Duration of Greenland Stadial 22 and ice-gas Δage from counting of annual layers in Greenland NGRIP ice core.

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Abstract

High-resolution measurements of chemical impurities and methane concentrations in Greenland ice core samples from the early glacial period allow the extension of annual-layer counted chronologies and the improvement of ice-gas Δages essential to the synchronization of ice core records. We report high-resolution measurements of a 50 metre section of the NorthGRIP ice core and corresponding annual layer thicknesses in order to constrain the duration of the Greenland Stadial 22 (GS-22) between Greenland Interstadials (GIs) 21 and 22, for which inconsistent durations and ages have been reported from Greenland and Antarctic ice core records as well as European speleothems. Depending on the chronology used, GS-22 occurred between approximately 89 (end of GI-22) and 83 ky b2k (onset of GI-21). From annual layer counting, we find that GS-22 lasted between 2696 and 3092 years and was followed by a GI-21 pre-cursor event lasting between 331 and 369 years. Our layer-based counting agrees with the duration of stadial 22 as determined from the NALPS speleothem record (3250±526 y) but not with that of the *GICC05modelext* chronology (2620 y) or an alternative chronology based on gas-marker synchronization to EPICA Dronning Maud Land ice core. These results show that *GICC05modelext* overestimates accumulation and/or underestimates thinning in this early part of the last glacial period. We also revise the possible ranges of NorthGRIP Δdepth (5.49 to 5.85 m) and Δage (498 to 601 y) at the warming onset of GI-21 as well as the Δage range at the onset of the GI-21 precursor warming (523 to 654 y), observing that $\delta^{15}N$ increases before CH_4 concentration by no more than a few decades.

1 Introduction

Ice core records are of great importance to paleoclimate studies due to their ability to archive several climate parameters in continuous, precisely dateable stratigraphic sequences. The year-round regularity and relatively high accumulation rate of snowfall in central Greenland has allowed determination of annual cycles in stable water isotopes, ions and dust back to 60 ky before 2000AD (b2k) (Svensson et al., 2008). Synchronization between ice core records is undertaken using a number of hemispheric or globally homogeneous signals, such as gases (e.g. Blunier and Brook, 2001; EPICA community members, 2006), their isotopic signatures (e.g. Severinghaus et al., 1998; Capron et al., 2010b) or large volcanic eruptions (e.g. Rasmussen et al., 2008; Parrenin et al., 2012). Inverse methods have been employed to produce consistent ice core chronologies combining relative and absolute chronological markers in several synchronized ice core records (Lemieux-Dudon et al., 2010).

The Greenland Ice Core Chronology 2005 (*GICC05*), of which the most recent extension is *GICC05modelext*, is based on counting of annual strata in ice cores back to 60 ky b2k. This common chronology for multiple Greenland ice cores employs annual layer counting of stable water isotopes from the surface to 7.9 ky b2k, annual layer counting of impurities and visual stratigraphy (greyscale images related to microparticle density) strata back to 60 b2k (Svensson et al., 2005; Svensson et al., 2008), and an ice-flow model (*ss09sea06bm*) chronology back to 123 ky b2k (Wolff et al., 2010). *GICC05modelext* offers the paleoscience community a chronological framework for the duration of the Holocene as well as the last glacial period, for which 25 stadial-interstadial oscillations have been identified based on the oxygen isotope ratio in ice ($\delta^{18}O_{ice}$) (NGRIP members, 2004).

The use of Greenland Interstadial (GI) and Greenland Stadial (GS) nomenclature is an attempt to standardize the description of Greenland millennial-scale temperature oscillations first known as Dansgaard-Oeschger (DO) events. The first numbering of DO events employed low-resolution $\delta^{18}O_{ice}$ record from the GRIP ice core, which failed to capture rapid, small-scale temperature changes now described as “precursor” and “rebound” events (Capron et al., 2010a). The assignment of precursor events to either the GI following or GS preceding has not yet been standardized, and hence can contribute to the discrepancies between the durations calculated for GS-22; it is important that authors specify whether they include or exclude precursor events from their evaluations of stadial durations. For example, Capron et al., (2010a) evaluated the duration of GS-22 from the mid-point of the $\delta^{18}O_{ice}$ transition at the end of GI-22, to the initial increase of $\delta^{18}O_{ice}$ at the onset of the GI-21 precursor event. In this work, we follow the same approach for evaluating the duration of GS-22. Where possible, we describe durations for both GS-22 and the GI-21 precursor period, which we define here as the duration from the onset of precursor warming (i.e., the end of GS-22 proper) to the mid-point of the $\delta^{18}O_{ice}$ transition in the subsequent GI-21 onset. With the recent development of high-resolution techniques for analysis of water isotopologues (Gkinis et al., 2011), impurities (Bigler et al., 2011) and methane content (Stowasser et al., 2012) in ice cores, a systematic nomenclature for identifying stadial and interstadial events and their substructure is clearly required.

Recent studies of Antarctic ice cores and European speleothems have identified discrepancies in the duration of GS-22, suggesting that the current model-based duration is underestimated. *GICC05modelext* indicates a GS-22 duration of 2620 years, from 87680 to 85060 y b2k, with a GI-21 precursor duration of 300 years (Wolff et al., 2010). Capron et al., (2010b) investigated the duration of Antarctic temperature oscillations in the EPICA Dronning Maud Land (EDML) ice core over the same time period and observed that the Antarctic Isotope Maxima that correspond to each set of Greenland stadial-interstadials (Fig. 1), which are characteristic of the thermal bipolar seesaw, were misaligned for GS-22. Aligning the EDML and NorthGRIP (NGRIP) ice core records by measurements of oxygen isotope ratios in O_2 ($\delta^{18}O_{atm}$) and CH_4 concentrations in the air trapped in the ice, they observed that the duration of GS-22 (and warming of the consequent Antarctic Isotope Maxima, AIM21) was discrepant with the linear relationship between GS duration and Antarctic warming proposed by EPICA community members (2006). The most recent indication of an underestimation of the duration of GS-22 in *GICC05modelext* is based on radiometrically-dated speleothems from the Northern Alps (Boch et al., 2011). Oxygen isotopes were used to identify the cold and warm stages that correspond to the Greenland stadials and interstadials in the NALPS speleothem record, which were compared to *GICC05modelext*. Based on the speleothem record, the duration of stadial 22 was 3250±526 (2σ) y. The exact duration of the stadial will likely be different in the speleothem and Greenland records due to possible variable lags and different criteria used for defining event boundaries, but we assume that these effects influence the duration estimate by an amount significantly smaller than the duration uncertainties. High-resolution analytical techniques allow the generation of an annual-layer counted chronology that can help to resolve the discrepancies described here.

Continuous flow analysis (CFA) techniques have been developed to improve the reliability and resolution of measurements of ice core impurities (e.g. Röthlisberger et al., 2000; Kaufmann et al., 2008; Bigler et al., 2011). For most analytes, they are replacing the traditional ion chromatographic technique and offering the potential for coupling to online measurements of methane (Stowasser et al., 2012) and water isotopologues (Gkinis et al., 2010). The improved resolution of CFA allows the possibility of direct determinations of annual layer thicknesses in Greenland ice back to the inception of the last glacial climate period (Svensson et al., 2011). Techniques for determination of various climate parameters at high resolution have also been applied to the study of timing and duration of various climate proxies during glacial (Steffensen et al., 2008) and GS terminations (Thomas et al., 2009).

Here we revise the duration of GS-22, based on the high-resolution measurement of insoluble dust particles, ionic impurities and visual stratigraphy in the NGRIP ice core. This technique offers the resolution of annual layers of <1 cm (Bigler et al., 2011), sufficient for the counting of annual layers during GS-22 and adjacent GIs. Combined with continuous measurements of CH_4 concentrations, we refine the ice depth-gas depth (Δdepth) and ice age-gas age (Δage) differences at this depth of the NGRIP record. This technique opens the potential for further refinement of *GICC05modelext* by evaluating annual layers and rapid gas transitions in the deepest sections of Greenland ice cores and synchronizing them with corresponding transitions in Antarctic ice cores.

2 Experimental

2.1 Ice core samples

Samples were obtained from the NorthGRIP ice core drilled in Northwest Greenland between 1997 and 2004 (NGRIP members, 2004). The samples correspond to the depth range 2679.05-2729.65 m of which only two 55 cm sections were unavailable (depths 2682.45-2682.90 and 2684.00-2684.55 m). A 35 x 35 mm section was cut for CFA analysis from the remaining "archive" piece. Optical line-scan images of the full ice core cross-section were collected at the drilling site (Svensson et al., 2005). $\delta^{18}O$ data were used to evaluate GS and GI events in the NGRIP (Wolff et al., 2010) and NALPS (Boch et al., 2011) records. As mentioned previously, we define GS-22 here as the cold Greenland stadial period occurring from the mid-point of the $\delta^{18}O$ transition at the end of GI-22, to the onset of the warming ($\delta^{18}O$ increase) of the GI-21 precursor event.

2.2 Measurements

The CFA system used for the measurements has been described by Bigler et al., (2011) and will be summarized here. The samples were melted on an aluminium melthead with a square inner sampling section (26 mm x 26 mm). A constant ice melting rate of 1.5 cm/minute produced meltwater at a rate of 8.4 mL/minute, of which 6 mL was directed to the analytical channels. The remaining 2.4 mL/minute was used to flush a sealed debubbler to ensure effective removal of air from the CFA analytical channels. The overflow air was delivered to a cavity ring-down spectrometer (Picarro Inc., CFADS36 $CO_2/CH_4/H_2O$ analyzer) for continuous measurements of methane concentrations (Stowasser et al., 2012). The debubbled meltwater was distributed to various analytical channels where continuous measurements of insoluble dust particles (>1.0 μm diameter), electrolytic conductivity, sodium and ammonium were conducted.

2.3 Layer-counting technique.

The technique used for layer counting is identical to the one used for the glacial part of *GICC05modelext* (Svensson et al., 2008). The parameters used for assignment of annual cycles included visual stratigraphy, electrolytic conductivity and insoluble dust particle concentration. Annual layers in sodium were not observed due to diffusion in the ice as well as the limited sampling resolution of ~3.5 mm for this analyte, compared to ~1.5 mm for electrolytic conductivity and ~3 mm for ammonium. Annual cycles in ammonium were identifiable only during the interstadials, when greater concentrations and thicker layers enabled their identification. It is worth noting that the two ions determined here have diffused to differing extents although the total electrolytic conductivity still shows reliable annual cycles. This suggests that other ions dominate the electrolytic conductivity of ice core meltwater: for example Moore et al. (1994) noted that acid species are most important for DC conductivity in solid ice whereas ammonium salts and probably chloride are also important for AC conductivity. Three people independently evaluated the data to produce three annual layer counting results. Where an annual layer was uncertain, it was assigned a value of ½ ± ½ years. The three independent counting results were then evaluated again to produce a consistent final counting result. The Maximum Counting Error (MCE) was calculated as the sum of the "uncertain" annual layers, and can be considered equivalent to a 2σ uncertainty interval (Andersen et al., 2006). For the sections where ice was not available to measure, the layer thickness has been linearly interpolated from the adjacent measured sections. A section of NGRIP ice demonstrating the assignment of annual layers is shown in Fig. 2.

3 Results

Concentrations of ice core impurities determined by high-resolution CFA were consistent with previously reported values for sodium, ammonium and conductivity in Greenland glacial ice (Bigler, 2004). We have determined average GS-22 (NGRIP depths 2687.5-2718 m) values of 8.6 ppb for ammonium, 70 ppb for sodium, 1.0 μS/cm for electrolytic conductivity and 56 x10^3 insoluble dust particles >1.0 μm/mL. While an impurity record for the whole NGRIP ice core is still in preparation, the results reported here are consistent with available records from GISP2 ice core (Mayewski et al., 1997) and NGRIP (Andersen et al., 2006;Ruth et al., 2002). From Fig. 2 it can be observed that diffusion has broadened the signals of sodium and ammonium such that annual layers cannot be identified based on these records at this depth in NGRIP. In the sections corresponding to warmer GI-21 and GI-22, thicker annual ice layers as well as greater concentrations of ammonium allowed the detection of annual peaks in this record.

Annual layer thicknesses (λ) were primarily determined from peaks in electrolytic conductivity, insoluble dust particles and visual stratigraphy. Figure 3 shows λ values reported here as well as those calculated by *ss09sea06bm*. The annual-layer counted λ values were consistently smaller than those calculated by the flow model. We assigned the onset and end of GS-22 as, respectively, depths 2718.0 and 2691.1 m, δ^{18}O values -40.12 and -39.82 and *GICC05modelext* ages of 87680 and 85060 ky b2k. Based on the annual-layer counting reported here, the duration of GS-22 was not less than 2696 and not more than 3092 years. These results are summarized in Table 1 and compared to previously reported durations for GS-22 and the GI-21 precursor period.

4 Discussion

4.1 Implications for Greenland ice core chronologies

The GS-22 duration range presented here (2696-3092 y) is inconsistent with that of *GICC05modelext* (2620 y) and indicates an overestimation of annual layer thickness in this part of the NGRIP ice core. *GICC05modelext* is constrained in the upper section by annual layer counting, but is essentially unconstrained for the lowest 650 m of ice: beyond the 60 ky limit of annual-layer counted strata, no independent chronological markers are currently available. Other lines of evidence exist to suggest that annual layer thicknesses are overestimated by the *ss09sea06bm* ice flow model: firn densification models used to reconstruct NGRIP temperatures from δ^{15}N measurements required annual snow accumulation rates to be decreased by 20% to produce a consistent result for GIs 9-17 (Huber et al., 2006); and annual layer counting of NGRIP Eemian and early glacial ice (Svensson et al., 2011) also suggest λ is partly overestimated in the deeper sections of NGRIP. Annual layer thicknesses are essentially dictated by two parameters - snow accumulation and vertical strain – thus an inaccurate evaluation of either parameter will contribute to an overall bias in λ. These findings indicate that *GICC05modelext* requires revision for the durations of GS-22 and probably also GI-21 and GI-22. To see if other deep sections of NGRIP are also affected by an inaccurate calculation of λ, we compare the record to an independent paleoclimate archive.

A number of precisely-dated speleothem records have recently been reported, allowing the possibility of comparing mid- and low-latitude climate variations to those recorded in the Greenland ice core records. Boch et al., (2011) reported a climate record of the Northern Alpine region of Europe, NALPS, produced from a stack of speleothems dated by high-resolution U-Th measurements. Although there are gaps in the record, it can be seen in Fig. 1 that NALPS replicates some of the DO oscillations observed in NGRIP ice, particularly the transitions at the onset and end of GS-21 (approximately 77 ky ago) and the entirety of GS-23 (approximately 105 ky ago). As demonstrated by Boch et al., (2011) the *GICC05modelext* and NALPS chronologies are in agreement within their uncertainties for most of the early glacial period between 77 and 115 ky. The two chronologies are discrepant between 78 and 103 ky, for which differences of 445 y (GI-23 onset) and 1010 y (GS-22 onset) were reported. As we demonstrate that *GICC05modelext* underestimates the duration of GS-22, we can thus conclude that the chronology also overestimates the duration of GI-22/GS-23/GI-23: otherwise it would not be consistent with the NALPS chronology for the early glacial period prior to GI-23. If *GICC05modelext* overestimates the snow accumulation rate at NGRIP – consistent with the findings of Huber et al. (2006) – it would possibly explain why there are too many years assigned to the GI-22/GS-23/GI-23 period, but it would not explain why too few years have been assigned to GS-22. The findings presented here offer a reliable dataset for tuning the *ss09sea06bm* model upon which *GICC05modelext* is based. In the absence of further constraints, we note that the overall assumptions underlying *ss09sea06bm* are robust: for the last 60 ky there was only a 705 y discrepancy between the model and the layer-counted GICC05 age scale (Wolff et al., 2010), so a similar discrepancy over the unconstrained period before 60 ky is not unreasonable.

4.2 Implications for Antarctic ice core synchronization

Constraints to *GICC05modelext* have also been proposed using isotopic markers and gas-based synchronization to the well-resolved EPICA Dronning Maud Land (EDML) ice core. Capron et al., (2010b) reported CH_4 concentrations, $\delta^{15}N$ and $\delta^{18}O_{atm}$ values in NGRIP and EDML ice, using these proxies to provide an alternative chronology for the deepest sections of NGRIP. Both CH_4 and $\delta^{18}O_{atm}$ are globally homogenous on decadal timescales while $\delta^{15}N$ has been demonstrated to respond to changes in the firn column temperature and thickness and thus can be employed to identify rapid warming events such as the onsets of GIs (Capron et al., 2010b). CH_4 and $\delta^{18}O_{atm}$ allow accurate synchronization between ice core gas records but uncertainties are introduced when transferring between gas and ice ages, denoted as Δage, for each ice core. Various models have been proposed to account for firn-column diffusion processes (summarized in Buizert et al., 2012) and it has recently been reported that impurity content also plays a significant role in firn densification processes (Hörhold et al., 2012).

Synchronization of ice cores through gas tracers is most precise when both records feature a small Δage, and hence high snow accumulation rate and temperature, such as at NGRIP and EDML. Earlier attempts to synchronize NGRIP with Vostok ice core experienced substantial difficulty due to the large Δage (up to 5000 y) associated with the low-accumulation site of Vostok (Landais et al., 2006). While gas tracers allow ice core records to be synchronized, they do not guarantee the accuracy of the ice-age chronology: thus a well-synchronized tiepoint should not be confused with a well-dated tiepoint. Transferring a chronology from one ice core to another involves three operations each with their uncertainties: the Δage conversion of the original timescale, then the synchronization of gas tracer tiepoints, then the Δage conversion in the synchronized record. We show here that the uncertainties involved in the transfer of the EDML chronology to *GICC05modelext*, in the case of GS-22, likely resulted in a less-accurate timescale than that which existed before.

The EDML-synchronized NGRIP chronology reported by Capron et al., (2010b), hereafter referred to as *NGRIP-EDML*, suggests a GS-22 duration at least 200 years greater than the maximum duration determined here. The *NGRIP-EDML* duration (3625±325 y) is greater than all other estimates for GS-22 shown in Table 1, and is only consistent with the upper limit of the NALPS-based duration of 3250±263 y. Regarding the absolute ages, *NGRIP-EDML* and *GICC05modelext* agree on the onset of GS-22 (respectively 87756±230 y b2k and 87680 y b2k) although the two chronologies are discrepant by 1 ky by the onset of GI-21. Interestingly, NALPS and *GICC05modelext* agree on the absolute age of the onset of GI-21 (respectively 85030±410 and 84760 y b2k) although the two chronologies are discrepant by 0.4 ky at the onset of GS-22. Now that the NALPS chronology is available as an independent age-control, it appears that the *NGRIP-EDML* synchronization produced an erroneously large duration for GS-22 by a combination of two factors: 1) the GS-22 onset was not shifted to an earlier age as would be expected for consistency with NALPS and 2) the GI-21 onset was shifted by 900 y to a later age which is now inconsistent with NALPS. We will attempt to explain the basis for these two factors: the first appears to result from the uncertainties associated with the gas tiepoints used for the synchronization; whereas the second suggests an inaccuracy in this part of the EDML chronology.

We note that different gas tracers with different uncertainties were used for the synchronization of EDML and NGRIP at the onset and termination of GS-22: two $\delta^{18}O_{atm}$ tiepoints were used at the onset of GS-22 whereas one $\delta^{15}N/CH_4$ tiepoint was applied at the termination of GS-22. The $\delta^{18}O_{atm}$ tiepoints used to fix the EDML ages of 84577 and 87627 y BP to NGRIP each carry large uncertainties (respectively 1220 and 570 y) – much larger than the differences between *GICC05modelext* and *NGRIP-EDML* at that age. On the basis of such poorly constrained tiepoints, there would be no need to adjust *GICC05modelext* to fit the existing EDML chronology. The opposite case applies for the $\delta^{15}N/CH_4$ tiepoint used at the termination of GS-22, which has a small uncertainty (150 y) and hence requires that the corresponding depth at NGRIP be fixed to the corresponding age of EDML: 83628 y b2k. In order to account for the well-constrained gas tiepoint at the GI-21 onset, the discrepancy in the resulting *NGRIP-EDML* chronology must result from inaccurate calculation of the Δages and/or inaccuracies in the EDML chronology. We demonstrate below that Capron et al. (2010b) applied an accurate estimate of the NGRIP Δage (approximately 500 y at the GI-21 onset) and hence the inconsistency in NGRIP-EDML must originate in either the Δage or absolute dating of this part of the EDML record.

The NGRIP Δage at the GI-21 onset can be constrained using CH_4 and $\delta^{15}N$ data and the annual-layer counted data reported here. In Fig. 4, we show CH_4 concentrations determined in high-resolution as well as the $\delta^{15}N$ values reported by Capron et al., (2010b). Due to solubility effects in the extraction lines the online CH_4 data was calibrated using contemporary values reported in the GISP2 ice core (Grachev et al., 2007). The start of the $\delta^{18}O_{ice}$ increase at the onset of the GI-21 was found at an NGRIP depth of 2687.8 m whereas the start of the associated CH_4 concentration increase can be attributed to the range 2693.3-2693.6 m (a gap in the CH_4 record precludes a more precise depth evaluation). This corresponds to a Δdepth range of 5.49 to 5.85 m and Δage range of 498 to 601 y, based on the annual-layer counting reported here. This evaluation was also undertaken for the onset of the GI-21 precursor warming and corresponding CH_4 concentration increase, as shown in Fig. 4, and found to have a Δage range of 523 to 654 y. These calculated Δage ranges are comparable to those employed by Capron et al. (2010b) in their *NGRIP-EDML* synchronization, as reported in their figure 5. Figure 4 also shows the relative phasing of $\delta^{15}N$ and CH_4 at the onset of GI-21, between NGRIP depths of 2693.3 m (latest possible CH_4 increase) and 2693.9 m (earliest possible $\delta^{15}N$ increase). The annual-layer counted chronology presented here shows that the maximum possible difference between $\delta^{15}N$ and CH_4 is 69±5 years, although the difference is most likely on the order of a few decades, consistent with the range of 25 to 70 years proposed by Huber et al. (2006).

Our revision of the duration of GS-22 gives further support to the thermal bipolar seesaw theory of heat exchange between the Northern and Southern hemispheres via oceanic circulation. Adapted from Capron et al., (2010a), Fig. 5 displays a strong correlation between the duration of Greenland cooling (GS duration) and the amplitude of Antarctic warming (temperature change during AIM events) for most of the past glacial period. The relationship is an empirical confirmation of the thermal bipolar seesaw model proposed by Stocker and Johnsen (2003) although it is apparent that GS-3, 19 and 22 are outliers from this relationship. It is of interest to note that the duration of GS-22 is only consistent with the linear fit in Fig. 5 if the duration of the GI-21 precursor period is not included. This suggests that the trigger of accelerating Atlantic meridional overturning circulation and associated heat transport from the Southern Ocean to the North Atlantic may lie with the climatic reorganization occurring during the precursor event, rather than that of the following GI onset. In summary, our findings suggest that the thermal capacity of the Southern Ocean heat reservoir is not exhausted during longer stadials such as GS-22 and instead implies that other climatic processes may have been responsible for the unexpectedly slight warmings of Antarctica during GS-3 and GS-19.

5 Conclusions

The development of a high-resolution CFA system has enabled the identification of thin (<1 cm) annual layers in early glacial ice from the Greenland NGRIP ice core. We demonstrate that during GS-22 the annual layer thickness λ calculated by the *ss09sea06bm* model is overestimated by approximately 10%, indicating a need to revise this section (including GIs 21 and 22) of the *GICC05modelext* chronology. The revised GS-22 duration presented here is not consistent with the gas-synchronized *NGRIP-EDML* chronology although it does agree with that of an independent U-Th dated speleothem record from the Northern Alps. Our proposed GS-22 duration is consistent with a strong correlation between GS duration and Antarctic warming as proposed by Stocker and Johnsen (2003). This work opens the possibility for annual layer counting in other polar ice cores for which absolute chronological markers are lacking. The combination of these data with high-resolution gas measurements in NGRIP will also help to constrain the Δage relationship in the ice core, thus allowing ice flow models and understanding of firn densification processes to be improved.

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Figure captions

Fig. 1. Comparison of temperature proxy records from Greenland, Europe and Antarctica. The Antarctic EPICA Dronning Maud Land (EDML) ice core $\delta^{18}O_{ice}$ record is shown in black (EPICA community members, 2006). The Greenland NorthGRIP ice core $\delta^{18}O_{ice}$ record is shown in blue [*NGRIP-EDML* gas-synchronized chronology, Capron et al. (2010b)] and red [*GICC05modelext* chronology, Wolff et al. (2010)]. The Northern Alps (NALPS) speleothem record is shown in green (Boch et al., 2011). Coloured markers at the bottom of the graph show the different timings and durations of GS-22 according to each archive and chronology.

Fig. 2. Example of Continuous Flow Analysis (CFA) measurements of NorthGRIP glacial ice and assignment of annual layers. Visual stratigraphy was measured by optical scanning at the drilling site, not by CFA. Vertical grey bars indicate "certain" (solid line) and "uncertain" (dotted line) years. Note that sodium, ammonium, conductivity and insoluble dust are plotted on logarithmic scales.

Fig. 3. Comparison of NorthGRIP ice core chronologies over the interval between GI-21 and GI-22. Also shown are NGRIP $\delta^{18}O_{ice}$ and annual layer thicknesses (λ) from the *ss09sea06bm* ice-flow model and from annual layer counting (this study). Numbers shown horizontally correspond to event durations in years calculated from *GICC05modelext* in red (Wolff et al., 2010), *NGRIP-EDML gas*-synchronized chronology in blue (Capron et al., 2010b) and annual layer counting in black (this study). Vertical numbers show NGRIP depths (black) corresponding to absolute ages in years before 2000AD from *GICC05modelext* (red) and EDML-synchronized NGRIP (blue) chronologies.

Fig. 4. Comparison of NorthGRIP ice core $\delta^{18}O_{ice}$ and trapped gas species for the determination of Δage. $\delta^{18}O_{ice}$ is shown in red [*GICC05modelext* chronology, Wolff et al. (2010)] while $\delta^{15}N$ is shown in blue (Capron et al., 2010b) and CH_4 concentration is shown in green (this study). Horizontal numbers indicate age differences between ice (red) and gas (green) transitions, while vertical numbers specify the depths assigned to temperature and gas features.

Fig. 5. Comparison of NGRIP stadial duration and EDML temperature change, modified from Capron et al. (2010a). Numbers indicate corresponding GI and AIM events, where the stadial duration is determined from the GS prior to the numbered GI. The durations of GS-22 (together with GI-21 corresponding to AIM21 in the figure) are shown for both EDML-synchronized [red, Capron et al. (2010b)] and annual-layer counted (black, this study) NGRIP chronologies.

Table 1. Summary of absolute ages of onset and end transitions associated with GS-22, and calculated durations from various NorthGRIP ice core chronologies as well as the NALPS speleothem record.

[a]Definitions of onsets, ends and durations of Greenland Interstadial (GI) and Greenland Stadial (GS) events are given in the text.

[b]From Wolff et al. (2010).

[c]From Capron et al. (2010b).

[d]Uncertainties are calculated as root-sum-of-squares of the GI precursor and GS onset uncertainties.

[e]Uncertainty shown here is half of the Maximum Counting Error (MCE) which can be considered equivalent to a 1σ uncertainty (1σ = ½ x MCE). MCE is described in the text.

[f]From Boch et al. (2011).

[g]Uncertainties reported as 2σ (Boch et al., 2011) are shown here as 1σ for consistency.

Chronology	GI-21 onset[a]	±1σ	GI-21 precursor onset[a]	±1σ	GS-22 onset[a]	±1σ	GS-22 Duration[a]	±1σ
GICC05modelext[b]	84760		85060		87680		2620	
NGRIP-EDML[c]	83634	230	84131	230	87756	230	3625	325[d]
(this work)							2894	99[e]
NALPS[f]	85030	205[g]	85440	205[g]	88690	165[g]	3250	263[d]