Supplemental Material

Age scale:

For the dating of the EDML and EDC ice cores (Figure S1) we used for the first time a new common time scale developed for Greenland and Antarctic ice core records. Central to this EDC3 time scale is a glaciological flow model[1] for the Dome C ice core, where ice flow is relatively simple due to its dome position. Accumulation rate changes in the core are estimated from the dependence of the saturation water vapor pressure on temperature[2] which itself is reconstructed from δD Free parameters (current accumulation rate, the temperature sensitivity controlling the glacial-interglacial accumulation amplitude as well as the sliding ratio, a vertical deformation parameter and the basal melting rate controlling the flow) are constrained in the model by various tie windows around absolute time markers. For the time period of the last 150.000 years discussed here those times are defined by volcanic horizons, rapid methane variations during glacial/interglacial transitions, or ^{10}Be anomalies which have been absolutely dated using the annual layer counted Greenland Ice Core Chronology (GICC05)[3-5] or have also been found in other radiometrically dated archives. The absolute dating uncertainty of this new EDC3 age scale is 1000 years for an age of 41,000 years and better than 2000 years for termination II with the error increasing for older ages. For internal coherence, a corresponding age scale (EDML1) has been derived for EDML by synchronizing the EDML and EDC ice cores using volcanic and dust tie points based on continuous sulfate, electrolytic conductivity, dielectric profiling, particulate dust and Ca^{2+} data available for both cores. Due to the common change in the Patagonian dust source strength and the hemispheric significance of major volcanic eruptions this procedure is justified. The multitude of unambiguous volcanic markers allowed for a synchronization to within typically 20 years or better for the last 75,000 years, which are the main focus of this paper. Between widely separated tie-points the maximum uncertainty occasionally can increase up to 140 years. The synchronization is better than 1000 years at the beginning of MIS5.5 and increasingly deteriorates for older ages in MIS6, where the synchronization relies on less unambiguous dust concentration changes. Beyond that a dust synchronization has not been achieved. Therefore, we restrict the discussion of our records to the last 150,000 years, where crossdating of the EDML and EDC core is sufficiently constrained.

In order to study the phase relationship between Greenland and Antarctica during MIS2-3 in more detail the EDML and NGRIP ice cores have been synchronized for the time span of the last 55 kyr using the global signal in atmospheric CH_4. This provides an age scale which may still be affected by systematic dating errors; however for this paper the important issue is that it synchronizes the two cores with an uncertainty that is governed mainly by the uncertainty in the ice age-gas age difference at the EDML site. The synchronization is based on a composite high resolution CH_4 record for Greenland. The highest resolution record is from NGRIP. Unfortunately this record covers so far only the period 48 to 38 kyr BP [6]. After 38 kyr BP we used GRIP data and before 48 kyr BP GRIP and GISP data [7]. GRIP and GISP CH_4 data were assigned a NGRIP gas age as follows: For each GRIP CH_4 value we find the depth where the age of the ice is the same as the age of the CH_4 value using the original GRIP Δage calculation [8]. Applying the match points from Rasmussen et al.[9] we find the corresponding depth in the NGRIP ice core. With the NGRIP time scale we calculate a new age which is also the new gas age of the GRIP CH_4 data point on the NGRIP time scale. Note that no new Δage calculation is applied. GISP values were used only before 48 kyr BP. The GISP data was matched on the NGRIP data before 55 kyr BP [10] and after 48 kyr BP. GISP CH_4 data in the gap of the NGRIP data was assigned a NGRIP age by interpolation.

Three similar synchronization methods have been used to assess the temporal coupling of both hemispheres. In the first method the high resolution Greenland composite CH_4 record has been matched with the EDML CH_4 record, making use of the global signal in atmospheric

CH_4 changes. For NGRIP we use the Δage confirmed by the synchronous effect of a fast temperature change in the ice and the gas record[10]. For EDML Δage was estimated using a firnification model[8]. Using the NGRIP age scale and the Δage at both sites we arrive at a synchronized time scale for the Greenland and Antarctic $\delta^{18}O$ records. The result of this approach has been displayed in Figure 3 of the main text. Figure S2 shows the magnitude of Δage for DML, GRIP (after 38kyr BP) and NGRIP (before 38Kyr BP). Δage for NGRIP is larger than for GRIP mainly due to the lower accumulation rate at NGRIP relative to GRIP. The shaded areas show an estimate for the uncertainty of the Δage calculation assuming 25% higher or lower accumulation rates. The effect on Δage is about equivalent to a 10% change in temperature. We estimate the total synchronization uncertainty at the start of DO events adding in quadrature the uncertainties for the synchronization of the CH_4 records and the two Δages for DML and the Greenland composite. Based on the resolution and the structure of the CH_4 records we estimate that the uncertainty for the CH_4 synchronization is small over the Younger Dryas (about 100 years) and on the order of 200 years for most DO events. For DO events 2 and 3 the uncertainty is larger about 300 years. The total synchronization uncertainty adds to 250 yr for the YD, 500 yr for DO2 and DO3, and about 400 yr for other DO events. In between the rapid CH_4 changes the synchronization uncertainty may be much larger. We estimate about 800 years where little CH_4 variations are found.

In a second approach the EDML CH_4 record, reflecting the temperature changes in the north, has been directly synchronized to the Greenland $\delta^{18}O$ record avoiding the calculation of Δage for the Greenland record but assuming that rapid temperature variations in the north and CH_4 changes occurred simultaneously. In the third approach the high resolution EDML CH_4 record, which is essentially reflecting the temperature changes in the north, has been directly compared to the EDML $\delta^{18}O$ record, representative for temperature changes in the Atlantic sector of the Southern Ocean. Δage has been estimated in this case using an alternative firnification model[11]. Conclusions on north-south temperature phase relationships in this method are somewhat compromised by the reduced resolution of the CH_4 record in Antarctica but this method avoids again the calculation of Δage for the Greenland records. Method 2 and 3 are not applicable for all temporal changes in the CH_4 record due to the different nature of the CH_4 and $\delta^{18}O$ signal. Nevertheless, all three approaches gave essentially the same results in terms of phasing between Greenland and Antarctic temperature variations. While the three methods differ in their way of synchronization they all share the estimate for the uncertainty in Δage at EDML as the main limiting factor for the accuracy of the synchronization.

The synchronization uncertainty as shown in Figure S2 is only slightly higher than for the Byrd GISP synchronization[7] but a factor 2-3 lower than at low accumulation sites such as EDC and Vostok[12]. An independent check of our CH_4 synchronization of the $\delta^{18}O$ records comes from the ^{10}Be peak at approximately 41,000 years before present. Here the direct synchronization of $\delta^{18}O$ records using ^{10}Be (which is accurate to within ±200 years[13]) and the CH_4 synchronization involving the gas age/ice age difference agree within the synchronization uncertainties. Moving away from the ^{10}Be tie point at 41,000 yr BP the modeled age scale and the CH_4 synchronized age scale deviate by as much as 600 years. Potential reasons for this difference may be systematic errors in the flow model or an error in the gas age/ice age difference or a combination of the two. Given the good correspondence of both synchronizations at 41,000 yr BP, a large systematic error in the gas/ice age difference, however, is unlikely to account for major parts of this offset. In summary the CH_4 synchronization allows a clear one-to-one assignment of AIMs and DO events in Greenland, but restricts the quantification of the exact phase relationship between peak warmth in Antarctica and stadial/interstadial transitions in Greenland to generally better than 400 years.

$\delta^{18}O$ and isotope temperature records

Calculation of the temperature reconstruction at EDC has been previously described[2]. For EDML a similar approach to convert $\delta^{18}O$ to temperature was taken. Surface temperatures T_S (in K) can be derived from the $\delta^{18}O$ records using the current linear gradient (r^2=0.89) of average $\delta^{18}O$ and surface temperature in Dronning Maud Land of 0.82 ‰/°C determined in extensive firn core and snow pit studies[14, 15].

In the case of EDML additional corrections had to be applied to the measured $\delta^{18}O$ data as shown in Figure S3 and described below.

a) sea water correction

Modern $\delta^{18}O$ and δD values in the EDML and EDC ice core reflect the depletion relative to present mean standard ocean water (SMOW). However, during the glacial the water isotopic signature of the ocean $\delta^{18}O_{sw}$ was higher due to the large isotopically depleted land ice masses. Accordingly, this offset of the isotopic signature of the water vapour at its ocean source has to be corrected[16]. We used the ice volume induced $\delta^{18}O$ change in sea water[17] based on a stack of benthic $\delta^{18}O$ sediment records[18] to correct for this effect. For the LGM the $\delta^{18}O$ sea water correction of about 1 ‰ implies an increase of the cooling at EDML relative to the Holocene by about 1.2 °C. The time scale of the sea water $\delta^{18}O$ record[17] was matched with EDC3/EDML1 by synchronizing high latitude temperatures[17] with the EDC δD record. Any age scale errors in the sea level corrected $\delta^{18}O$ data are thereby minimised, however, such errors are small on millennial time scales because sea level changes are slow.

b) altitude/upstream correction

In contrast to the EDC ice core, which is located on a dome position, the EDML ice core lies on a gently sloping ridge near a saddle point with small but non negligible (about 1m/yr) horizontal flow velocities for most of the upstream flank. Accordingly, deeper ice at EDML originates from upstream positions at higher altitudes while the ice at Dome C essentially originates at the current drill site over the entire length of the core. Using a nested 3 dimensional flow model[19, 20] we can e.g. show that ice at an age of 150,000 years in the EDML ice core was deposited approximately 160 km upstream, i.e. about 240 m higher in altitude. In addition, overall altitude changes of the ice sheet during past climate conditions also affect the local $\delta^{18}O$ signal at the site of deposition. In essence, measured $\delta^{18}O$ values deeper in the core are representative for the site of upstream deposition and not the current drill site. Accordingly, a systematic decline in $\delta^{18}O$ due to the higher altitude and lower temperature is expected. Using the 3D flow model nested into a large scale ice sheet model we were able to reconstruct both the upstream site of deposition as well as the overall altitude change of the ice sheet at that site. The latter elevation changes are primarily driven by local accumulation changes.

Subsequently we used the recent linear gradient (r^2=0.90) between $\delta^{18}O$ and altitude of -0.96 ‰ /100 m derived from the snow pit and shallow firn core data[14, 15] to correct the measured and sea level corrected $\delta^{18}O$ signal to our drill site location. For instance in MIS5.5, this leads to a correction in $\delta^{18}O$ of about +2.7 ‰, translating to a warming of 3.3 °C. Sea water and upstream/altitude corrected as well as uncorrected $\delta^{18}O$ and δD values are shown in Figure S3 together with sea level changes and upstream altitudes of snow deposition. The error introduced by these corrections is mainly determined by the accuracy of the modeled overall elevation changes which can be estimated to be ± 50 m which translates into a $\delta^{18}O$ error of ± 0.5 ‰ equivalent or a surface temperature error of ± 0.6 °C.

c) accumulation rates

Accumulation rates e.g. used in the CH_4 synchronization were estimated from the thermodynamic dependence of precipitation rate on the temperature at the elevation of cloud formation over the ice sheet[2]. This inversion temperature T_I (in °K) at the site and time of deposition is deduced from the sea level (but not upstream) corrected $\delta^{18}O$ record assuming a linear relationship between surface and inversion temperature at EDML as shown for the East Antarctic plateau[21], i.e.

T_I=0.67T_s+88.94

The local accumulation rate is then calculated (similar as for EDC[2]) according to

A=A_0*f(T_I)/f(T_I^0)*(1+β(T_I-T_I^0))

where T_I^0 is the present-day inversion temperature at the EDML drill site (242.20 K) assuming that the very good linear spatial relationship between altitude and temperature today holds also back in time. A_0 is the present-day accumulation rate of 64 $kgm^{-2}yr^{-1}$ at the EDML drill site, β is a constant fitting parameter, and f(T_I) is given by:

f(T_I)=(B_s/T_I-1)/T_I^2 * exp(-B_s/T_I)

where B_s=6148.3 K and an equivalent relation holds for f(T_I^0). The f function basically takes into account the temperature dependent change of saturation vapour pressure, whereas the parameter β takes into account glacial-interglacial changes of accumulation that are not explained by this relationship. β=0.045 has been empirically determined by fitting the spatial variation in recent upstream accumulation rates derived from firn cores[14, 15] and an extended surface radar survey[22, 23]. This leads to average glacial accumulation rates around the EDML drill site which are around 45 % of current values. For the glacial period the error introduced by the altitude correction is less than 15 %. However for the glacial period potential changes in water vapour transport may come into play which may affect the application of the recent spatial $\delta^{18}O$/temperature gradient. Modelling results[16] show that this effect is much smaller than for the Greenland ice sheet. Accordingly, we estimate the glacial accumulation rates to be accurate within ± 30 %. For MIS5.5 the average reconstructed accumulation at the drill site is 102 $kgm^{-2}yr^{-1}$. The MIS5.5 accumulation rate at the place of deposition, on the other hand, is found to be similar to today’s value at EDML. That is because despite in general warmer climatic conditions during MIS5.5 the ice originated from a location with colder and drier conditions than in the EDML drill site region. Because circulation is expected to be similar for MIS5.5 and Holocene conditions the main error for the accumulation rate estimate during MIS5.5 stems from the altitude correction, which amounts to about ± 0.7 cm water equivalent / year or less than 10%.

References

1. Parrenin, F., Jouzel, J., Waelbroeck, C., Ritz, C. & Barnola, J.-M. Dating the Vostok ice core by an inverse method. Journal of Geophysical Research 106, 31837-31851 (2001).
2. EPICA community members. Eight glacial cycles from an Antarctic ice core. Nature 429, 623-628 (2004).
3. Rasmussen, S. O. et al. A new Greenland ice core chronology for the last glacial termination. Journal of Geophysical Research 111, D06102 (2006).
4. Andersen, K. K. et al. The Greenland Ice Core Chronology 2005, 15-42 kyr. Part 1: Constructing the time scale. Quaternary Science Reviews, accepted (2006).
5. Svensson, A. et al. The Greenland Ice Core Chronology 2005, 15-42 kyr. Part 2: Comparison to other records. Quaternary Science Reviews, accepted (2006).
6. Flückiger, J. et al. N_2O and CH_4 variations during the last glacial epoch: Insight into global processes. Global Biogeochemical Cycles 18, GB1020 (2004).
7. Blunier, T. & Brook, E. J. Timing of millennial-scale climate change in Antarctica and Greenland during the last glacial period. Science 291, 109-112 (2001).
8. Schwander, J. et al. The age of the air in the firn and the ice at Summit, Greenland. Journal of Geophysical Research 98, 2831-2838 (1993).
9. Rasmussen, R. A. et al. Synchronisation of the NGRIP, GRIP, and GISP2 ice cores across MIS2 and palaeoclimatic implications. Quaternary Science Reviews, submitted (2006).
10. Huber, C. et al. Isotope calibrated Greenland temperature record over Marine Isotope Stage 3 and its relation to CH_4. Earth and Planetary Science Letters 245, 504-519 (2006).
11. Goujon, C., Barnola, J. M. & Ritz, C. Modeling the densification of polar firn including heat diffusion: application to close-off characteristic and gas isotopic

fractionation for Antarctic and Greenland sites. Journal of Geophysical Research 108, 4792 (2003).

12. Blunier, T. et al. Asynchrony of Antarctic and Greenland climate change during the last glacial period. Nature 394, 739-743 (1998).

13. Raisbeck, G., Yiou, F. & Jouzel, J. Cosmogenic ^{10}Be as a high resolution correlation tool for climate records. Geochimica et Cosmochimica Acta 66, A623 (2002).

14. Oerter, H. et al. Accumulation rates in Dronning Maud Land, Antarctica, as revealed by dielectric-profiling measurements of shallow firn cores. Annals of Glaciology 30, 27-34 (2000).

15. Graf, W. et al. Stable isotope records from Dronning Maud Land, Antarctica. Annals of Glaciology 35, 195-201 (2002).

16. Jouzel, J. et al. Magnitude of isotope/temperature scaling for interpretation of central Antarctic ice cores. Journal of Geophysical Research 108, 4361 (2003).

17. Bintanja, R., van de Wal, R. S. W. & Oerlemans, J. Modelled atmospheric temperatures and global sea levels over the past million years. Nature 437, 125-128 (2005).

18. Lisiecki, L. E. & Raymo, M. E. A Pliocene-Pleistocene stack of 57 globally distributed benthic δ^{18}O records. Paleoceanography 20, PA1003 (2005).

19. Huybrechts, P. Sea-level changes at the LGM from ice-dynamic reconstructions of the Greenland and Antarctic ice sheets during the glacial cycles. Quaternary Science Reviews 21, 203-231 (2002).

20. Pattyn, F. A new three-dimensional higher-order thermomechanical ice sheet model: basic sensitivity, ice stream development, and ice flow across subglacial lakes. Journal of Geophysical Research 108, 2382 (2003).

21. Jouzel, J. & Merlivat, L. Deuterium and oxygen 18 in precipitation: Modeling of the isotopic effects during snow formation. Journal of Geophysical Research 89, 11749-11757 (1984).

22. Rybak, O., Huybrechts, P., Steinhage, D. & Pattyn, F. Dating and accumulation rate reconstruction along the Dome Fuji - Kohnen radio-echo-sounding profile. Geophysical Research Abstracts 7, 05421 (2005).

23. Steinhage, D., Nixdorf, U., Meyer, U. & Miller, H. Subglacial topography and internal structure of central and western Dronning Maud Land, Antarctica, determined from airborne radio echo sounding. Journal of Applied Geophysics 47, 183-189 (2001).

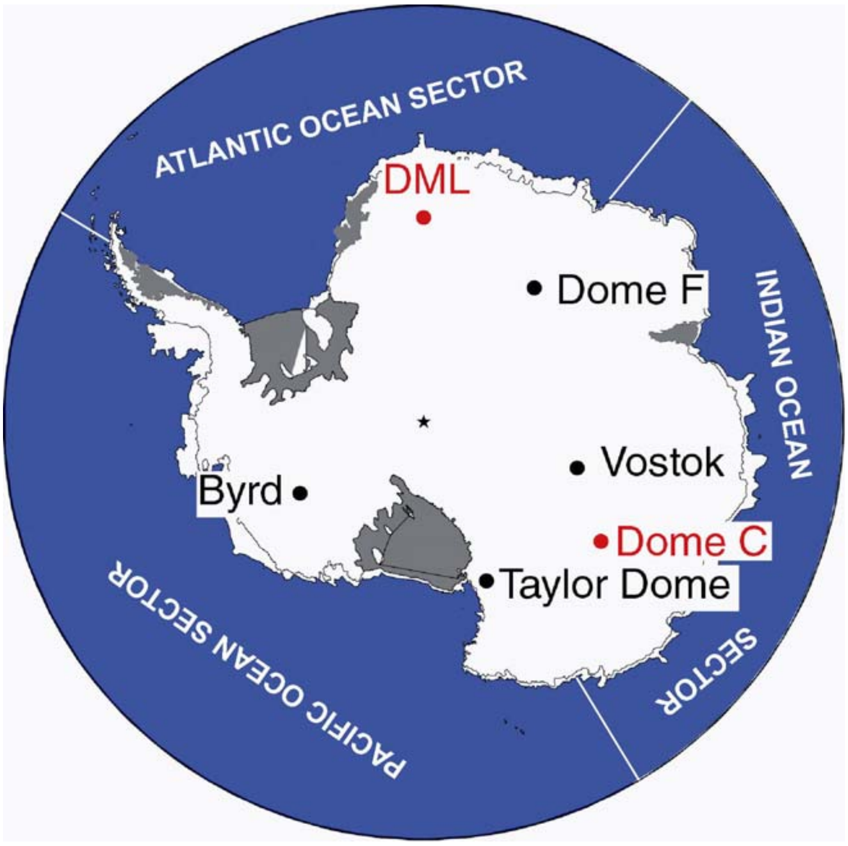

Figure S1: Map of the Antarctic continent indicating the EPICA drill sites in Dronning Maud Land (DML) and at Dome C together with previously drilled deep ice cores.

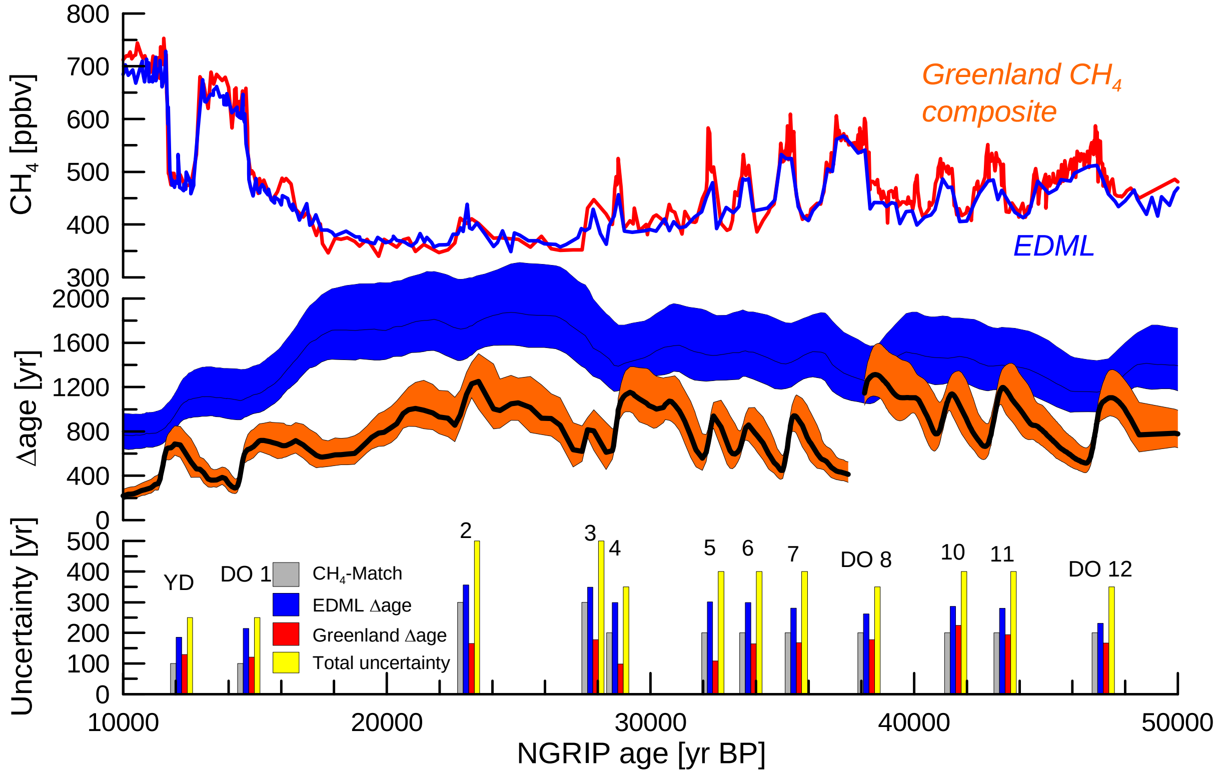

Figure S2: Top: CH_4 records for Greenland and EDML. Middle: Δage with uncertainty corresponding to a 25% change in accumulation. The effect is comparable to a 10% change in temperature. Blue for EDML and red for the Greenland composite, respectively. Before 38 kyr BP the synchronization is based on NGRIP data and the NGRIP Δage is shown. After 38kyr the synchronization is based on GRIP CH_4 data and the GRIP Δage is shown. Bottom: Contributions to the synchronisation uncertainty for individual rapid climate changes. Grey bar represents the uncertainty of the CH_4 synchronization. Blue and Red bars show the uncertainty of Δage assuming a 25% change in accumulation for EDML and the Greenland composite, respectively. The three components are added in quadrature to a total uncertainty for the synchronization of the ice records (yellow bars).

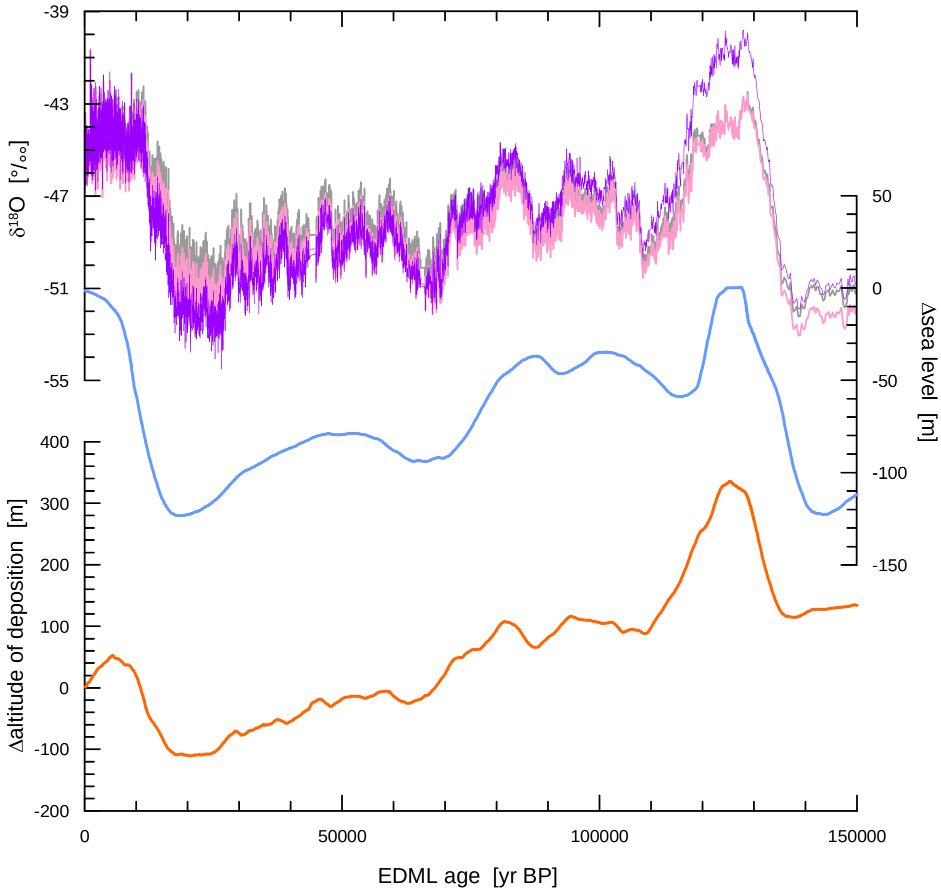

Figure S3: Top: Corrected $\delta^{18}O$ record at EDML: measured $\delta^{18}O$ data representative for the upstream site of deposition (grey); sea level corrected $\delta^{18}O$ data representative for the upstream site of deposition (pink); sea level and upstream corrected $\delta^{18}O$ record representative for the EDML current drill site (purple). Middle: Sea level changes used for the correction as derived from benthic $\delta^{18}O$ and ice sheet modeling[17]. The strongest effect is encountered for peak glacial periods where the continental ice volume was largest; Bottom: Elevation of the initial place of snow deposition relative to the current drill site at 2892m a.s.l. determined by a high-resolution higher order flow model[20] nested in a 3D large ice sheet model[19] used for altitude/upstream correction. This curve comprises both upstream effects (long-term upward trend in the correction) as well as local altitude changes of the ice sheet at the site and time of snow deposition in the past (variations around the long-term trend)[19].