation rate variations on a millennial timescale from 6 ky BP on.

Possible rapid or short duration changes in accumulation rates are smoothed out in the gas age timescale due to the gradual enclosure process at the bottom of the firn layer. This implies that even small short-term irregularities in the gas age may represent large short-term accumulation rate changes. On the other hand, small irregularities in the gas age may also arise from uncertainties in the synchronization. Our method is therefore not suited for detecting fast short-termed accumulation rate changes. We therefore consider these millennial scale variations as uncertain. The long-term trend, however, is a robust result of our calculations.

The change in slope of the long-term trend of the accumulation rate around 6 ky BP is largely dependent on the accuracy of the timescale at this age. At 6 ky BP, the potential uncertainty sources are estimated as follows: Dome C ice age ± 200 years, Dome C Δage ± 200 years, synchronization uncertainty ± 250 years and Taylor Dome Δage calculations ± 250 years. These uncertainties can clearly not account for the difference between the new timescale and st9810 of about 1700 years at 6 ky BP.

For ages older than 8 ky BP, the error in the Dome C gas age may be larger, due to a lack of independent control points. The CO_2 synchronization also has a larger error for ages older than 6 ky BP due to the smaller resolution and the shape CO_2 of the record. As mentioned above, the Dome C timescale is a little too young at the Younger Dryas. However, correcting this according to the GISP2 timescale would result in an even lower accumulation rate at Taylor Dome between 8 and 11.5 ky BP. Importantly, the long-term accumulation rate changes inferred for Taylor Dome do not depend on the assumption that the Dome C timescale is strictly correct. We therefore conclude that the mean accumulation rate between 11 and 6 ky BP was significantly lower than between 6 and 1 ky BP.

The question arises if the deduced accumulation rates could not be influenced by errors in the assumed thinning deduced from flow models. One independent way to check our results is the comparison with the isotopic composition of nitrogen ($\delta^{15}N$ of N_2) [27] enclosed in the bubbles. Due to gravitational fractionation, $\delta^{15}N$ is an indicator for minimum firn thickness (bubble close off depth) [28]. There is an uncertainty of about 10 m in this calculation depending on the thickness of the uppermost porous layers of the firn where gases are well mixed with the atmosphere. Accumulation changes of a factor two would have a significantly larger impact on the close-off depth. Fig. 5 compares close-off depth calculated from $\delta^{15}N$ and from the Herron–Langway densification model [25], showing that both indicate a significant change around 6 ky. The $\delta^{15}N$ calculations suggest an even shallower close-off depth at ages older than 8 ky, which may indicate one of the following:

- The advective zone is deeper prior to 8 ky. This is plausible, because at Taylor Dome today, areas with lower accumulation rate show permeable depth hoar formation to depths of several meters [12].
- The accumulation rate prior to 8 ky is lower than we calculated, supporting our primary conclusion that accumulation rates have significantly increased through the Holocene.
- There is a smaller amount of dynamic thinning than calculated [21,22]. We consider this unlikely,

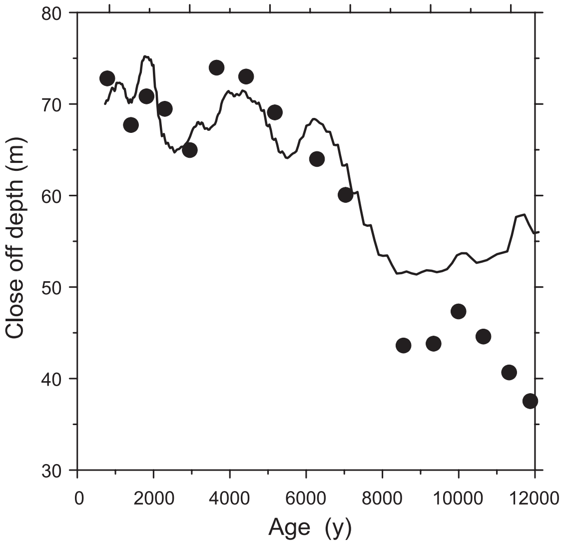

Fig. 5. Comparison of close-off depths calculated from the Herron–Langway densification model and from $\delta^{15}N$ measurements [27]. For Herron–Langway, a bubble-close-off density of 0.82 g/cm^{-3} is used; for $\delta^{15}N$, an advective layer thickness of 5 m is used.

> but if it is correct, then we would have overestimated accumulation rate in the early part of the record, and that would also be consistent with our primary conclusion.

In summary, the $\delta^{15}N$ data confirm the results based on the synchronization and it may suggest even lower accumulation rates in the early Holocene. The accumulation rate change of about a factor two is unexpected, on the basis of most previous estimates of accumulation rate change in the Holocene, which generally show little or no trend. A notable exception is the Law Dome cores [32], which shows a Holocene trend of similar magnitude. Thus, in at least two near-coastal locations, significant changes in precipitation or ablation have occurred during the Holocene. Importantly, the accumulation rate increase at both these sites corresponds with a long temperature decrease, as recorded both in the temperature proxies $\delta^{18}O$ and δD [2,12], and from borehole temperature measurements (G.D. Clow, personal communication). This is in contradiction with the strong correlation of the accumulation rate with $\delta^{18}O$ values found in the Greenland records for the last glacial period [29] (though not for the Holocene [30]) and inferred for most other Antarctic ice cores. It is expected that at near-coastal sites like Taylor Dome and Law Dome, snowfall may be dependent on non-temperature linked effects like the moist–air cyclonic activity or sea ice conditions [12]. A decoupling of temperature from accumulation has also been reported in some parts of the Siple Dome [31] ice cores. The very strong decoupling of accumulation from temperature suggested by our new Taylor Dome timescale, however, is larger than might have been expected a priori and raises questions about the validity of other ice core timescales, as one of the often-used assumptions is that the accumulation rate depends on the saturation vapor pressure over the ice [13,14,33,34].

7. Conclusions

Detailed measurements of the CO_2 concentration on the Dome C and DML ice cores exhibit differences up to 6 ppmv to the measurements of Indermühle et al. [4] from Taylor Dome. We attribute this disagreement to differences in the respective timescales. A new chronology for the Taylor Dome ice core established through CO_2 synchronization reveals that the accumulation has changed substantially during the Holocene, with a long-term increase that shows little relation with the temperature history. Many timescales using ice flow models, especially those for Antarctic cores, are based partly on the assumption that the accumulation rate varies as the saturation vapor pressure over ice and is therefore a function of local temperature. This assumption is clearly not valid at Taylor Dome, and is likely to be substantially incorrect at other sites as well, notably in locations such as Law Dome and Siple Dome, which are at relatively low elevation and near coastal regions. At more-inland sites such as Dome C, independent validation of the ice core timescales suggests that the assumption is reasonable; however, it is unlikely to be strictly valid and caution is urged in applying it.

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