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Synchronizing ice cores from the Renland and Agassiz ice caps to the Greenland Ice Core Chronology

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[1] Four ice cores from the Agassiz ice cap in the Canadian high arctic and one ice core from the Renland ice cap in eastern Greenland have been synchronized to the Greenland Ice Core Chronology 2005 (GICC05) which is based on annual layer counts in the DYE-3, GRIP and NGRIP ice cores. Volcanic reference horizons, seen in electrical conductivity measurements (ECM) have been used to carry out the synchronization throughout the Holocene. The Agassiz ice cores have been matched to the NGRIP ice core ECM signal, while the Renland core has been matched to the GRIP ice core ECM signal, thus tying the cores to GICC05. Furthermore, it has been possible to synchronize the Renland ice core to NGRIP-GICC05 in the glacial period back to 60,000 years b2k (years before A.D. 2000), on the basis of a matching of transitions between stadials and interstadials. This work brings the total number of ice core records that have been rigorously tied to the GICC05 timescale up to nine. Renland annual layer thicknesses are increasing with depth during the period from 7 to 8.5 ka b2k, a highly unusual observation only matched by a similar thickness increase in the glacial section of the Renland core some 60 ka ago. Annual layer thicknesses in the Agassiz ice cores point to a well-developed Raymond bump in the Agassiz ice cap.

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1. Introduction

[2] The Greenland ice sheet and surrounding ice caps in the Canadian high arctic and along the Greenland east coast are outstanding archives of past northern hemisphere atmospheric conditions. During the past decades, several ice coring efforts have been made in order to retrieve continuous records for the study of past climatic conditions at these locations [*Dansgaard and Johnsen*, 1969; *Fisher*, 1979; *Hooke and Clausen*, 1982; *Fisher et al.*, 1983, 1995, 1998; *Langway et al.*, 1985; *Johnsen and Dansgaard*, 1992; *Dansgaard et al.*, 1993; *Mayewski et al.*, 1994; *North Greenland Ice Core Project Members*, 2004].

[3] To fully exploit the wealth of information provided by the ice cores, accurate dating of the records is essential [e.g., *Hammer et al.*, 1978]. Having ice cores from different regions, cross dating of the records is of great importance, because thoroughly cross dated records allow studies of local climate differences irrespectively of absolute dating inaccuracies [e.g., *Rogers et al.*, 1998]. Furthermore, it is possible to retrieve more accurate regional climatic signals by stacking the cross dated records [*Johnsen et al.*, 1997; *White et al.*, 1997; *Vinther et al.*, 2003; *Andersen et al.*, 2006a]. Volcanic reference horizons have recently been used to cross date several Greenland ice cores as part of the Copenhagen dating initiative [*Rasmussen et al.*, 2006, 2008; *Vinther et al.*, 2006]. Furthermore multiple Antarctic ice cores have been cross dated using volcanic reference horizons as part of the EPICA project [*Udisti et al.*, 2004; *Ruth et al.*, 2007; *Severi et al.*, 2007].

[4] Since the 1970s and 1980s when the drilling and dating of the Renland and Agassiz cores took place, many advances have been made with respect to ice core data from the Greenland ice sheet. Indeed during the past few years the Copenhagen Dating Initiative has brought several landmark results, such as fixing the end of the Younger Dryas at 11.7 ka b2k (b2k is a short for before A.D. 2000). Annual layer counting in the NGRIP ice core record has been accomplished all the way back to 60,000 years b2k [*Andersen et al.*, 2006b; *Svensson et al.*, 2008], the GRIP and GISP2 ice core records have been synchronized to NGRIP back to 32,000 years b2k [*Rasmussen et al.*, 2008] and a combined and synchronized dating of the DYE-3, GRIP and NGRIP ice cores has been accomplished throughout the Holocene and the termination [*Rasmussen et al.*, 2006; *Vinther et al.*, 2006].

[5] Hence given the new GICC05 timescale and the availability of ECM records showing past volcanism from

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central Greenland ice cores it makes sense to revisit the dating of the Renland and Agassiz ice cores. Here we present the synchronization of four ice cores from the Agassiz ice cap and one ice core from the Renland ice cap to GICC05. The Agassiz ice cores have been synchronized to GICC05 throughout the Holocene, while the Renland ice core has been synchronized to GICC05 all the way back to 60,000 years b2k, which is the present limit of GICC05.

2. Ice Core Data

[6] General information concerning the location and characteristics of the relevant ice cores can be seen in Figure 1 and Table 1. In the following, a more detailed description of the specific data sets used for the cross dating is given.

2.1. Agassiz

[7] Four ice cores from the Agassiz ice cap on Ellesmere Island (see Table 1) are included in this cross-dating effort. The A84 and A87 cores were drilled on a dome on the ice cap (and within 30 m from each other), whereas the A79 ice core was drilled ~1300 m southwest of the dome, and the A77 ice core was drilled some 2300 m south of the dome [*Fisher et al.*, 1995]. The three sites are on the same flow line along which there are various amounts of winter scouring of snow. The location of the dome is determined by the bed topography which shows an elevation maximum under the dome [*Fisher et al.*, 1995]. As a consequence, the thickness of the ice cap is at a minimum of 120–130 m at the dome, rapidly increasing with distance to the dome, to almost 340 m at the A77 drill site.

[8] Electrical conductivity measurements (ECM) [*Hammer et al.*, 1980] have been carried out on the A77, A79 and A84 ice cores [*Zheng et al.*, 1998] with a varying resolution that in general increases from about 10 cm at the top of the cores to about 1 cm at the onset of the Holocene. The ECM data were acquired manually in this resolution and have subsequently been digitized.

[9] δ^{18}O data are available throughout the length of all four Agassiz ice cores. The sampling of the δ^{18}O data has been carried out in accordance to cutting scales in order to account for flow related thinning of the annual layers (typically a cutting scale is based on model predicted annual layer thicknesses and used to obtain a fixed number of samples per year). Typical sample sizes are in the range of 1–20 cm for the A77 core and 2–30 cm for the A79, A84 and A87 ice cores.

2.2. Renland

[10] The Renland ice core is drilled close to the summit of the Renland ice cap. Bedrock topography is very complex with bedrock elevation differences of 300–400 m within 2 km from the drill site. The drilling was carried out at a location with a relatively shallow ice thickness of 325 m; ice thicknesses of more than 600 m exist less than 2 km south of the drill site [*Johnsen et al.*, 1992].

[11] Renland ECM data have been digitized from analogue data in 1 cm resolution throughout the core, while δ^{18}O samples have been cut in 5 cm resolution for the top 124.3 m and in 2.5 cm resolution below that depth.

2.3. GRIP

[12] The GRIP ice core is drilled at the summit of the Greenland ice sheet (see Figure 1). ECM data are available in 1 cm resolution throughout the Holocene that spans the upper 1624 m of the core. The δ^{18}O samples have been cut in various sizes, but never at a coarser resolution than 55 cm [*Johnsen et al.*, 1997].

2.4. NGRIP

[13] The NGRIP ice core is drilled 325 km NNE of the summit of the Greenland ice sheet (see Figure 1). The Holocene section spans the upper 1492 m of the ice core and ECM data are available throughout the Holocene in 1 cm resolution or higher. The coarsest resolution of NGRIP δ^{18}O samples is 5 cm.

2.5. GICC05 Timescale

[14] The GICC05 timescale is based on annual layer counting in the DYE-3, GRIP and NGRIP ice cores during the Holocene. Layer counting and synchronization of the three ice cores were carried out simultaneously, always making use of the best data sets available for any age interval. During the past 8 ka the time scale is based on annual layer counting in δ^{18}O and δD data [*Vinther et al.*, 2006], while the early Holocene is based mainly on annual layer counting in chemical impurity data [*Rasmussen et al.*, 2006]. The glacial section of GICC05 is based on annual layer counting in NGRIP impurity data only [*Andersen et al.*, 2006b; *Rasmussen et al.*, 2006; *Svensson et al.*, 2006, 2008]. The maximum counting error on the GICC05 timescale is estimated to be approximately 100 years at the transition from the glacial to the Holocene at 11.7 ka b2k [*Rasmussen et al.*, 2006; *Vinther et al.*, 2006], increasing to approximately 2600 years some 60 ka ago [*Svensson et al.*, 2008].

2.6. Existing Timescales for Agassiz and Renland Ice Cores

[15] A timescale based on annual layer counting of chemical impurity data in multiple sections of the A77 core covers the past 8 ka and is estimated to have a maximum error of 10% [*Fisher et al.*, 1983]. Timescales for the A79, A84 and A87 cores were based on flow modeling efforts tuned to existing noncontinuous Greenland volcanic ECM profiles and the end of the Younger Dryas transition from DYE-3 [*Hammer et al.*, 1986; *Fisher et al.*, 1983, 1995]. There was the understanding that the Agassiz ages could be shifted when the Greenland chronology improved. Since then the Greenland transition dating has shifted from 10.7 ka b2k to 11.7 ka b2k [*Rasmussen et al.*, 2006] and much improvement made in the intercore Holocene chronologies using the presently available continuous ECM records [*Vinther et al.*, 2006]. When it became clear that the transition was at 11.7 ka b2k the early Agassiz timescales for the A79, A84 and A87 cores were simply stretched linearly to fit. Given the nonlinear nature of layer thinning near the beds of these shallow cores, this in retrospect was not a wise way to make the adjustment. For all these reasons we feel it is time to bring the Agassiz cores into alignment with the new Greenland GICC05

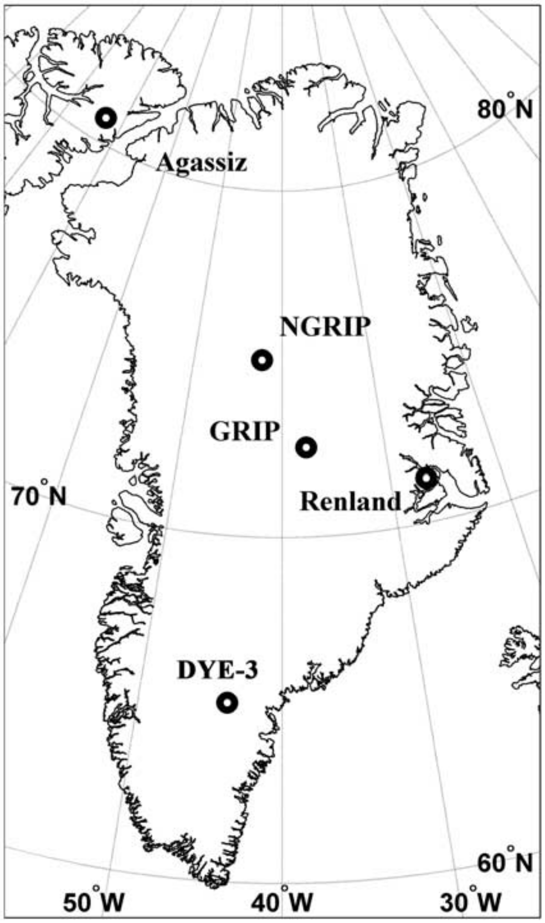

Figure 1. Drill site locations for selected Greenland and Canadian ice cores.

chronology using the continuous ECM data sets. Successful matching of volcanic reference horizons have already been carried out between Greenland and the four Agassiz ice cores for the past 1000 years [*Fisher et al.*, 1995; *Zheng et al.*, 1998].

[16] The timescale for the Renland ice core is based on annual layer counting in δ^{18}O data back to A.D. 1179 extended by annual layer counting in ECM back to A.D. 934 [*Johnsen et al.*, 1992]. Below A.D. 934 the dating on the Renland ice core is based on ice flow modeling, using the last termination and the culmination of the Eemian warm period as fix points [*Johnsen and Dansgaard*, 1992].

3. Methodology

[17] Synchronization of reference horizons is the general approach applied to transfer the GICC05 timescale to the Renland and Agassiz ice cores.

[18] During the Holocene this can be done using volcanic reference horizons that are detectable in ECM measurements (volcanic deposits affect the ice acidity and thereby the conductivity of the ice). Shape-preserving piecewise cubic Hermite interpolation [*Moler*, 2004] is used in between reference horizons to form the timescales. This interpolation technique assures a one to one depth/age relation and a continuous annual layer thickness profile.

[19] During the glacial period, synchronization is carried out through matching of the steepest δ^{18}O gradients during transitions between stadial and interstadial periods, as ECM no longer resolves the volcanic deposits. Interpolation between reference horizons is based on the assumption that annual layer thicknesses remain constant within each stadial/interstadial period, but changes abruptly at the transitions. This is a first-order approach based on the δ^{18}O accumulation relationship observed in the long Greenland ice cores [*Andersen et al.*, 2006b].

[20] It should be noted that only the Renland ice core can be synchronized to GICC05 during the glacial, as the glacial stratigraphies in the Agassiz ice cores have too little resolution and are too close to the bed to avoid tectonic flow discontinuities.

[21] In the following a detailed description of the synchronization effort is given for the two locations in question.

3.1. Renland

[22] While the Renland stratigraphy is undisturbed and continuous at least 60 ka back in time, it is by no means simple to interpret. *Johnsen and Dansgaard* [1992] found that an approximately 60–65 ka old section of the Renland core is abnormally thick in comparison with the surrounding ice. This is a very clear warning that Boudinage effects [*Staffelbach et al.*, 1988] and maybe the mountainous bedrock exert a significant influence on layer thicknesses in the lower sections of the ice core, a fact that severely complicates the interpretation of the ice core profile.

[23] Another warning sign is the apparent lack of clear 8.2 ka b2k and 9.3 ka b2k cold events in the Renland Holocene δ^{18}O record (these events are seen in other

Table 1. Ice Core Characteristics

Ice Core	Elevation, m a.s.l.	Latitude, °N	Longitude, °W	Mean Air Temperature,[a] °C	Accumulation, m Ice per Year	Ice Core Length, m	Year Core Drilled
Agassiz 77	1670	80.7	73.1	−24.5	0.175	336	1977
Agassiz 79	1700	80.7	73.1	−22.3	0.115	139	1979
Agassiz 84	1730	80.7	73.1	−21.9	0.098	128	1984
Agassiz 87	1730	80.7	73.1	−21.9	0.098	129	1987
GRIP	3230	72.58	37.64	−32	0.23	3027	1989–1992
NGRIP	2917	75.10	42.32	−32	0.19	3090	1996–2004
Renland	2350	71.27	26.73	−18	0.50	325	1988

[a]Measured at ~10 m depth.

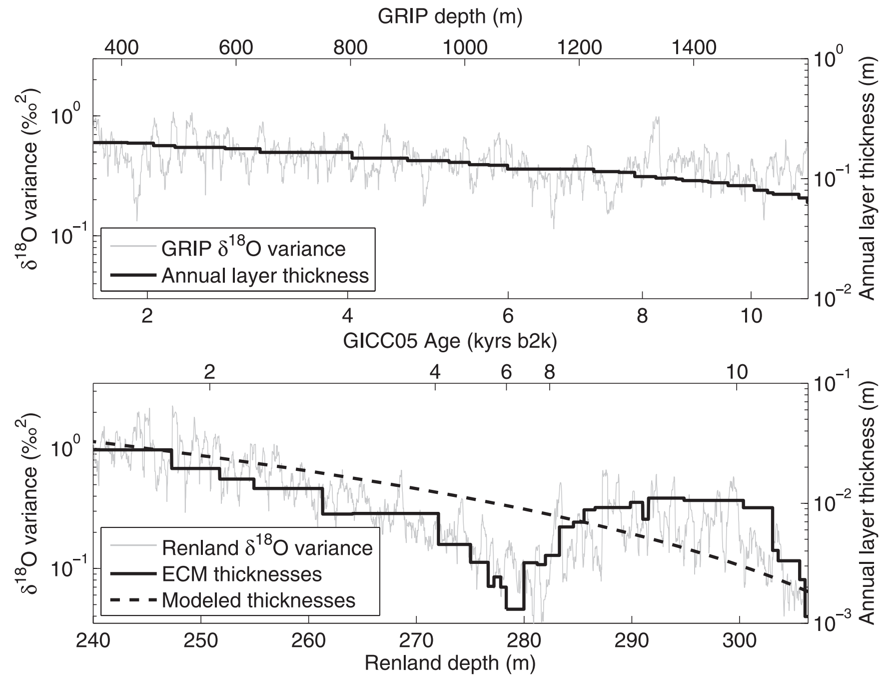

Figure 2. Running 20 sample variances for (top) GRIP δ^{18}O and (bottom) Renland δ^{18}O during the Holocene. The GRIP δ^{18}O sample size is 55 cm, while the Renland δ^{18}O sample size is 2.5 cm. Heavy lines are annual layer thicknesses based on layer counting (GRIP) and the new corresponding Renland annual layer thicknesses obtained by matching Renland ECM to the GRIP ECM record. The dashed curve shows modeled annual layer thicknesses from *Johnsen and Dansgaard* [1992].

Greenland ice cores [*Rasmussen et al.*, 2007]) and the appearance of hitherto unrecognized cold events at 4.7 ka b2k and 6.2 ka b2k [e.g., *Fisher et al.*, 1996] when the Renland δ^{18}O data are shown on the modeled timescale proposed by *Johnsen and Dansgaard* [1992].

3.1.1. Holocene Period

[24] When transferring a timescale to an ice core through matching of volcanic reference horizons it is preferable to have a flow modeled timescale as guidance; thus avoiding the risk of straying away from a physically meaningful solution. In the case of Renland, however, the suspicion that flow models severely underestimate the complexity of the flow over the highly uneven bedrock calls for caution.

[25] Therefore it was decided to use a completely different approach in guiding the volcanic matching based on an analysis of the variance in the δ^{18}O record. The reasoning behind this approach is that in a climatically stable period the assumption can be made that both the long-term average and the variance of annual δ^{18}O should be constant [*Johnsen et al.*, 1997]. If an average is made over many years, this average will approach a constant climatic δ^{18}O value. Now, having δ^{18}O samples of constant length while annual layer thicknesses change with depth, the δ^{18}O samples will on average represent a varying number of years. Assuming that the deviations of the annual δ^{18}O averages from the climatically constant value are random and that the annual δ^{18}O averages have the variance v, then the variance of an δ^{18}O sample spanning N years (v_N) will be given by:

$$v_N = v/N \tag{1}$$

Having a sample size s and an annual layer thickness λ, we can write:

$$s/\lambda = N \tag{2}$$

If s and v are constants this in turn implies

$$v_N \propto \lambda \tag{3}$$

Hence the variance of equally sized δ^{18}O samples is proportional to the annual layer thicknesses in a climatically stable period.

[26] In Figure 2 (top) a test of the variance methodology has been made using GRIP δ^{18}O data that cover most of the Holocene (the GRIP ice core was chosen, as it is the ice core nearest to Renland). A reasonably good correspondence between δ^{18}O variance and annual layer thicknesses can be seen, but it is worth noting that the climate during the early Holocene (8–11.7 ka b2k) was more unstable than the climate during the past 8 ka. In fact the early Holocene climate was punctured by climatic downturns such as the 8.2 ka b2k cold event that induced the variance peak at about 1330 m. Such events do represent clear violations of the condition of climatic stability, hence yielding a higher variance for the period from 8 to 11.7 ka b2k than for the climatically stable period from 0 to 8 ka b2k.

[27] In Figure 2 (bottom), Renland δ^{18}O variance and modeled annual layer thicknesses [*Johnsen and Dansgaard*, 1992] are plotted. It is immediately clear that annual layer thicknesses from the simple flow model fails to capture the evolution of Renland δ^{18}O variance with depth, confirming

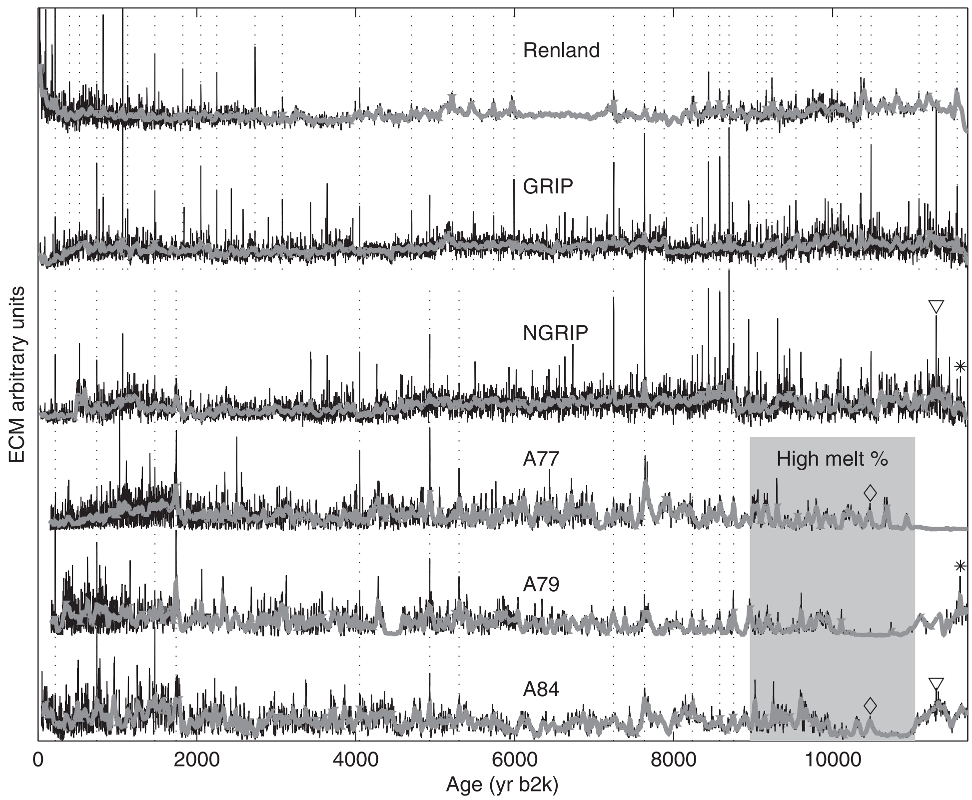

Figure 3. Annual electrical conductivity measurements (ECM) for the Renland, GRIP, NGRIP and Agassiz ice cores after synchronization of the ice cores. Heavy gray lines are centennially smoothed ECM profiles. Match points are shown with dotted lines; the diamonds, triangles and stars signifies special match points (see text).

suspicions that flow in the Renland ice cap could be more complex than originally anticipated.

[28] Given this result, it was decided to use the Renland δ^{18}O variance, to guide the volcanic matching. The Renland ECM record was therefore matched to the ECM from the nearby GRIP core taking into account that annual layer thicknesses should decrease rapidly to a depth of ~280 m and then be allowed to increase with depth to ~290 m. The resulting annual layer thicknesses in between ECM fix points can be seen as the heavy curve in Figure 2 (bottom), while the ECM matching of GRIP and Renland can be seen in Figure 3. Renland δ^{18}O using the ECM matching to GRIP and thereby to the GICC05 timescale is shown in Figure 4. GRIP δ^{18}O is also plotted in Figure 4 for easy comparison with the Holocene Renland δ^{18}O profile. The age differences between the old (modeled) Renland timescale [*Johnsen and Dansgaard*, 1992] and the new timescale matched to GICC05 can be seen in Figure 5.

3.1.2. Glacial Period

[29] During the glacial period, the transfer of the GICC05 timescale to Renland has been based on a matching of the transitions between stadials and interstadials (also called Dansgaard-Oeschger events), using the period with the largest δ^{18}O gradient in the cores to match the transitions [*Andersen et al.*, 2006b]. The matching was carried out between NGRIP and Renland δ^{18}O, whereas the closer GRIP core was not used because the GICC05 timescale is based on annual layer counting in the NGRIP core only during the glacial. The resulting Renland δ^{18}O profile and the NGRIP δ^{18}O profile for the past 60,000 years can be seen in Figure 6.

3.2. Agassiz

[30] The alignment of the Agassiz cores to GICC05 is eased considerably by the presence of the A77 ice core timescale that is based on sections of annual layer counting in the A77 core. This timescale is believed to be accurate within 10% for the past 8000 years [*Fisher et al.*, 1983].

[31] It was therefore decided first to align the A79 and A84 ECM records to the A77 timescale and thereafter adjust the three timescales to GICC05. The final adjustment could then be carried out using volcanic reference horizons seen in all three cores and the NGRIP ice core (NGRIP is the GICC05 ice core in the nearest vicinity of Agassiz). It should be noted that the δ^{18}O variance method used to support the Renland dating is not a feasible approach for the Agassiz dating, as the variance is likely affected by significant and varying degrees of surface melting at Agassiz during the Holocene [*Koerner and Fisher*, 1990] and because the sampling interval for δ^{18}O was variable over the Holocene.

[32] The ECM match after the final adjustment can be seen in Figure 3; this match is obtained by adjusting the A77 timescale by less than 5% for the past 8 ka (see Figure 5 for age differences between the old and new timescales). It should be noted that a period of heavy

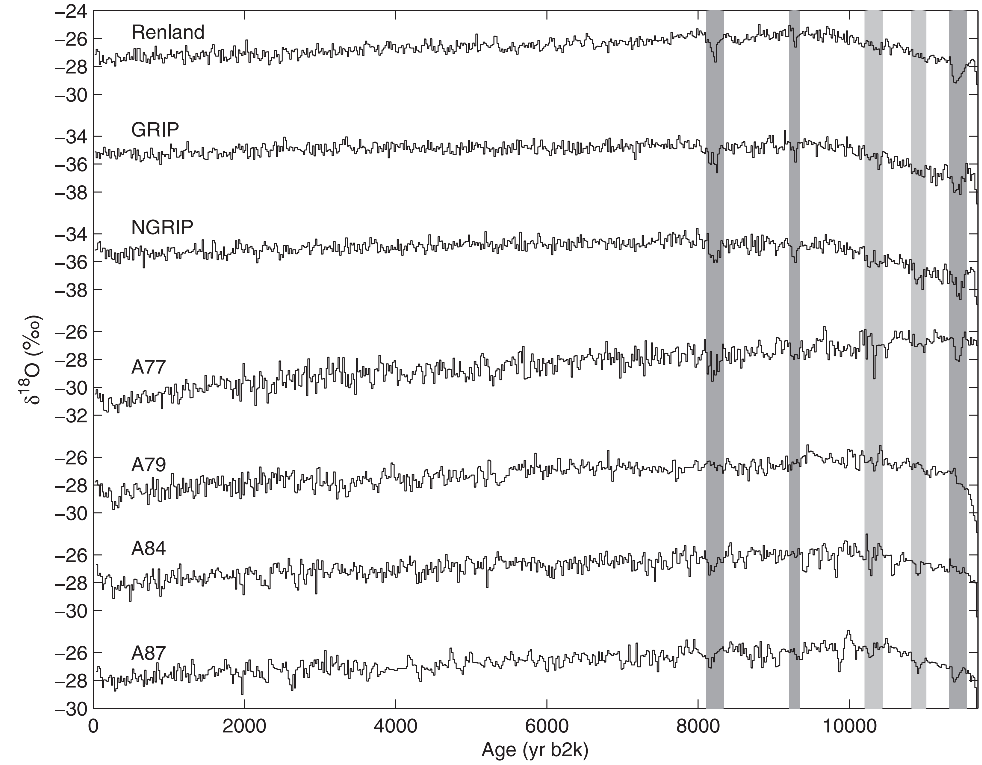

Figure 4. Holocene 20-year δ^{18}O records from synchronized Renland, GRIP, NGRIP and Agassiz ice cores. Dark shading signifies climatic oscillations seen clearly in both GRIP and NGRIP δ^{18}O, while light shading marks oscillations seen most prominently in NGRIP δ^{18}O.

melting seriously affects Agassiz ECM in the period from 9 ka b2k to 11 ka b2k, prohibiting matching to NGRIP during this period. Before 9 ka b2k it was therefore necessary to relax the demand that reference horizons should be visible in all three Agassiz cores. The reference horizons marked by a triangle and a star in Figure 3 are only visible in some cores. The diamond match point is based on a combination of an ECM maximum and a

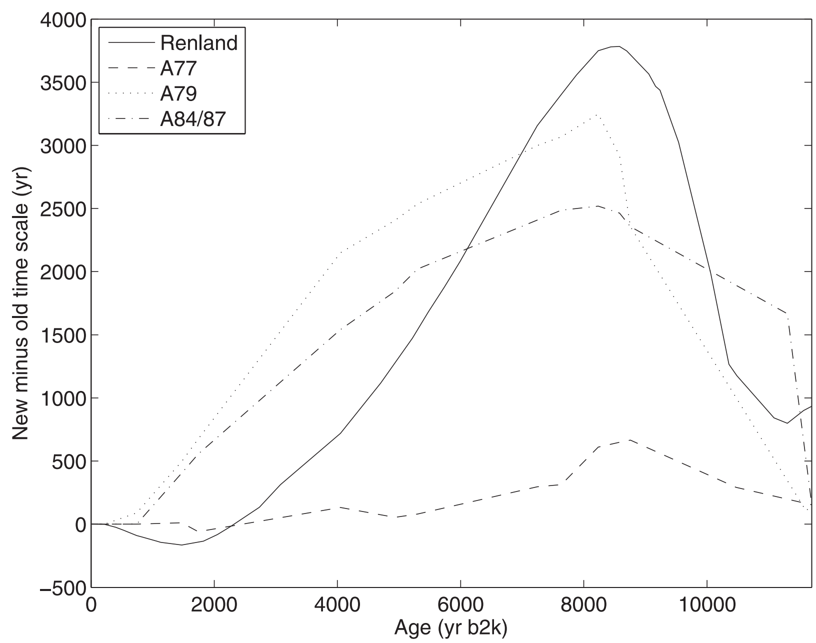

Figure 5. Differences between the new GICC05 timescale and old timescales for the Renland and Agassiz ice cores. Note that the old timescales for the Renland, A79 and A84 cores were based on flow modeling, while the 0–7500 year b2k period of the old timescale for the A77 core was based on multiple sections of annual layer counting.

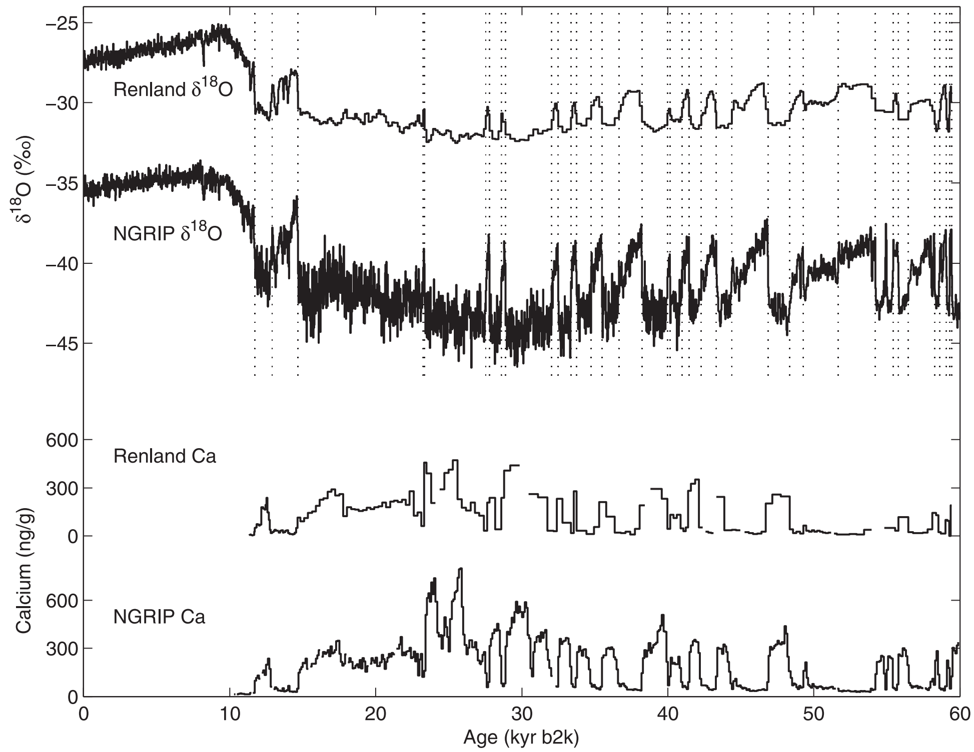

Figure 6. Renland and NGRIP (top) δ^{18}O and (bottom) calcium records for the past 60,000 years after synchronization using stadial to interstadial transitions in δ^{18}O. All match points are shown as dotted lines. The NGRIP δ^{18}O (calcium) record is shown in 20 (100) year resolution while the glacial Renland δ^{18}O and calcium records are shown in the maximum resolution permitted by the δ^{18}O (calcium) data sample size.

δ^{18}O minimum some 10.4 ka ago. The transition from the glacial to the Holocene 11.7 ka (the maximum age presented in Figure 3) ago has also been used to constrain the timescales, somewhat mitigating the lack of common fix points before 9 ka b2k.

[33] Figure 4 presents the Agassiz δ^{18}O records after alignment to GICC05. The A84 timescale has been used with minor modifications for the A87 core, as ECM is not available for the A87 core (the A84 timescale has simply been stretched to fit A87 at the 8.2 ka b2k cold event and at the transition). This approach is reasonable as the two cores were drilled less than 30 m apart.

4. Dating Uncertainties

[34] Uncertainties on the new timescales are not easily quantified, as they are dependent both on the accuracy of the matching and on layer thickness fluctuations in between match points; issues that are both very difficult to asses. In the following uncertainties on the timescales are estimated both by ascertaining the sensitivity of the timescales to removing match points one at a time and by comparison of the timing of rapid variability in the aligned δ^{18}O records. In general the total uncertainty of the timescales can be estimated (conservatively) as a sum of the uncertainty in the alignment to the GICC05 timescale and the uncertainty on the GICC05 itself. During the Holocene the latter uncertainty increases from 2 years or less during the 0–2 ka period to ~40 years at 8 ka and further to ~100 years at the transition (11.7 ka) [*Rasmussen et al.*, 2006; *Vinther et al.*, 2006].

4.1. Renland

[35] For the Holocene section of the Renland timescale, it is encouraging that the 8.2 ka b2k cold event, the 9.3 ka b2k cold event, and the 11.5 ka b2k Preboral oscillation line up closely with corresponding events visible in the GRIP δ^{18}O profile (see Figure 4). The most uncertain section of the matching is the period from 5 ka b2k to 7.3 ka b2k, were annual layer thicknesses in the Renland core are below 3 mm. It is estimated that the matching uncertainty in this section is approximately 200 years, while uncertainties elsewhere in the Renland Holocene profile are about 100 years or less. These uncertainties should of course be added to GICC05 uncertainties related to the annual layer counting in the DYE-3, GRIP and NGRIP cores [*Rasmussen et al.*, 2006; *Vinther et al.*, 2006]. It should also be noted that uncertainties in the A.D. 934 to A.D. 1988 part of the timescale, which is based on annual layer counting, are estimated to be a few years only.

[36] For the glacial section of the Renland core, it is estimated that matching uncertainties could be as high as 500 years in the section with the fewest fix points (15–28 ka b2k), which could be a somewhat conservative estimate as clear features in NGRIP and Renland calcium records [*Bigler*, 2004; *Hansson*, 1994] (withheld from the matching) line up within 300 years during this period (see Figure 6). Again it is stressed that the matching uncertainties should be added to GICC05 uncertainties related to the

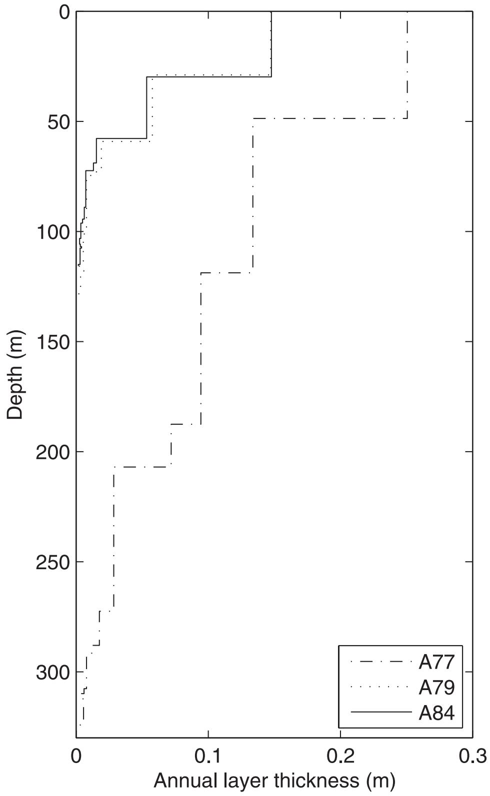

Figure 7. Annual layer thicknesses for the Agassiz ice cores based on the matching shown in Figure 3.

annual layer counting in the NGRIP core [*Andersen et al.*, 2006b; *Svensson et al.*, 2006, 2008].

4.2. A77

[37] Uncertainties for the new A77 ice core timescale are most likely less than 5% for the past 8 ka and 200–300 years for the 8 ka to 11.7 ka b2k period. This assessment is based on the low level of adjustment that was required to fit the original A77 timescale to GICC05 and the good alignment of several cold events in the NGRIP and A77 δ^{18}O records during the early Holocene (see Figure 4).

4.3. A79, A84, and A87

[38] It is encouraging that the new timescales for the A84 and A87 cores bring a reasonable degree of alignment between cold events in NGRIP, A77, A84 and A87 δ^{18}O records during the 8–11.7 ka b2k period (see Figure 4). Interestingly, the alignment of the A87 δ^{18}O seems to be superior to the alignment of A84 δ^{18}O. This is somewhat counterintuitive as the A87 timescale is based on the A84 timescale. Another noteworthy difference between A84 and A87 δ^{18}O is the lack of a 11.5 ka b2k Preboral oscillation in the A84 ice core, while the A87 core has a clear and well-aligned Preboral oscillation. The prominent A87 Preboreal oscillation alignment supports the A84 timescale and therefore forces the conclusion that the Preboreal oscillation is simply absent in A84 δ^{18}O. This should probably be seen as an indication of a high noise level in early Holocene Agassiz δ^{18}O data; and near bed tectonic discontinuities due to flow (folds, faults etc).

[39] The A79 δ^{18}O record (see Figure 4) shows a complete lack of all early Holocene cold events, further underlining the potential melt problems affecting Agassiz records during this period. The general agreement between the A79, A84 and A87 cores with respect to the long-term evolution of Agassiz δ^{18}O does, however, create some level of confidence in the A79 dating (note that the Holocene trend in A77 δ^{18}O and to a lesser extent that of A79, is caused mainly by upstream effects and should therefore not be expected to be equal to the similar trends in A84 and A87 δ^{18}O records).

[40] Taking all theses considerations into account it is estimated that uncertainties on the A79, A84 and A87 timescales can be up to 400 years in periods with few common fix points (2–4 ka b2k, 5.5–7 ka b2k and 9–11 ka b2k). Uncertainties for the past two millennia are probably less than 5% because of the availability of several ECM reference horizons and the better data resolution due to thicker annual layers near the top of the cores (see Figure 7).

5. Discussion

[41] The most remarkable finding in this dating effort is without doubt the Holocene Renland annual layer thickness profile (see Figure 2). The physical mechanisms behind the increase in annual layer thicknesses with depth at approximately 280 m (corresponding to an age of 7–8.5 ka b2k) in the Renland core are certainly not well understood. In fact, it would be tempting to reject the result as physically improbable, had the combined evidence of the ECM matching, the δ^{18}O variance and the alignment of the cold events seen in Holocene δ^{18}O not been so convincing. Furthermore, the knowledge that a similar section of increasing annual thicknesses with depth exists in a 60–65 ka old section of the core adds to the confusion [*Johnsen and Dansgaard*, 1992]. Flow over a highly uneven bedrock can create fluctuations in annual layer thicknesses [*Parrenin et al.*, 2004]. Hence it is speculated that such flow could be a key factor in the formation of these odd sections in the Renland ice core, as could associated Boudinage effects [*Staffelbach et al.*, 1988], which can make soft layers, such as glacial layers with a high dust content, grow or shrink irregularly depending on local stresses induced by bedrock obstacles. Another issue could be ice from the main Greenland ice sheet affecting the outflow of the glaciers from the Renland ice cap. It is known that the Greenland ice sheet surrounded Renland and thereby blocked or slowed outflow glaciers until 7–9 ka ago [*Funder*, 1978]. Hence the age when Renland outflow glaciers became unblocked seems to coincide with the age of decreasing annual layer thicknesses with time in the Renland ice core. The unblocking mechanism cannot, however, explain the glacial section of increased annual layer thicknesses, as the cold glacial conditions would rather inhibit unblocking events. Another possibility is that past changes in the thickness of the Renland ice cap could have affected the annual layer thickness profile [*Parrenin et al.*, 2007], but the limited horizontal extension of the ice cap makes the drastic ice thickness changes needed to explain the changes in annual layer thicknesses very unlikely [*Johnsen et al.*, 1992]. Indeed Boudinage effects seem to be a more likely explanation of the section of increasing annual thicknesses with

depth in the glacial section of the core [*Johnsen and Dansgaard*, 1992; *Johnsen et al.*, 1992].

[42] The annual layer thickness profiles for the Agassiz ice cores (see Figure 7) are easier to comprehend. The dome on which the A84 and A87 cores are drilled is fixed in position by an underlying peak in bedrock topography. Hence the rapid thinning observed in the top of the ice cores on (A84 and A87) and near (A79) the dome could very well be the manifestation of a Raymond bump [*Raymond*, 1983] in the internal layering structure of the Agassiz ice cap. A Raymond bump in an ice cap is formed at an ice divide when ice is frozen to bedrock, because then vertical velocity at middepths will be lower at the divide than on the flanks [*Raymond*, 1983]. For the Agassiz ice cap the upward arching nature of the internal layers in the Raymond bump will be reinforced by the high point in the underlying bedrock topography. Layer tilting observed in the vertical holes of the A84 and A87 cores supports this interpretation. The tilting begins within 20 m of the surface and it grows to 12 degrees about 20 m from the bed after which the tilting approaches the bed angle. Corroborating evidence for this interpretation is that no rapid thinning is observed in the A77 ice core that was drilled a few km away from both the dome and the bedrock high point. In Figure 5 it can be seen that the fact that the original A79 and A84/87 timescales did not take the Raymond bump into account made them too young. As expected maximum age differences occur around 8 ka b2k corresponding to the depth of the observed maximum layer tilting.

[43] From a climatological point of view it is very interesting that δ^{18}O from the Renland ice core and the Agassiz cores that were drilled on or near the dome (i.e., not A77 which is seriously affected by upstream effects) show a climatic δ^{18}O optimum 8–10.5 ka ago. However, the melt layer record [*Koerner and Fisher*, 1990] from the same cores near or at the top of the dome, indicates an even earlier optimum. *Fisher* [1992] speculates that the early Holocene δ^{18}O values for Agassiz and other records are "contaminated" by source ocean water that is mixed with −35 per mil melt from the shrinking ice sheets. If that is the case, then the purely climatic δ^{18}O optimum should have been even earlier than 10.5 ka b2k. The Renland climatic optimum seems to occur a little later. Interestingly a climatic optimum is very weakly expressed (if seen at all) in δ^{18}O of the GRIP and NGRIP ice cores. A temperature reconstruction based on inversion of GRIP borehole temperatures does indicate a climatic optimum in central Greenland as well, but occurring markedly later (4–8 ka ago) [*Dahl-Jensen et al.*, 1998], but the similar GISP2 temperature analysis puts the thermal optimum considerably earlier [*Cuffey and Clow*, 1997].

[44] Another interesting climatological feature to study in the aligned δ^{18}O records are the 8.2 ka b2k and 9.3 ka b2k cold events and the Preboreal oscillation (11.5 ka ago). From Figure 4 one can conclude that the 8.2 ka b2k cold event and the Preboreal oscillation were significant events in the entire Greenland region. The 9.3 ka b2k cold event is certainly significant in the Renland and Greenland records but much less so in the Agassiz ice core records, probably because of the effects of increased summer melting and increased percolation and mixing of meltwater in the snowpack. It is also worth noting that two cold events occurring between 10 ka and 11 ka b2k appear to be strongest in the northernmost Greenland and Canadian high arctic, as they can best be detected in the Agassiz and NGRIP ice cores. This clearly shows that one should be very cautious using cold events in the δ^{18}O records for cross-dating purposes; a finding in line with the conclusions of *Rasmussen et al.* [2007].

6. Conclusion

[45] The GICC05 timescale based on ice cores from the Greenland ice sheet has been applied to ice cores from the Agassiz and Renland ice caps. During the Holocene the alignment of the Agassiz and Renland ice cores was accomplished by matching of volcanic reference horizons that are detectable in ECM data with those from GRIP and NGRIP. During the glacial, the Renland ice core has been matched to NGRIP, the transitions between stadials and interstadials being used as match points.

[46] The resulting annual layer thickness profile for the Renland core shows increasing annual layer thicknesses with depth in the period from 7 to 8.5 ka b2k, a highly unusual observation only matched by a similar thickness increase in the glacial section of the Renland core some 60 ka ago. The nature of these increases in annual layer thicknesses are not well understood.

[47] The resulting Agassiz annual layer thicknesses are more straight forward. Annual layers in the ice cores drilled at the dome thin much more rapidly than layers in the ice core drilled farthest away from the dome. This is due to the shallow ice thickness at the dome and to the flow properties near domes in general.

[48] Nine Greenland and Canadian ice cores have now been put on the GICC05 timescale. This will facilitate much more rigorous interpretations of intercore geographical differences in the future, and ease the accessibility of ice core data in general.

7. Online Data Access

[49] The δ^{18}O data on the GICC05 timescale (shown in Figures 4 and 6) can be downloaded from http://www.icecores.dk. Data files containing the match points (shown in Figures 3 and 6) are also available from http://www.icecores.dk.

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