Point-by-point reply to comments of the two anonymous reviewers.

First of all we would like to thanks both reviewers for their comments. We have mostly followed them in the revised version as described below.

Reviewer 1

R1 requires in his main comment: ”In particular I would recommend emphasizing and discussing more the revisited chronology for the Nussloch loess/paleosol sequence, which is the one element that is innovative with reference to Rousseau et al., 2017 in terms of data.

DDR: As this paper is the follow-up of Rousseau et al. (2017) in which the revised chronology of Nussloch sequence is decribed, and the precise correlation betwen the paleosols and the Greenland interstadials, we did not think it was useful to repeat it in this manuscript but just refer to it

Specific comments

2, 30-31: Check parentheses

DDR: done

2, 37: Check the punctuation “events: For the last”

DDR: done

2, 39: “Dust concentration would require at least fifteen years to decrease”. Why “would require”? Please explain

DDR: because of the building of the sentence

2, 41: either “that occurs” or “occurring”

DDR: corrected with ”that occurs”

2, 43: Check the punctuation “variable as well: High-resolution studies”

DDR: done

2, 53-56: In this paragraph please explain more clearly what is the added value of this paper compared to e.g. Rousseau et al., 2017

DDR: sentence added

2, 54-55: it may be more clear if sequences of deposition rates were somehow aligned in a graph or tables with those from Europe to facilitate the comparison of the relative variability

DDR: In Rousseau et al 2017, correlations between the main European loess sequences are presented in the supplmentary figure x. This is our expectation to produce another paper with such results concerning all identified GS

3, 66: briefly explain the differences/advantages etc of the visual vs algorithmic approaches

DDR: sentence added

3, 66: “with an increase”?

DDR: because when passing from stadials to interstadials values, the d18O ratio becomes lighter, the negative values evolving towards zéro

3, 73-75: Please discuss more in detail the reasoning behind this type of approach, and why it applies to Nussloch but not to the Chinese loess sequences discussed later in the manuscript, for instance

DDR: sentence added

4, 15-17: The size of the sources may not have varied, but how about their emissions? Could you comment on what the Chinese loess records show in this respect?

DDR: sentence added and reference to data from Japan Sea marine core MD01-2407 given explaining the varying dominance between Gobi and Taklamakan deserts during GS and GI

6, 98: Do you mean "particularly high"?

DDR: yes, corrected

Reviewer 2

Specific Comments

The manuscript strongly refers to Rousseau et al. (2017, under revision), and to some extend also to Moine et al. (2017, in press). Both articles are meanwhile published online.

DDR: the references in press or under revision have been updated

Page 3, line 74 "stop of the eolian sedimentation": As a model assumption this may be justified. It is not sure however, if sedimentation stopped totally or continued with a strongly reduced rate as is the case for some steppe soils. This uncertainty which would be propagated to the timing and to the MAR should be addressed in the text.

DDR: sentence has been added precising that this is available for west European loess sequences in which no steppe soils have been described during glacial interval. This comment is therefore not relevant. Furthermore in their paleomag study of Nussloch sequence, Taylor et al. 2014 have shown that their was no eolian enrichment in the paleosols (brown arctic paleosols and tundra gleys).

Page 4, lines 11-37: It is stated that maximum activity of present day dust storms in Asia occurs in April. Which evidence allows to resume this for the last glacial? Seasons probably shifted a bit due to more continental climate leading to longer winter and shorter spring.

DDR: sentence added explaing that our reasoning is base on modelling experiment performed for Europe where we indeed identified some shift in the maximum of emission but that much.

Page 6, line 97 to 98: The IRSL ages given by Frechen et al. (2003) are prone to age underestimation. Thus, MAR may be overestimated.

DDR: As Frechen et al 2003 is the only reference available for Europe, this is the reason why we cite dit. Now Frechen et al. (2013) fairly referred to published data and determined the published MAR values accordingly. This is the reason why we are focusing on Nussloch data to illustrate our aim that to produce reliable data for model-observation comparison, the used sequences must have been properly dated with a serious dating work but also a precise description of the stratigraphy.

Technical Comments

Page 3, lines 67 and 69: does „1s" mean „1 sigma"? (Also further down in the text). If so use Greek σ. GI duration of "1048±1163 years" and "1053±1068 years": Error is larger than the mean value. Clarify that this is probably due to few long interstadials. See also page 3, lines 87 and89.

DDR: "1σ" corrected all over the manuscript. This is due to a problem a transfer between two computers. Clarification given

Page 5, line 47: replace "along" by "at the eastern margin of"

DDR: done

Page 5, line 77: "Greenland warmings leading *to* Antartic coolings"

DDR: no reviewer 2 is wrong. We refer to the paper which conclusion is that Greenland warmings are leading Antarctic coolings

Page 13, line 41: records

DDR: corrected

Page 13, line 43: sequences

DDR: corrected

Page 13, line 46: Rousseau et al. 2017

DDR: corrected

Page 13, line 54: unit for dust should be “part/µL” (see Fig. 4)? Also, indicate which color indicates δ^{18}O and which one dust.

DDR: unit corrected (another mispelling due to transfer of the draft version between to different word processor). Color precised in Fig 4 and 2

Page 13, line 58: rewrite “Hpa” as hPa (hectopaoscal).

DDR: corrected

Figure 3, column “MAR”: **1952 – 1952.** Identical values (type error?)

DDR: no these are the good estimates

Figure 5: Can you replace the out-dated unit “mb” by “hPa”?

DDR: corrected

Editor

Last sentence of the conclusion corrected

Eurasian contribution to the last glacial dust cycle: how are loess sequences built?

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Key words: Palaeoclimatology, Glaciology, Geomorphology, Atmospheric science, Climate Science, Geophysics, Oceanography, loess

Abstract. The last 130,000 years have been marked by pronounced millennial scale climate variability, which strongly impacted the terrestrial environments of the Northern Hemisphere especially at middle latitudes. Identifying the trigger of these variations, which are most likely associated with strong couplings between the ocean and the atmosphere, still remains a key question. Here, we show that the analysis of $\delta^{18}O$ and dust in the Greenland ice cores, and a critical study of their source variations, reconciles these records with those observed on the Eurasian continent. We demonstrate the link between European and Chinese loess sequences, dust records in Greenland, and variations of the North Atlantic sea ice extent. The sources of the emitted and transported dust material are variable and relate to different environments corresponding to present desert areas, but also hidden regions related to lower sea level stands, dry rivers, or zones close to the frontal moraines of the main Northern Hemisphere ice sheets. We anticipate our study to be at the origin of more sophisticated and elaborated investigations of millennial and sub-millennial continental climate variability on the Northern Hemisphere.

1 Introduction

During the last glacial interval, abrupt climate changes have been documented worldwide in different types of records, but especially in ice cores (Dansgaard et al., 1969, 1982; Johnsen et al., 1992; Johnsen et al., 1972, 2001). Their interpretation mostly focused on the more spectacular character corresponding to abrupt warmings (named Dansgaard-Oeschger -DO- events, Broecker et al., 1990) of some ten degrees to interstadial conditions in Greenland (Kindler et al., 2014). These warmings were followed by a schematic two-step return to stadial conditions. Modeling experiments are able to reconstruct this abrupt warming and the two-step return to stadial conditions, indicating a periodicity of about 1500 years (Schulz, 2002; Rahmstorf, 2003) which, however, still remains questionable (Ditlevsen et al., 2007; Thomas et al., 2011; Boers et al., 2017). More precisely, the very high-resolution analysis of the last deglaciation in the North Greenland Ice Core Project (NGRIP) record (North Greenland Ice Core Project, 2004), Greenland, revealed that different parameters show different abruptness of the warming events. For the last two warming events (14.7 and 11.7 ka b2k), deuterium excess increased within one to three years, alongside with more gradually increasing temperatures as represented by δ^{18}O. Dust concentration would require at least fifteen years to decrease, preceding the deuterium excess increase by 10 ± 5 years (Steffensen et al., 2008). Considering carefully the DO events noticed during the last climatic cycle in NGRIP, some variability that occurs as the last deglaciation timing of transitions does not seem to reproduce every time in the older parts of the record (Rousseau et al., 2017). The climate trend, cooling and increase in dustiness, within these particular events is variable as well. High-resolution studies of the temperature signal in older interstadials show the occurrence of sub-millennial scale elements like precursor events of about centennial duration before the interstadial itself, rebound events exhibiting abrupt cooling towards stadial conditions, and cooling events occurring towards the end of the interstadial (Capron et al., 2010). These sub-millennial events make the understanding of the climate variability during these interstadials even more complicated than a simple warming followed by a two-step cooling. Ice cores nevertheless provide much more information than on temperature and dust concentration only, as they release records of numerous components of the climate system, isotope values of the transported water vapor, mineral aerosols and greenhouse gas concentrations, chemical elements, etc., which show different origins and transport patterns to the high latitude ice-sheets. Such richness in proxies allows comparisons with other records of millennial scale variability preserved in both marine (Henry et al., 2016) and terrestrial deposits, as well as in other ice cores (Barbante et al., 2006; Buizert et al., 2015). In this paper, after briefly describing the abrupt changes observed in the very high resolution δ^{18}O and dust records from NGRIP (North Greenland Ice Core Project, 2004), we compare the dust particle sedimentation rates over Europe and China as expressed in key loess sequences (Fig. 1). This is a complementary study of Rousseau et al. (2017), which essentially focused on paleosol development. In the last section we provide an interpretation of the link between Greenland dust records and Eurasian loess sequence development.

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2 Analysis

We investigate in this study the 18 Greenland interstadials (GI), labeled from 17.1 to 2 (Rasmussen et al., 2014), which have been identified during the MIS 3 and 2 (59 – 14 ka b2k) interval. We performed this comparison by studying in parallel the δ^{18}O (NGRIP members, 2004; Gkinis et al., 2014) and the dust (Ruth et al., 2003) records from the NGRIP ice core at the highest resolution. These two indices correspond to different sources, marine and continental, respectively, but also to different origins, mostly Atlantic (Masson-Delmotte et al., 2006) and East Asian (Biscaye et al., 1997; Svensson et al., 2000; Bory et al., 2002), respectively. The two indices are not directly related so that if similarities would appear, this should highlight a more global phenomenon.

The compilation of the 18 GI in the NGRIP record (Rousseau et al., 2017) shows that DO events can be characterized using a numerical algorithm (see supplementary material) by an increase of δ^{18}O occurring on average in 36.4 ± 13.4 (1σ) years, with a mean GI duration of 1048 ± 1163 (1σ) years (Tab. 1). When determined visually by considering the onset of the abrupt change at the start and the return to the same initial value as the end of the event, the δ^{18}O changes occur, on average, in 55.4 ± 16.1 (1σ) years, with a mean duration of 1053 ± 1068 (1σ) years. The larger errors than the mean values are due to the few long intervals. These two methods have been described in detail in Rousseau et al. (2017). Although both methods allow identifying the GI and their parameters (onset, transition and duration), the numerical approach allows also to identify statistically significant events that the virtual one could consider as questionable. However, we consider that these two methods are complementary, the reason why we decided to release values obtained by both of them. These compiled characteristics fit with the values generally considered from the literature (Wolff et al., 2010; Rasmussen et al., 2014;).

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Following the detailed correlations defined between Nussloch and NGRIP stratigraphies (Fig. 2) (Rousseau et al., 2002, 2007b, 2017), we then applied the dates obtained for every start and end of a GI, from both the δ^{18}O and the dust NGRIP timescale, to the loess sequence. This was performed by considering that in west European loess sequences, paleosols developed from the underlying loess deposits after a stop of the eolian sedimentation (Taylor et al., 2014), and that the eolian sedimentation itself restarted on top of the developed paleosols. This makes the time evolution non-linear and a bit more complex, than the classical continuous sedimentation observed in other terrestrial, marine, and ice core records (Kukla and Koci, 1972; Rousseau et al., 2007a). Therefore, a determined eolian interval, equivalent to a Greenland stadial (GS), includes the loess unit and the overlying paleosol (blue arrow in Figure 3), while the paleosol development itself fits with the GI duration (red arrow in Figure 3). Doing so, the Nussloch stratigraphy can be read as expressed in Table 2, allowing then to better estimate the sedimentation and the mass accumulation rates required for comparison with other loess records and model outputs. In Chinese loess sequences on the contrary, no such paleosols developed during the last climate cycle. Therefore, own reasoning do not apply to these records.

3 Discussion

Mineral dust record in the NGRIP ice core is obtained from variations in dust concentration, measured in the terms of the number of particles larger than 1 micron per milliliter of melt water, which shows also abrupt changes that are quite synchronous to the DO events expressed in the δ^{18}O record (Mayewski et al., 1994; Ruth et al., 2003; North Greenland Ice Core Project, 2004; Rasmussen et al., 2014). Abrupt decreases in the dust concentration occur in 60 ± 21.2 (1σ) years on average, with a mean GI duration of 1079 ± 1135 (1σ) years when determined with the same algorithm as for δ^{18}O; when determined visually, the dust decrease occurs in 56.8 ± 19.6 (1σ) years on average, with a mean duration of 1079 ± 1079 (1σ) years (Tab. 1). Interestingly, the dust change reaches its minimum value on average about 6 years after the δ^{18}O. These abrupt changes also correspond to abrupt temperature differences of on average 11.6 ± 2.7 (1σ) °C for the GI 17.1 to 2 (Kindler et al., 2014) Tab. 1). The amplitude of the change in the dust concentration corresponds in average to a factor of 6 in about 57 years. These values are different from previous investigations of the GRIP dust

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record, which were showing much more rapid changes in a few years, but they seem more realistic than extremely abrupt shifts that would be particularly difficult to interpret from a dynamical point of view.

Isotope studies of the dust recorded in the Greenland ice cores demonstrated an Asian origin for both summer and winter seasons (Biscaye et al., 1997; Svensson et al., 2000), while the analysis of modern dust preserved in modern firn indicates a different origin for summer (essentially Takla Makan) and winter (Takla Makan and northern Chinese and Mongolian deserts) (Bory et al., 2002). The transport of the modern chemical aerosols towards Greenland also partly supports an Asian origin and therefore allows interpreting the dust record in the ice cores (Goto-Azuma and Koerner, 2001). Indeed, the major dust event recorded in China in April 6, 2001, the largest ever-recorded dust storm worldwide, provides relevant information about the Asian dust transport, past and present, towards Northern Hemisphere ice-sheets. The identification of the dust particles related to this event on top of Mt Logan, Alaska, indicates that the assumption of Asian dust origin also in the past is particularly adequate (Zdanowicz et al., 2006). The presence of the large Laurentide ice-sheet over North America at least at the last glacial maximum caused a split of the polar jet stream, inducing two main pathways for the Asian fine dust transport eastwards (Fig. 4). A comparison of the different GI dust records indicates that the dust concentration falls in about 60 years by a factor of 8 from the beginning of the warming during DO events. These values are similar to the variations of a factor of 5 to 7 during four decades observed during the 15.5 - 11.5 ka b2k interval (Steffensen et al., 2008). Reducing so drastically the dust concentration in the ice core implies a similar drastic reduction of the dust concentration in the atmosphere, relying on changes in the sources, in the transport, and/or in the deposition of the particles (Fischer et al., 2007).

Concerning the changes in the sources, several points can be taken into consideration. At present the amount of dust emitted from different Chinese deserts into the atmosphere occurs mostly in April, about 43.4% of the 1,451 Mt of dust emitted from 1996 to 2001 (Laurent et al., 2006). However, these sources do not behave similarly. While the average quantity of dust annually emitted is similar in the Gobi and Takla Makan deserts, the frequency of the dust storms are different, more numerous in the Takla Makan than in the Gobi (Laurent et al., 2005). A reduction in the size of these sources does not seem to be a reliable cause, as these deserts did not vary much in the relevant past (Rittner et al., 2016). Therefore, a reduction in the availability of dust material should be sought by considering atmospheric circulation changes. Studying the ESR intensity signal from marine core MD01-2407 from the Japan Sea, Nagashima et al. (2011) have shown that Mongolian Gobi source was dominant during GS while Takalamakan soirce was dominant source during GI, with some variation between the interstadials. The analysis of Chinese speleothems from caves located southward of the Chinese Loess Plateau (CLP) indicates millennial-scale variations in the stalagmite growth, related to variations in precipitation over the cave area linked to stronger summer monsoon activity, which are synchronous to the GI (Wang et al.., 2001, 2008). From two key Chinese loess sequences, Sun et al. (2012) have described abrupt millennial-scale changes expressed by detailed synchronous mean grain size variations over the 60-10 ka b2k interval in deposited wind blown material, from coarser material during GS to thinner particles during GI. The sedimentation rate estimated from the key sequences of Jingyuan and Gulang varies between 6 and 63 cm/kyr for Jingyuan and between 10 and 130 cm/kyr for Gulang, respectively (Fig. 4). Therefore, as meridional circulation prevailed at least in Eastern Asia due to the monsoonal system, aridity could have been reduced during the favorable season (around April, with some variation, delay, depending of GS or HS as observed in eastern Europe by Sima et al., (2013)) of dust emission of these short intervals (Sun et al., 2012). A recent study of the decline of the snow cover over Northeast Russia, Southwest Asia and Northern India, Tibetan Plateau, reports the snow cover decline creates favorable dynamical conditions for strong winds over the Arabian Sea and thus favoring a stronger summer monsoon (Goes et al., 2005). Complementarily, a modeling experiment indicates that a strong East Asian monsoon could be related to planetary waves related to the extension of the Northern Hemisphere ice sheets, affecting the precipitation band at the latitude of the CLP (Yin et al., 2008). However, as the main interval for dust emission is April, one can hardly assume the summer monsoon as the main driver of a reduction of dust emissions. On the contrary, modern East Asian dust storms are related to surges of cold air originating from Siberia, and such conditions should have been reduced during the GI compared to GS at least during April, the main dust emission season. Reduced cold outbreaks could have resulted from the reduction of the snow cover due to warming Eurasia and to a negative feedback related to dust deposition on snow as deduced from another modeling experiment (Krinner et al., 2006).

Europe has been strongly impacted by these North Atlantic millennial-scale climate changes, as observed in different types of deposits (Genty et al., 2003; Müller et al., 2003; Rousseau et al., 2002, 2007b) (Fig. 1). The influence of the westerlies and the position of the polar jet stream were constrained by the variation in the extension of the sea ice during the last glacial interval (Sima et al. , 2009; 2013). Furthermore, the presence of ice sheets over Great Britain, Scandinavia and of an ice cap over the Alps enhanced the zonal circulation that reflects the location of the thickest loess deposits (Fig. 1B). Extensive investigation of European loess series along a west to east transect at 50°N (Fig. 1B) reveals that the millennial-scale climate variations observed in the North Atlantic are preserved in these particular eolian deposits (2009; Antoine et al., 2001; Rousseau et al., 2002; 2007b). They clearly show alternating loess and paleosol units, which are continental equivalents, respectively, to the GS and GI (Moine et al., 2017; Rousseau et al., 2017) (Fig. 2, 3). The Nussloch loess sequence along the Rhine valley is the most detailed record for the interval 50 to 15 ka b2k. The nature of the observed paleosols is related to the duration of the corresponding GI themselves (Rousseau et al., 2017): GI8, the longest of the last 8 GI, is represented in Nussloch by a brown arctic soil, while the youngest GI correspond to tundra gleys or embryonic soils (oxidized horizons) for GI3 and GI2, which are particularly short (Antoine et al., 2009; Rousseau et al., 2002; 2007b) (Fig. 2, 3). An estimate of the duration of the continental equivalent of GI can be deduced from the Greenland dust record by considering the interval after the abrupt warming, when the dust concentration was minimum in the atmosphere and therefore shows low values in the Greenland ice cores. Such succession is observed over a more than 2000 km wide area from Western Europe eastward to Ukraine during the last climatic cycle (Rousseau et al., 2011), showing the influence of the zonal circulation, as it is the case in modern time (Fig. 5 A, B). In the Nussloch key sequence, the sedimentation rate of dust particles varies between 23 and 157 cm/kyr for the loess units synchronous to GS. These values are similar to those observed in the Northern edge of the CLP by Sun et al. (2012) (Tab. 2, Fig. 1A, 4), supporting an apparently similar eolian characteristic within a more global dynamics. Furthermore, modeling experiments show that dust emission mainly occurred in April (Sima et al., 2009) as nowadays in modern deserts, although the European sources are not deserts at all presently. These modeling studies also indicate that the zonal circulation not only prevailed during the GI intervals, but also during the GS as recorded by loess deposits. For the coarsest material these eolian units are composed of material of local and regional (up to about 500 km) origin, mainly from dried river beds (Rousseau et al., 2014). The finest grains originate from longer distances, but still from deflation areas, mostly located in the emerged English Channel, North Sea or Northern European plain, and at the margin of the Fennoscandian frontal moraines (Sima et al., 2009; Rousseau et al., 2014) (Fig. 1B). Since in Kurtak, Siberia (Fig. 1A, 4) we observe similar and synchronous alternations between eolian loess units and paleosols to those observed over Europe (Haesaerts et al., 2005), we infer that a zonal circulation similar to the present one (Fig. 5) was prevailing over Eurasia during both GS and GI, synchronizing the loess-paleosol sequences between Europe and Asia

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(Haesaerts et al., 2005). The initial warming over Greenland and the North Atlantic is transported eastward by the prevailing zonal circulation. As explained above, this propagating warming should have reduced the production of cold surges contributing to the strong atmospheric dynamics (Sun et al., 2012) responsible for the dust emission in Northern Chinese deserts, which are the main dust suppliers of both CLP and Greenland ice-sheet. The stronger winds during GS and weaker winds during GI permitted the record of DO-like intervals in Chinese loess sequences through grain size variations with coarser material deposition during GS and finer during GI (Sun et al., 2012).

All the mechanisms described above involve the Northern Hemisphere and do not address the origin of these abrupt changes. Recent investigations in Antarctic ice core WAIS (Buizert et al., 2015) have demonstrated the north-to-south directed transfer of the abrupt changes with Greenland warmings leading Antarctic coolings; the associated heat transfer is argued to be modulated by the Atlantic Meridional Overturning Circulation rather than by the atmosphere (Henry et al., 2016). Although the origin of the DO events is not yet elucidated, the Northern Atlantic changes still remain the drivers of those observed over Eurasia. Indeed, the modern cyclonic pattern of moisture transport towards the Greenland ice sheet (Masson-Delmotte et al., 2006) depends on the sea surface conditions over the North Atlantic Ocean and clear pathways of this transport have been identified (Chen et al., 1997). During the last climate cycle, this pattern was related to both the sea ice extent and the size and expansion of the Laurentide ice sheet in North America, which impacts the Northern Hemisphere atmospheric circulation (Kutzbach, 1987). The large changes in deuterium excess at the onset of the warming reveal large variations in the moisture source regions. These variations are most likely associated with changes in sea-ice extent, which shift the source regions, combined with changes in atmospheric circulation patterns (Masson-Delmotte et al., 2006 Sodermann et al. 2008, 2010).). Due to the changing albedo, sea-ice extent itself directly impacts the atmospheric circulation. On the other hand, sea ice is mainly driven by the meridional overturning oscillation, which would have thus induced the observed δ^{18}O and hence temperature changes noticed on the Greenland ice cores (Henry et al., 2016). In turn, this would have also impacted the Northern Hemisphere atmospheric circulation, contributing to the abrupt millennial-scale changes including the DO events in Eurasian terrestrial records. At middle latitude these changes constrained the emission of local and regional dust particles, their transport and their deposition in the loess sequences, which can be characterized by similar sedimentation rates over the area corresponding to a general climate dynamics, but nevertheless different mass accumulation rates (MAR) related to the bedrock of the source areas of the deposited material. In a previous study, Kohfeld and Harrison (2003) estimated MAR over CLP varying between 21 and 809 g/m^2/yr for MIS 3 and between 60 and 5238 g/m^2/yr for MIS 2. In Europe, Frechen et al. (2003), applying the same method, indicate MAR varying between 100 and 7000 g/m^2/yr with particular high values for Nussloch (1213-6129 g/m^2/yr). These estimates are higher than those determined in our study after re-evaluation of the chronology of the key sequence, still following the same calculation, which yields MAR varying values between 376 and 2586 g/m^2/yr (376 – 1952 g/m^2/yr for MIS3 and 724 - 2586 g/m^2/yr for MIS2) or between 395 and 2515 g/m^2/yr (395 - 1952 g/m^2/yr for MIS3 and 723 - 2515 g/m^2/yr for MIS2) when considering the δ^{18}O and dust related NGRIP chronologies, respectively (Tab. 2). Still, as Nussloch represent an exceptional record of MIS 3 and 2, we consider our results as corresponding to the highest boundary values for this time interval in European deposits.

4 Conclusion

Our study thus shows that a strong emphasis has to be placed on the past dust record, which is still poorly understood and weakly integrated in general circulation models. The important uncertainties associated with mineral aerosols in the recent IPCC report (Solomon et al., 2007) are a clear indication that more must be done on this particular parameter.

Because this is a key factor in the climate system, understanding the past dust cycle is an important requirement, especially when estimating the dust load in the past atmospheres, and this should open new fields of investigation for a better constraint of the climate variability in different contexts.

The present study provides new insights in the analysis of the millennial scale variability and of abrupt climate changes by proposing the links gathering atmospheric, marine and continental records. It shows that the complete understanding of the whole climate system requires investigations at high resolution in every domain with the support of modeling experiments. In the present study, we show that both $\delta^{18}O$ increase and dust decrease take place over an interval of about 50 years on average from the start of the abrupt change. This corresponds to the four decades previously mentioned for the two warmings occurring during the 15.5-11.5 ka b2k interval, which are associated with strong resumptions of the meridional overturning circulation (McManus et al., 2004). This makes the potential change in the atmospheric dynamics more reliable. Our investigation provided an explanation of the record of the abrupt climate changes in the northern hemisphere dust records, both in the Greenland ice sheet and over Eurasia. It shows that dust should be considered one of the major players of the past climate millennial variability.

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Acknowledgments

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The used data sets in this study are available at " www.icecores.dk"

Authors contributions

DD Rousseau designed research, DDR, SJJ, AS, MB, AS and JPS performed research, SJJ, AS, MB and JPS performed drilling and analysis of NGRIP ice core, AS performed modeling experiment, DDR designed and performed loess sequences investigation, DDR performed the new Nussloch chronological sequence, calculated the associated sedimentation rates and MARs, NB performed the algorithmic determination of the DO events in both $\delta^{18}O$ and dust NGRIP records, DDR, NB and AS wrote the paper.

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Figure captions

Figure 1. Studied records in this paper. A Location of the different records over Greenland and Eurasia. B. Map of the European loess. Indication of the depth of the LGM maximum sea-level low stand, of the expansion of the Greenland, Iceland, British and Fennoscandinavian ice-sheets. Location of European key loess sequences. Map drawn by P. Antoine in Rousseau et al. (2014) modified

Figure 2. Stratigraphic correlations between Nussloch paleosols and NGRIP interstadials (GI) (modified from Rousseau et al., 2017). Map as in Fig. 1. δ^{18}O (‰, in blue) and the dust concentration (part/µl, in brown) records in the NGRIP ice core over the interval between 60 ka and 15 ka b2k. Nussloch stratigraphic column from Antoine et al. 2016 modified.

Figure 3. Nussloch stratigraphy with the identification of the loess and paleosol units as discussed in the text. Arrows indicate the time's arrow during the dust depositions (in blue) and paleosol developments (in red). Sedimentation and Mass accumulation (MAR) rates as estimated from NGRIP δ^{18}O and dust chronologies. The insert at the bottom of the figure explains how time should be read when considering European loess sequences. Nussloch stratigraphic column from Antoine et al. 2016 modified.

Figure 4. Map of the maximum extension of the last climate cycle ice-sheets in Northern Europe. Schematic location of the polar jet stream with location of regions or areas (in black) and of sites (in red) discussed in the text. δ^{18}O (‰, in blue) and the dust concentration (part/µl, in brown) records in the NGRIP ice core over the interval between 60 ka and 15 ka b2k. Dust concentrations are shown on a logarithmic scale. Map was compiled by Jürgen Ehlers available at http://www.qpg.geog.cam.ac.uk/lgmextent.html

Figure 5. Impact of Atlantic climate conditions over Eurasia. Modern monthly average wind speed, in ms^{-1}, at 850 hPa (A) and at 300 hPa (B) pressure levels for March, June, September, December and April (main dust emission month) over Eurasia. Wind vectors plotted over shading and contours at 3 m s^{-1} interval. Data source: NCEP reanalysis monthly wind components on a 2.5 × 2.5° long/lat grid for the interval 1971–2000.

Table 1. NGRIP ice-core record. Estimates of NGRIP GI start, end and duration, GI abrupt transition start, end and duration (from Rousseau et al. submitted), Temperature reconstruction for the GI transitions as published by Kindler et al. (2014). a) and b) NGRIP transition dates determined visually and algorithmically, respectively.

Table 2. Nussloch loess sequence loess and paleosol units and their chronological equivalents (GS and GI) in the NGRIP ice-core record. a) and b) NGRIP transition dates determined visually and algorithmically respectively.

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