Clim. Past Discuss., 4, 761–789, 2008
www.clim-past-discuss.net/4/761/2008/

Climate of the Past Discussions

Climate of the Past Discussions is the access reviewed discussion forum of *Climate of the Past*

The southern hemisphere at glacial terminations: insights from the Dome C ice core

R. Röthlisberger[1], M. Mudelsee[1,2], M. Bigler[3], M. de Angelis[4], H. Fischer[5,6], M. Hansson[7], F. Lambert[6], V. Masson-Delmotte[8], L. Sime[1], R. Udisti[9], and E. W. Wolff[1]

[1]British Antarctic Survey, Natural Environment Research Council, Cambridge, UK
[2]Climate Risk Analysis, Hannover, Germany
[3]Niels Bohr Institute, University of Copenhagen, Denmark
[4]Laboratoire de Glaciologie et Géophysique de l'Environnement, Grenoble, France
[5]Alfred Wegener Institut, Bremerhaven, Germany
[6]Climate and Environmental Physics, University of Bern, Switzerland
[7]Department of Physical Geography and Quaternary Geology, Stockholm University, Sweden
[8]Laboratoire des Sciences du Climat et de l'Environnement, Gif-sur-Yvette, France
[9]Department of Chemistry, University of Florence, Italy

Received: 21 May 2008 – Accepted: 23 May 2008 – Published: 19 June 2008

Correspondence to: R. Röthlisberger (rro@bas.ac.uk)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The many different proxy records from the European Project for Ice Coring in Antarctica (EPICA) Dome C ice core allow for the first time a comparison of nine glacial terminations in great detail. Despite the fact that all terminations cover the transition from a glacial maximum into an interglacial, there are large differences between single terminations. For some terminations, Antarctic temperature increased only moderately, while for others, the amplitude of change at the termination was much larger. For the different terminations, the rate of change in temperature is more similar than the magnitude or duration of change. These temperature changes were accompanied by vast changes in dust and sea salt deposition all over Antarctica.

Here we investigate the phasing between a South American dust proxy (non-sea-salt calcium flux, nssCa), a sea ice proxy (sea salt sodium flux, ssNa) and a proxy for Antarctic temperature (deuterium, δD). In particular, we look into whether a similar sequence of events applies to all terminations, despite their different characteristics. All proxies are derived from the EPICA Dome C ice core, resulting in a relative dating uncertainty between the proxies of less than 20 years.

At the start of the terminations, the temperature (δD) increase and dust (nssCa flux) decrease start synchronously. The sea ice proxy (ssNa flux), however, only changes once the temperature has reached a particular threshold, approximately 5°C below present day temperatures (corresponding to a δD value of –420‰). This reflects to a large extent the limited sensitivity of the sea ice proxy during very cold periods with large sea ice extent. At terminations where this threshold is not reached (TVI, TVIII), ssNa flux shows no changes. Above this threshold, the sea ice proxy is closely coupled to the Antarctic temperature, and interglacial levels are reached at the same time for both ssNa and δD.

On the other hand, once another threshold at approximately 2°C below present day temperature is passed (corresponding to a δD value of –402‰), nssCa flux has reached interglacial levels and does not change any more, despite further warming.

This threshold behaviour most likely results from a combination of changes to the threshold friction velocity for dust entrainment and to the distribution of surface wind speeds in the dust source region.

1 Introduction

The climate of the late Quaternary has been marked by repeated changes between glacial and interglacial periods. The reasons for such changes are still not entirely understood, although it seems clear that orbital forcing and internal feedback mechanisms involving greenhouse gases play a vital role (Huybers, 2006; Köhler and Fischer, 2006 and references therein). There are various processes that are influenced by and that exert an influence on the evolution of temperature and atmospheric CO_2. In high southern latitudes, the impact of sea ice extent and its connection to southern hemisphere winds and other factors that may contribute to ocean upwelling are of particular interest (Le Quere et al., 2007; Toggweiler et al., 2006).

The ice core from Dome C, Antarctica, that has been drilled in the framework of the European Project for Ice Coring in Antarctica (EPICA), provides a record of the last nine glacial – interglacial terminations in terms of changes in high latitude temperature (Jouzel et al., 2007), changes in greenhouse gases (Siegenthaler et al., 2005; Spahni et al., 2005) and various aerosols (Lambert et al., 2008; Wolff et al., 2006). Here we look into the pattern and phasing at terminations in different parameters, namely δD representing Antarctic temperature, nssCa flux, a proxy for aspects of South American climate (Röthlisberger et al., 2002; Wolff et al., 2006), and ssNa flux, which is related to the sea ice extent around Antarctica (Wagenbach et al., 1998; Wolff et al., 2003). The aim is to identify robust pattern and phase-relationships at glacial terminations between Antarctic temperature, South American conditions and the sea ice based on the ice core record from Dome C.

All parameters were measured along the same core, i.e. the records are all on the same timescale (Parrenin et al., 2007). The uncertainty in matching the three parameters is always much smaller than the resolution of δD. Therefore, the data offers excellent control of the relative timing between the proxies. However, the uncertainty of the absolute age is estimated 3 ka at 100 ka BP and approximately 6 ka for older sections of the ice core. In terms of event durations, the accuracy of the chronology is estimated to be 20% back to 410 ka BP and possibly 40% for older sections (Parrenin et al., 2007).

2 Methods

2.1 Data

The ice core was drilled from 1996 to 2004 and has been analysed for stable water isotopes (δD, Jouzel et al., 2007) at 55 cm resolution. The analysis of the soluble impurities (e.g. sodium (Na^+) and calcium (Ca^{2+})) has been done by seven European laboratories with different methods (Röthlisberger et al., 2008[1]), and low-resolution data along most of the core, using a previous age-scale, have already been published (Wolff et al., 2006). In this study, we used the data obtained by continuous flow analysis (CFA), (Röthlisberger et al., 2000), which resulted in a high-resolution record (of the order of 1 cm, corresponding to less than a year in the Holocene, approximately 3 years at 410 ka BP during marine isotope stage (MIS) 11, and 20 years at 800 ka BP during MIS 20). In the top part (0 to 450 ka BP), these data were downsampled to 20 years resolution by using the median of the data in each 20-a interval in order to reduce the computing time. Below that, computing time was within reasonable limits for the high-resolution data, so that 1 cm data were used for further analysis. Fluxes,

[1] Röthlisberger, R., Becagli, S., Bigler, M., Castellano, E., Angelis, M. d., Federer, U., Fischer, H., Fundel, F., Hansson, M., Hutterli, M. A., Jonsell, U., Karlin, T., Kaufmann, P., Lambert, F., Littot, G., Morganti, A., Mörth, C.-M., Mulvaney, R., Ruth, U., Severi, M., Andersen, M.-L. S., Steffensen, J., Twarloh, B., Udisti, R., Wegner, A., and Wolff, E. W.: Intercomparison of methods used for chemical analysis of the EPICA ice cores, Environ. Sci. Technol., in preparation, 2008.

CPD
4, 761–789, 2008
Glacial terminations in the EPICA Dome C ice core record
R. Röthlisberger et al.

being representative of atmospheric concentrations at sites where dry deposition is assumed to dominate, were calculated using the accumulation rates derived from the EDC3 timescale (Parrenin et al., 2007) (Fig. 1). The change points in accumulation rate are different from the change points in nssCa and ssNa flux, thus the uncertainty in reconstructing accumulation rate will translate into the ssNa and nssCa fluxes. However, in view of flux changes of the order of a factor of 2 to 4 in ssNa fluxes and 7 to 30 in nssCa fluxes over the nine glacial-interglacial terminations, the 30% uncertainty in accumulation rate is relatively small.

Both Ca and Na in the ice core originate from sea salt aerosol and terrestrial dust. However, Ca is predominantly of terrestrial origin, while Na derives mainly from sea salt. We calculated the non-sea-salt fraction of Ca of terrestrial origin (nssCa) and the sea-salt fraction of Na (ssNa) as in (Röthlisberger et al., 2002), using a Ca/Na weight ratio of 1.78 for terrestrial material (Rt), and 0.038 for sea water (Rm). The contribution from crustal material to total Na depends on the composition of the dust source material, and higher ratios Rt of the terrestrial source material could be used (Bigler et al., 2006), resulting in lower ssNa concentrations during glacial periods, but hardly any changes for interglacial periods. The effect of choosing different values for Rt on nssCa is negligible. For the aim of this study, the exact amplitude of glacial-interglacial changes in ssNa does not affect the timing of the changes, and the results remain within error bars regardless of which values are used to calculate ssNa and nssCa.

The data presented here are on the EDC3 timescale (Parrenin et al., 2007). The uncertainty in absolute ages is of the order of 6000 a for ice older than 130 ka. However, since all three records have been analysed on the same ice core, the uncertainty between nssCa flux, ssNa flux and δD is of the order of a few centimetres, i.e. always much less than the resolution of δD. This allows a very good time control in comparing the phasing of the different proxies at glacial terminations.

CPD
4, 761–789, 2008

2.2 RAMPFIT

In order to estimate the exact timing of a glacial termination in an objective way, we used a regression approach (RAMPFIT, Mudelsee, 2000). RAMPFIT is a weighted least-squares method that fits a ramp to the data. It estimates the level of a parameter for glacial (x2) and interglacial (x1) conditions and a linear change between the change points t1 and t2 (Fig. 2). A measure of the uncertainty of these estimated change points is based on a set of 400 bootstrap simulations for each parameter and each termination (Mudelsee, 2000;Politis and Romano, 1994).

A simulated time series is generated by adding a sequence of successive residuals to the fitted ramp. The length of the sequence of residuals is defined by the persistence of the data (four times the persistence time), thus preserving the autoregressive properties of the original data in the simulated time series. The ramp fitting is then repeated on the simulated data, giving a set of simulated ramp parameters, $t1^*$, $x1^*$, $t2^*$ and $x2^*$. This procedure is repeated 400 times, and the standard deviation of these 400 $t1^*$ values is used as bootstrap standard error for t1 (see histograms in Fig. 2). The bootstrap standard errors for x1, t2 and x2 were calculated analogously.

While the algorithm of RAMPFIT provides an objective estimate for the change points in a given data set, there are nevertheless some parameters that need to be chosen subjectively in the fitting procedure (e.g. the selection of the fit interval) that influence the result. For this study, we normally chose 2 ka beyond either end of the termination. In some instances, we chose shorter intervals in order to exclude sections of the data that had large deviations from a constant level and would thus distort the ramp. The parameters used for each termination are listed in the supplementary material http://www.clim-past-discuss.net/4/761/2008/cpd-4-761-2008-supplement.pdf (Table S1).

RAMPFIT minimizes the systematic deviations from constant glacial and interglacial levels and from the assumed linear change from glacial to interglacial conditions. However, a glacial termination does not necessarily conform to this simplified shape. For example, the interglacial levels need not be constant, or the termination may not progress linearly, but may change slope over time. This is illustrated in Fig. 3, where the Termination IV in nssCa flux is shown. Assuming a linear change over the entire termination results in change points that deviate from the change points that result from the assumed two-step termination. Alternatively, the glacial or interglacial levels are not constant, as for example the interglacial levels in δD in Termination III and IV, which reach high values early in the interglacial, but drop after a few thousand years (Fig. 4). This impacts the resulting levels and thus change points that RAMPFIT estimates. In other words, the choice of the fit interval used for RAMPFIT had some influence on the resulting change point estimates.

While we are aware of the limitations of the ramp model, we still think it provides valuable insights into the phasing at glacial terminations. A model is supposed to bring out the major properties of a system rather than reflecting the full complexity of the data. Additional parameters in a model that would lead to a better fit between model and data do not necessarily improve the understanding of the system. In the case of quantifying phasing at glacial terminations as presented in this paper, we decided that a ramp, and in some cases a two-step ramp, provides a sufficiently complex description of the data, especially for the main purpose of defining change points.

3 Results and discussion

The final ramps as calculated using RAMPFIT are shown in Fig. 4 and the estimated change points and error estimates are given in Table 1. A schematic of a termination is shown in Fig. 5. Across all terminations, δD and nssCa flux start to change synchronously (within error estimate, indicated by arrow a in Fig. 5), while ssNa flux shows a delayed onset of the glacial termination by a few thousand years (arrow b in Fig. 5). On the other hand, the end of the termination is normally synchronous between ssNa flux and δD (arrow d in Fig. 5). Interglacial levels of nssCa flux are either reached at the same time as δD and ssNa flux (Terminations I, V, VI, VII, VIII; arrow c in Fig. 5) or several thousand years earlier (Terminations II, III, IV, IX). In Terminations VI and VIII, the amplitude of the temperature change was relatively small. In these terminations, ssNa flux did not change significantly.

The δD in the ice core record is used primarily as a proxy for Antarctic temperature. However, especially at glacial terminations, other factors that have an influence on δD such as isotopic composition of seawater, moisture source region and local topography changes potentially changed quite significantly too. Therefore, the timing of the change in temperature compared to the changes in δD may be different. However, the change point estimates with RAMPFIT were also done on the reconstructed Dome C temperature T_{site} (not shown), which takes changes in moisture source region into account (Stenni et al., 2003). Estimates for the beginning of interglacial periods (t1) tend to be a few hundred years later in T_{site} than in δD, however, considering the uncertainty in the estimates, the change points were not significantly different from the change points estimated based on δD.

While the time difference between the start of the deglaciation in δD and the change point in ssNa flux tends to vary between 1 and 5 ka, the level of δD (–420±5‰) at the beginning of the termination in ssNa flux (t2) seems to be nearly constant over all terminations (Table 2). Similarly, the timing of the end of the termination in nssCa flux (t1) and δD varies considerably (0 to 2.5 ka), but the level of δD (–402±8‰) is more or less constant (Table 2). In other words, there are threshold levels in δD that correspond to the onset of changes in ssNa flux and to the end of changes in nssCa flux. These thresholds give rise to the apparent phase lags at the start or end of terminations. At glacial inceptions, the same threshold value seems to hold for ssNa flux (not shown). However, nssCa flux tends to build up more gradually at glacial inceptions. Nevertheless, the threshold found for glacial terminations defines the level below which the millennial-scale variability in nssCa flux correlates with δD.

These thresholds are illustrated in Fig. 6. While there seems to be a fairly close relationship between nssCa flux and δD during glacial periods up to δD of approximately –402‰ the relationship vanishes beyond this point and nssCa flux seems to be unrelated to δD. For ssNa flux, there is a good correlation with δD for values higher than approx. –420‰ however, below that, the ssNa flux seems to stay more or less constant.

3.1 Coupling of South America and Antarctica

The generally close coupling between South American dust flux and Antarctic climate during cold glacial conditions has been discussed recently based on the dust particle numbers in the Dome C ice core compared to δD (Lambert et al., 2008), and similar threshold levels below which the coupling manifests itself are derived. The factors that could influence the dust deposition in Antarctica are various parameters at the source (size of source area; conditions at the source, i.e. soil moisture, surface wind speed, vegetation, snow cover), atmospheric long-range transport (i.e. wind systems and wind speed) as well as the atmospheric lifetime of the dust particles. The implication of the threshold is that there is a point in the evolution of the climate system (represented by Antarctic temperature) beyond which one or more of these factors either ceases to change or ceases to influence dust.

Based on various transport models, changes in long-range transport (e.g. shorter transport times due to stronger winds) are unlikely to account for a large proportion of the observed changes (Krinner and Genthon, 2003; Lunt and Valdes, 2001), in line with evidence based on the size distribution of the dust particles (Lambert et al., 2008). Based on the comparison of the dust records from the two EPICA ice cores, Fischer et al. (2007) conclude that transport and lifetime effects have changed dust fluxes in Antarctica by less than a factor of 2, while Lambert et al. (2008) suggest that approximately a factor 5 of the glacial-interglacial change in dust flux might be explained by changes to the atmospheric lifetime while another factor of 5 is due to changes at the source. However, the change in atmospheric lifetime due to a reduced hydrological cycle is difficult to quantify. Results from a dust tracer model forced by a GCM showed only a marginal increase in lifetime, although with considerable uncertainty due to a poorly constrained scavenging ratio (Lunt and Valdes, 2002). The model produced a greatly increased Patagonian dust source during the LGM, mostly due to a decrease in soil moisture, with some contribution of decreased vegetation and increased land area during periods of low sea level.

Based on results from an atmospheric general circulation model (HadAM3), we looked into the relationship between changes in temperature at Dome C and various parameters of South American climate. It has been shown that the model provides a good representation of the present-day westerlies (Sime et al., 2008[2]) and modern Antarctic climatology (Connolley and Bracegirdle, 2007). In order to study the sensitivity of the South American climate to changing conditions, several model experiments were run with the present-day setup but with imposed sea surface temperature (SST) anomalies (Sime et al., 2008[2]). A robust result from all model experiments was the weakening and southward shift of the westerly wind belt associated with a warming at Dome C (Fig. 7). The change in latitude is related to the SST gradient in the southern hemisphere. The sensitivity of this change may be slightly higher for colder Dome C temperatures. Dust entrainment is related to surface wind speed by a power law, so that a modest decrease in surface wind speed at the most relevant latitudes could lead to a strong change in dust entrainment. This could therefore provide a link between the dust entrainment and the temperature at Dome C. The effect of changes in SST on dust entrainment may also be influenced by associated changes in precipitation. Increasing southern hemisphere SST leads to increased precipitation over Patagonia, therefore reducing the potential dust uplift due to raised soil moisture. Increased precipitation also promotes vegetation cover, as the major limiting factor for vegetation growth in Patagonia is precipitation (Markgraf et al., 2002), which further reduces dust uplift. Additionally, changes in South American topography due to ice cap disintegration at glacial terminations may have had an influence on wind pattern over the South American dust source.

From this analysis it is difficult to distinguish between the possible impacts of wind

[2]Sime, L., Le Quere, C., Heywood, K., De Boer, A., Bopp, L., Wolff, E. W., and Connolley, W. M.: Influence of changes in boundary conditions on Southern ocean winds at the last glacial inception, in preparation, 2008.

shifts over dust source regions and of non-linear processes involved in dust entrainment. It is likely that the threshold velocity for dust entrainment was reduced during glacial periods due to less precipitation and therefore less vegetation cover. Additionally, the average wind speed was increased during glacial periods, and potentially also the gustiness (i.e. the likelihood of substantially higher than average wind speeds over short periods of time). Due to the non-linear relationship between dust entrainment and wind speed, especially near an entrainment threshold, even small increases in average wind speeds and gustiness could have a significant impact on dust entrainment. The combination of the changes in wind speed distribution and threshold velocity could qualitatively explain the observed threshold behaviour in the Dome C nssCa flux record. However, from the rather low resolution model analysis it is difficult to discount the possibility that changes in the pattern of the South American winds relative to dust entrainment regions, related to ice-sheet changes or more general changes in the position of the westerlies, may have significantly affected the threshold behaviour we observe in the records.

3.2 Sea salt – sea ice relationship

In Antarctica, a large proportion of sea salt aerosol originates from sea ice surfaces rather than open water (Rankin et al., 2000; Wagenbach et al., 1998;Jourdain et al., 2008). Therefore, sea salt fluxes at Dome C have been used to infer past changes in sea ice extent in the Southern Ocean sector close to Dome C (Wolff et al., 2006; Wolff et al., 2003). As a first order approximation, one would expect to see a coupling between Antarctic temperature and sea ice extent. This should manifest in a general agreement in the δD and ssNa flux records from Dome C. While there indeed seems to be a strong correlation between δD and ssNa during mild stages (r=–0.80, significant at the 95% confidence level (Mudelsee, 2003), using 55 cm averages for ssNa flux and δD and all data with δD>–420‰), the relationship seems to break down during cold glacial conditions (r=–0.19, still significant at the 95% confidence level, for data with δD<–420‰). Obviously, during this time, one expects large sea ice extent around Antarctica, extending to over a thousand kilometres from the coast into the Southern Ocean (Gersonde et al., 2005). Sea salt aerosol produced at the distant margin of the sea ice cover will need to be transported over such long distances before reaching Dome C. However, it has been shown that the atmospheric sea salt aerosol concentration rapidly decreases with increasing transport distance, with only a small percentage of the original amount remaining after 500 km of transport (Minikin et al., 1994). Increasingly colder conditions will likely be accompanied by additional sea ice at the outer edge, at a distance of several hundred kilometres. But despite adding a considerable sea salt source area, the transport distance is so large that only a small fraction of this extra sea salt aerosol makes it to the East Antarctic plateau (Fischer et al., 2007). Although this requires confirmation, it appears likely that eventually, the effect of additional sea ice cannot be discriminated any more in the sea salt records. In other words, sea salt flux as a proxy for sea ice reaches some sort of saturation.

In view of this, the delayed onset of changes in ssNa flux with respect to the start of the warming at glacial terminations can be seen as the time when the sea ice proxy starts to respond to changes in sea ice again, i.e. when sea ice has retreated far enough so that further changes leave an imprint in the sea salt aerosol flux at Dome C. The end of the termination is synchronous in δD and ssNa, reflecting the expected relationship between Antarctic temperature and sea ice.

3.3 Rate of change

The results from RAMPFIT can also be used to calculate the rate of change over each glacial termination. The glacial – interglacial amplitude is estimated as the difference between x1 and x2, while the duration of a termination and its uncertainty were calculated directly by RAMPFIT. The uncertainty in duration, as well as in t1 and t2 for δD (see Table 1), is likely underestimated by RAMPFIT for Terminations VI, VII, VIII, IX. This is caused by the coarse temporal resolution of the δD data. For these four terminations, the average spacing between data points is used as an estimate of the uncertainty of the change points and the duration, but this may still underestimate the true uncertainty.

As seen in Fig. 8, the rate of change in δD was rather similar for all terminations, of the order of 0.01‰/year, which is equivalent to approximately 2°C/ka. Only for the early part of Termination III and for Termination IX the temperature seemed to rise at a slower rate (see Table 3). This was also observed in the rate of change in nssCa flux (not shown). The second warming step in Termination I, on the other hand, may have been exceptionally fast, as previously identified by (Masson-Delmotte et al., 2006) based on an independent analysis of the same data set. However, the uncertainty of this large rate of change is substantial, and the average rate of change observed during the other terminations lies well within the error bar. Generally, rates of change for ssNa and nssCa flux over the corresponding intervals were also rather similar for all terminations. The first step in nssCa flux change at Termination IV was faster than average, however, it was followed by a period of rather constant nssCa flux (which was not seen in δD), before resuming the change into full interglacial conditions (see Fig. 4). Averaged over the entire Termination IV, the rate of change in nssCa flux was very similar to the one observed at other terminations.

This implies that regardless of the final amplitude of the glacial – interglacial temperature change, the climate system keeps changing at a steady pace. The duration of the termination is therefore shorter in the case where the interglacial temperatures were cool compared to the cases where rather warm interglacial temperatures were reached. This could be viewed as an external trigger (orbital forcing) timing the start of a glacial termination, but internal amplifiers and feedbacks governing the rate of change; the factors that determine at what point (in time or climate) the termination ends remain uncertain.

4 Conclusions

The analysis of the nine glacial terminations recorded in the Dome C ice core has provided insights into the phasing at glacial termination. Over all terminations, a consistent pattern emerged, involving threshold values beyond which a coupling between Antarctic temperature and Patagonian dust proxy (nssCa flux) on the one hand and the response of the sea ice proxy (ssNa flux) on the other hand manifested itself.

Changes in South American dust emissions and Antarctic temperature are synchronous during cold glacial conditions but the dust response fades for conditions warmer than approximately 2°C below the present-day temperature at Dome C. The close link between dust and Antarctic temperature may be caused by the changes in wind pattern and precipitation over Patagonia that co-evolve with changes in temperature at Dome C.

Sea salt aerosol is closely linked to Antarctic temperature for interglacial conditions and conditions down to approximately 5°C cooler than present day. For these conditions, sea salt aerosol at Dome C can be used as a first-order proxy of sea ice in the Indian Ocean sector around Antarctica. For colder climate, the proxy is reaching some sort of saturation and fails to respond to likely further increases in sea ice extent. One result of this analysis is that we are no longer safe in suggesting that sea ice responded late in terminations and using this to apportion causes of CO_2 change; this conclusion was probably an artefact of the apparent threshold in response to sea ice change (Röthlisberger et al., 2004; Wolff et al., 2006).

The rate of change over glacial terminations as determined from the duration and the amplitude of the changes in δD seems to be rather similar over all glacial terminations. This suggests that once a glacial termination is triggered, the climate system progresses at its own pace. An exception with regard to this is a 3000 a period early on in Termination III where the rate of change seemed to be reduced significantly compared to the other terminations. It remains to be seen what caused this period to progress more slowly.

Acknowledgements. This work is contribution No. xy to the European Project for Ice Coring in Antarctica (EPICA), a joint European Science Foundation/European Commission (EC) scientific programme, funded by the EC and by national contributions from Belgium, Denmark, France, Germany, Italy, The Netherlands, Norway, Sweden, Switzerland and the UK. The main logistical support at Dome C was provided by IPEV and PNRA.

References

Bigler, M., Röthlisberger, R., Lambert, F., Stocker, T. F., and Wagenbach, D.: Aerosol deposited in East Antarctica over the last glacial cycle: Detailed apportionment of continental and sea-salt contributions, J. Geophys. Res., 111, D08205, doi:08210.01029/02005JD006469, 2006.

Connolley, W. M. and Bracegirdle, T. J.: An Antarctic assessment of IPCC AR4 coupled models, Geophys. Res. Lett., 34, L22505, doi:22510.21029/22007GL031648, 2007.

Fischer, H., Fundel, F., Ruth, U., Twarloh, B., Wegener, A., Udisti, R., Becagli, S., Castellano, E., Morganti, A., Severi, M., Wolff, E. W., Littot, G. C., Röthlisberger, R., Mulvaney, R., Hutterli, M. A., Kaufmann, P., Federer, U., Lambert, F., Bigler, M., Hansson, M., Jonsell, U., De Angelis, M., Boutron, C., Siggaard-Andersen, M.-L., Steffensen, J. P., Barbante, C., Gaspari, V., Gabrielli, P., and Wagenbach, D.: Reconstruction of millennial changes in dust emission, transport and regional sea ice coverage using the deep EPICA ice cores from the Atlantic and Indian Ocean sector of Antarctica, Earth Planet. Sci. Lett., 260, 340–354, 2007.

Gersonde, R., Crosta, X., Abelmann, A., and Armand, L.: Sea-surface temperature and sea ice distribution of the Southern Ocean at the EPILOG Last Glacial Maximum–a circum-Antarctic view based on siliceous microfossil records, Quat. Sci. Rev., 24, 869–896, 2005.

Huybers, P.: Early Pleistocene glacial cycles and the integrated summer insolation forcing, Science, 313, 508–511, 2006.

Jourdain, B., Preunkert, S., Cerri, O., Castebrunet, H., Udisti, R., and Legrand, M. R.: Year round record of size-segregated aerosol composition in central Antarctica (Concordia station): Implications for the degree of fractionation of sea-salt particles, J. Geophys. Res., doi:10.1029/2007JD009584, in press, 2008.

Jouzel, J., Masson-Delmotte, V., Cattani, O., Dreyfus, G., Falourd, S., Hoffmann, G., Minster, B., Nouet, J., Barnola, J. M., Chappellaz, J., Fischer, H., Gallet, J. C., Johnsen, S., Leuenberger, M., Loulergue, L., Luethi, D., Oerter, H., Parrenin, F., Raisbeck, G., Raynaud, D., Schilt, A., Schwander, J., Selmo, E., Souchez, R., Spahni, R., Stauffer, B., Steffensen, J. P., Stenni, B., Stocker, T. F., Tison, J. L., Werner, M., and Wolff, E. W.: Orbital and Millennial Antarctic Climate Variability over the Past 800 000 Years, Science, 317, 793–796, 2007.

Köhler, P. and Fischer, H.: Simulating low frequency changes in atmospheric CO_2 during the

last 740 000 years, Clim. Past, 2, 57–78, 2006, http://www.clim-past.net/2/57/2006/.
Krinner, G. and Genthon, C.: Tropospheric transport of continental tracers towards Antarctica under varying climatic conditions, Tellus, 55B, 54–70, 2003.
Lambert, F., Delmonte, B., Petit, J.-R., Bigler, M., Kaufmann, P., Hutterli, M. A., Stocker, T. F., Ruth, U., Steffensen, J. P., and Maggi, V.: Dust-climate couplings over the past 800,000 years from the EPICA Dome C ice core, Nature, 452, 616–619, 2008.
Le Quere, C., Rodenbeck, C., Buitenhuis, E. T., Conway, T. J., Langenfelds, R., Gomez, A., Labuschagne, C., Ramonet, M., Nakazawa, T., Metzl, N., Gillett, N., and Heimann, M.: Saturation of the Southern Ocean CO_2 Sink Due to Recent Climate Change, Science, 316, 1735–1738, 2007.
Lunt, D. J. and Valdes, P. J.: Dust transport to Dome C, Antarctica at the Last Glacial Maximum and present day, Geophys. Res. Lett., 28, 295–298, 2001.
Lunt, D. J. and Valdes, P. J.: Dust deposition and provenance at the Last Glacial Maximum and present day, Geophys. Res. Lett., 29, 2085, doi:2010.1029/2002GL015656, 2002.
Markgraf, V., Webb, R. S., Anderson, K. H., and Anderson, L.: Modern pollen/climate calibration for southern South America, Palaeogeography, Palaeoclimatology, Palaeoecology, 181, 375–397, 2002.
Masson-Delmotte, V., Dreyfus, G., Braconnot, P., Johnsen, S., Jouzel, J., Kageyama, M., Landais, A., Loutre, M.-F., Nouet, J., Parrenin, F., Raynaud, D., Stenni, B., and Tuenter, E.: Past temperature reconstructions from deep ice cores: relevance for future climate change, Clim. Past, 2, 145–165, 2006, http://www.clim-past.net/2/145/2006/.
Minikin, A., Wagenbach, D., Graf, W., and Kipfstuhl, J.: Spatial and seasonal variations of the snow chemistry at the central Filchner-Ronne Ice Shelf, Antarctica, Ann. Glaciol., 20, 283–290, 1994.
Mudelsee, M.: Ramp function regression: a tool for quantifying climate transitions, Computers and Geosciences, 26, 293–307, 2000.
Mudelsee, M.: Estimating Pearson's Correlation Coefficient With Bootstrap Confidence Interval From Serially Dependent Time Series, Mathematical Geology, 35, 651–665, 2003.
Parrenin, F., Barnola, J. M., Beer, J., Blunier, T., Castellano, E., Chappellaz, J., Dreyfus, G., Fischer, H., Fujita, S., Jouzel, J., Kawamura, K., Lemieux-Dudon, B., Loulergue, L., Masson-Delmotte, V., Narcisi, B., Petit, J. R., Raisbeck, G., Raynaud, D., Ruth, U., Schwander, J.,

Severi, M., Spahni, R., Steffensen, J. P., Svensson, A., Udisti, R., Waelbroeck, C., and Wolff, E.: The EDC3 chronology for the EPICA dome C ice core, Climate of the Past, 3, 485–497, 2007.
Politis, D. N. and Romano, J. P.: The stationary bootstrap, J. Am. Stat. Assoc., 89, 1303–1313, 1994.
Rankin, A. M., Auld, V., and Wolff, E. W.: Frost flowers as a source of fractionated sea salt aerosol in the polar regions, Geophys. Res. Lett., 27, 3469–3472, 2000.
Röthlisberger, R., Bigler, M., Hutterli, M., Sommer, S., Stauffer, B., Junghans, H. G., and Wagenbach, D.: Technique for continuous high-resolution analysis of trace substances in firn and ice cores, Environ. Sci. Technol., 34, 338–342, 2000.
Röthlisberger, R., Mulvaney, R., Wolff, E. W., Hutterli, M. A., Bigler, M., Sommer, S., and Jouzel, J.: Dust and sea-salt variability in central East Antarctica (Dome C) over the last 45 kyrs and its implications for southern high-latitude climate, Geophys. Res. Lett., 29, 1963, doi:1910.1029/2002GL015186, 2002.
Röthlisberger, R., Bigler, M., Wolff, E. W., Joos, F., Monnin, E., and Hutterli, M. A.: Ice core evidence for the extent of past atmospheric CO2 change due to iron fertilisation, Geophys. Res. Lett., 31, L16207, doi:16210.11029/12004GL020338, 2004.
Siegenthaler, U., Stocker, T. F., Monnin, E., Lüthi, D., Schwander, J., Stauffer, B., Raynaud, D., Barnola, J.-M., Fischer, H., Masson-Delmotte, V., and Jouzel, J.: Stable carbon cycle-climate relationship during the late pleistocene, Science, 310, 1313–1317, 2005.
Spahni, R., Chappellaz, J., Stocker, T. F., Loulergue, L., Hausammann, G., Kawamura, K., Flückiger, J., Schwander, J., Raynaud, D., Masson-Delmotte, V., and Jouzel, J.: Atmospheric methane and nitrous oxide of the late pleistocene from Antarctic ice cores, Science, 310, 1317–1321, 2005.
Stenni, B., Jouzel, J., Masson-Delmotte, V., Röthlisberger, R., Castellano, E., Cattani, O., Falourd, S., Johnsen, S. J., Longinelli, A., Sachs, J. P., Selmo, E., Souchez, R., Steffensen, J. P., and Udisti, R.: A late-glacial high resolution site and source temperature record derived from the EPICA Dome C isotope records (East Antarctica), Earth Planet. Sci. Lett., 217, 183–195, doi:110.1016/S0012-1821X(1003)00574-00570, 2003.
Toggweiler, J. R., Russell, J. L., and Carson, S. R.: Midlatitude westerlies, atmospheric CO2, and climate change during the ice ages, Paleoceanography, 21, 2006.
Wagenbach, D., Ducroz, F., Mulvaney, R., Keck, L., Minikin, A., Legrand, M., Hall, J. S., and Wolff, E. W.: Sea-salt aerosol in coastal Antarctic regions, J. Geophys. Res., 103, 10 961–

910 974, 1998.

Wolff, E. W., Rankin, A. M., and Röthlisberger, R.: An ice core indicator of Antarctic sea ice production?, Geophys. Res. Lett., 30, 2158, doi:2110.1029/2003GL018454, 2003.

Wolff, E. W., Fischer, H., Fundel, F., Ruth, U., Twarloh, B., Littot, G. C., Mulvaney, R., Röthlisberger, R., De Angelis, M., Boutron, C. F., Hansson, M., Jonsell, U., Hutterli, M. A., Lambert, F., Kaufmann, P., Stauffer, B., Stocker, T., Steffensen, J. P., Bigler, M., Siggaard-Andersen, M.-L., Udisti, R., Becagli, S., Castellano, E., Severi, M., Wagenbach, D., Barbante, C., Gabrielli, P., and Gaspari, V.: Southern ocean sea-ice extent, productivity and iron flux over the past eight glacial cycles, Nature, 440, 491–496, 2006.

Table 1. The timing of glacial terminations in δD, log(nssCa flux) and log(ssNa flux). t1 corresponds to the time when interglacial levels are reached, t2 to the time when the first deviation from glacial levels is observed. In some instances the analysis with RAMPFIT was done over two subsections in order to take account of a two-step shape of the termination. See methods for details regarding RAMPFIT. The uncertainty in t1 and t2 for δD is likely underestimated by RAMPFIT for Terminations VI, VII, VIII, IX due to the coarse temporal resolution of the data. For these terminations, the values in brackets are derived by RAMPFIT. The values in italic correspond to the average spacing of the data at that age, which is used as an estimate of the uncertainty.

	δD				nssCa				ssNa			
Term.	t1	±	t2	±	t1	±	t2	±	t1	±	t2	±
I	11686	235	12350	252	10990	620	13970	548	11330	186	13370	239
	14796	147	17630	150	14150	132	17630	86				
II	129459	82	135402	110	132091	190	135371	110	129731	192	133731	103
III	242867	111	246528	148	245491	354	246871	339	242891	455	246451	202
	248293	641	251915	718	248111	347	252091	303				
IV	334103	301	341121	403	336392	358	338752	353	334792	313	338732	198
					339872	114	341132	116				
V	425813	471	430693	617	425053	201	430833	151	425973	426	429013	405
VI	529157	(246) *340*	531284	(233) *540*	529055	234	531405	203				
VII	626073	(83) *720*	629486	(58) *1320*	625922	218	629886	203	625715	158	627438	129
VIII	737354	(225) *580*	740867	(214) *590*	737784	184	741171	192				
IX	787298	(221) *640*	796449	(106) *1040*	789788	325	796937	346	787083	96	788270	70
									789590	128	792007	115

Table 2. Levels of δD at the change points of glacial sea salt ($t2_{ssNaflux}$) and interglacial dust ($t1_{nssCaflux}$). Missing values in $t2_{ssNaflux}$ and values in parentheses in $t1_{nssCaflux}$ represent terminations where the thresholds for ssNa flux and nssCa flux were not reached.

Termination	δD(‰) $t2_{ssNaflux}$	δD(‰) $t1_{nssCaflux}$
I	–412.6	–392
II	–416.2	–401.1
III	–426.8	–413.2
IV	–419	–400.4
V	–426.4	–392.8
VI	–	(–416.6)
VII	–419	–405.3
VIII	–	(–417.4)
IX	–420.2	–407.2
Average	–420	–402
Standard deviation	5.1	7.6
Standard error	1.9	2.9

CPD
4, 761–789, 2008

Table 3. Rate of change in δD over terminations.

Termination	Duration (years)	Change rate (‰/year)	±
Ia	664	–0.025	0.0170
Ib	2834	–0.011	0.0011
II	5943	–0.011	0.0003
IIIa	3661	–0.013	0.0009
IIIb	3622	–0.003	0.0011
IV	7018	–0.010	0.0009
V	4880	–0.008	0.0016
VI	2127	–0.007	0.0015
VII	3413	–0.010	0.0029
VIII	3513	–0.007	0.0011
IX	9151	–0.005	0.0004

CPD

4, 761–789, 2008

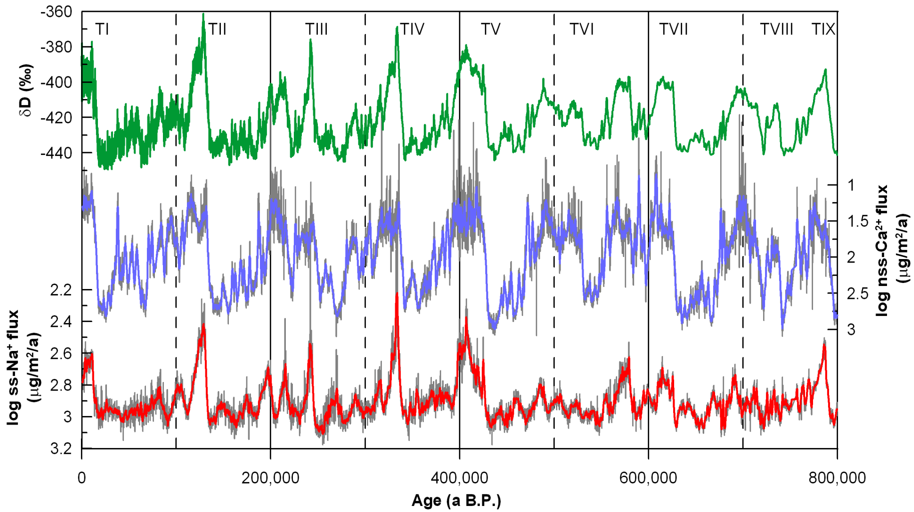

Fig. 1. Overview of entire data set. Shown are 0.55 m averages of δD (green) and 100 year averages of the logarithm of nssCa and ssNa flux (grey) overlaid by a 11-point running average (blue, red). Y-axes of nssCa flux and ssNa flux have been reversed in order to facilitate comparison with δD.

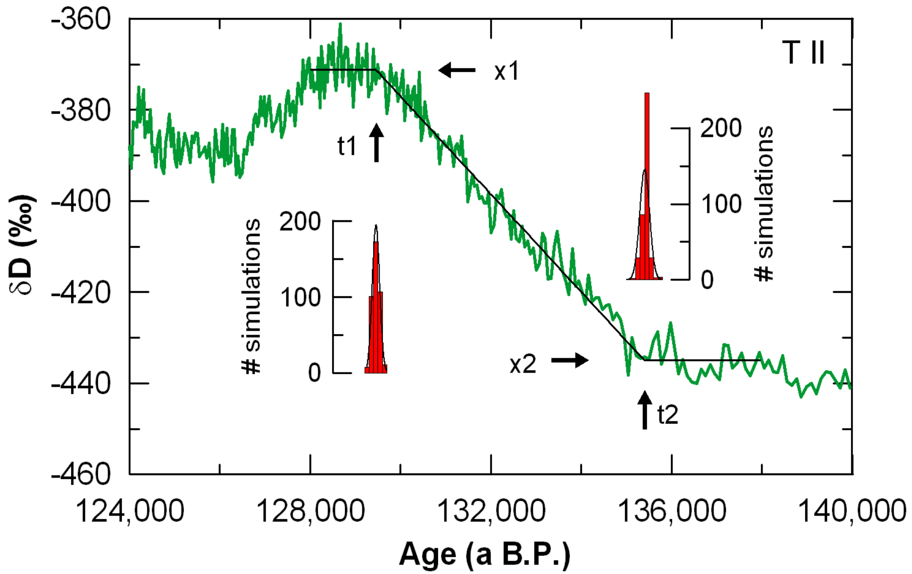

Fig. 2. Example of RAMPFIT results for δD at Termination II. The black line represents the ramp that best fits the data based on weighted least-squares regression. Arrows indicate the levels x1 and x2 and the change points t1 and t2. The histograms show the change points for 400 bootstrap simulations. The distribution of these simulated change points is used to derive an estimate of the uncertainty of the change points.

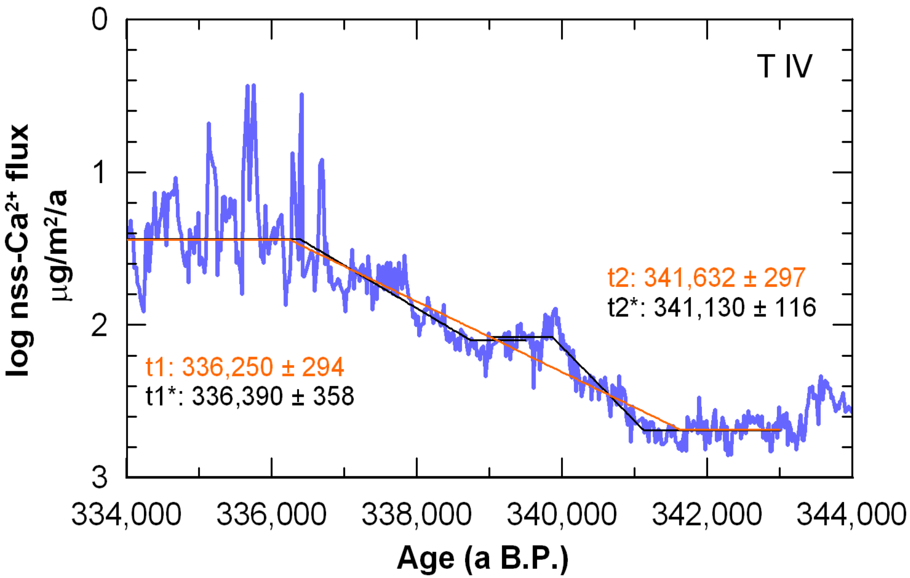

Fig. 3. Example of RAMPFIT results for nssCa^{2+} flux at Termination IV. The y-axis has been reversed. The orange line corresponds to a ramp fitted over the entire section; the black lines correspond to two separate ramps. The estimated change points are given for the single ramp (t1, t2) and for the corresponding two-step ramp (t1*, t2*).

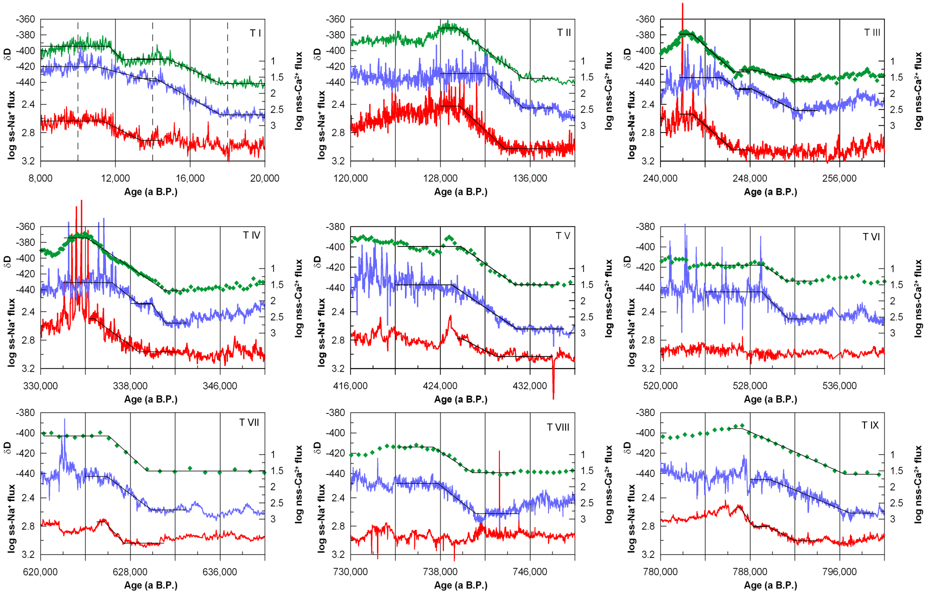

Fig. 4. Glacial terminations and ramps (black) estimated by RAMPFIT. δD in ‰ (green), nssCa (blue) and ssNa fluxes (red) in $\mu g/m^2/a$. Y-axes for ssNa and nssCa have been reversed.

CPD

4, 761–789, 2008

Glacial terminations in the EPICA Dome C ice core record

R. Röthlisberger et al.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

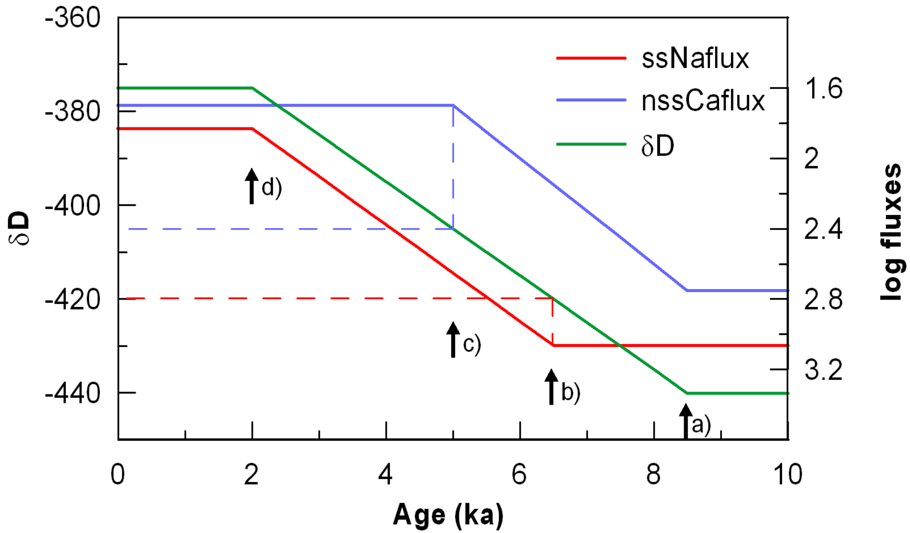

Fig. 5. Schematic of a glacial termination. Arrows indicate change points in nssCa flux and ssNa flux (Y-axis for log fluxes reversed). Dashed lines indicate the threshold levels in δD.

CPD
4, 761–789, 2008

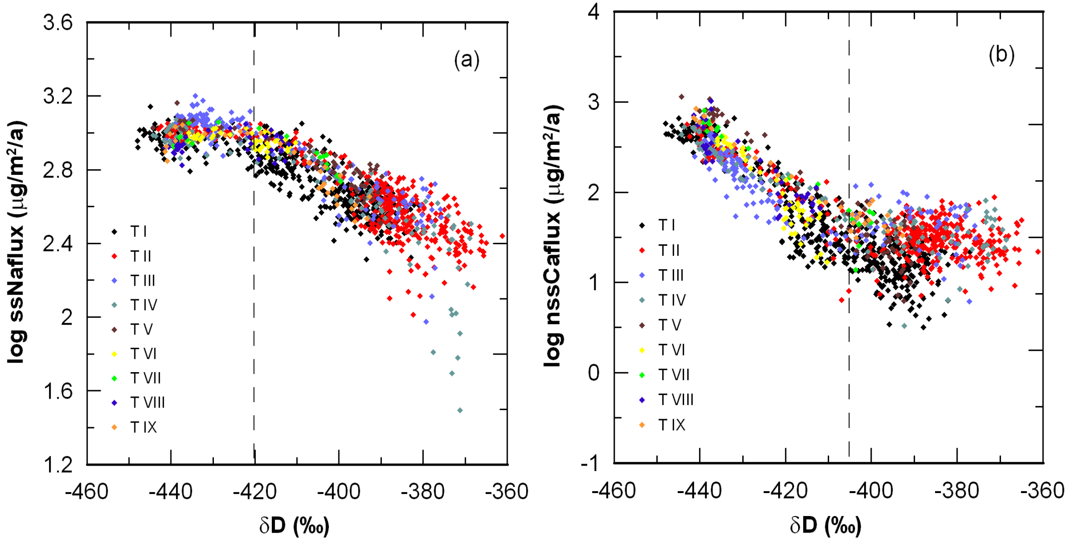

Fig. 6. Sea salt **(a)** and dust flux **(b)** versus δD over glacial terminations. The thresholds are indicated by a vertical dashed line. They are reflected in the different slopes in the relationship between sea salt (dust) and δD above and below the thresholds. The data from each termination are plotted in a different colour.

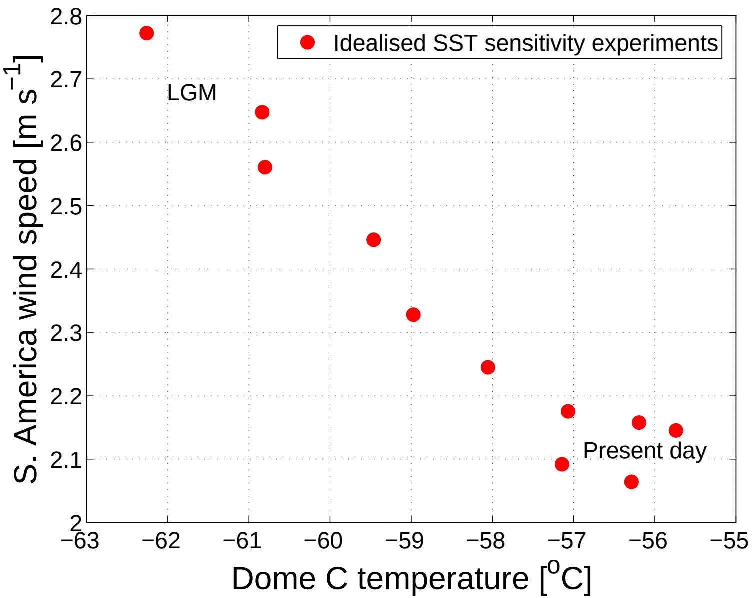

Fig. 7. Relationship between South American wind speed and temperature at Dome C for a set of experiments with the Hadley centre atmospheric general circulation model HadAM3. Each data point represents a different amount of cooling of present-day SST, and shown are the resulting annual average wind speeds over South American landmasses south of 40° S against modelled temperature at Dome C.

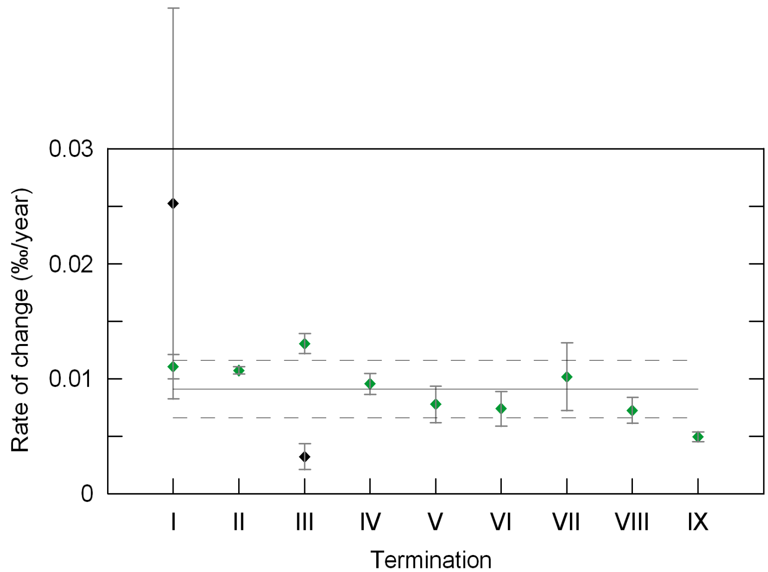

Fig. 8. Rate of change calculated based on termination ramps in δD. For T I and T III, two ramps were fitted to the data (see Fig. 4 and Table 1), and the rate of change has been calculated for each ramp separately. Error bars correspond to one standard error. The black diamond at T I corresponds to the short warming around 12 ka BP. It seems as if this warming was exceptionally fast, however, the uncertainty is large due to the short duration compared to the uncertainty in the determination of t1 and t2. The early part of Termination III seems to be exceptionally slow (black diamond) compared to the other terminations (see also Fig. 4). Also, Termination IX seems to progress slower than average. However, the uncertainty of the rate of change is most likely considerably underestimated. The horizontal lines represent the average rate of change (solid) plus/minus one standard deviation (dashed), calculated from all data except the two black data points.

CPD

4, 761–789, 2008