Dear reviewers,

We are grateful for the detailed suggestions, and we believe that these suggestions will considerably improve our study. Below, we address the comments in blue and the revised texts in the manuscript in green.

All the best, on behalf of all co-authors,

Jinhwa Shin

Anonymous Referee #2

Received and published: 24 January 2020

Shin et al. present new records of ice core CO2, CH4, and d15N from the EPICA dome C core during MIS 6. They show that the CO2 maxima tend to lag Antarctic d18O maxima, by an amount that increases thought the glacial period. The magnitude of CO2 increase scales with the duration of North Atlantic stadial period, suggesting a key role of AMOC variations in millennial-scale CO2 variability.

The data and analysis are obviously of interest to the broader paleoclimate community, and this paper should be published with only minor corrections. I believe that the manuscript can be clarified in some places. The main conclusion seems to be that MIS6 behaves very similarly to the last glacial period (as expected). Owing to this similarity, the discussion is somewhat long and involves a lot of speculation – much of which has already been said in earlier work (for example Bereiter et al. 2012).

Throughout the paper the authors present speculative climatic mechanisms, or uncorroborated results from individual model simulations as established fact. One example: "Due to the reduction of Summer Monsoon intensity in East Asia, salinity at the surface of the Pacific Ocean is increased. Thus, AABW and North Pacific Deep Water (NPDW) transport is enhanced (Menviel et al., 2014). Enhanced NPDW transport ventilates deep Pacific carbon via the Southern Ocean which may lead to atmospheric CO2 increases." While this is not a bad description of Menviel 2014, I think this would be better presented with some caution because while possibly correct, this is in no way a consensus view.

This paragraph (P11L12-P11L22) removed.

Throughout the paper, the authors compare MIS 3 and MIS6. In several places the authors write that MIS3 and MIS6 had different "background conditions". I am not sure what is meant by that. In what way are they really different? Both periods represent a range of orbital conditions, sea ice volumes, ITCZ positions, Heinrich events etc. So there are many places where they are very similar. I would advise the authors remove this idea that these two glacial periods are somehow very different – I don't think they have made the case that they are (and their data surely suggest that the carbon cycle responds in a very similar manner).

We do not claim that the last two glacial periods are "very different" as the reviewer states, but rather slightly different as also stated by Margari et al., 2010 and Gottschalk et al. (2020). This is an important distinction, which we attempt to clarify in the revision below. Our analysis focuses on whether these slight differences can impact the variability of CO_2 on millennial time scales. This is of course already known to be the case for periods presenting more marked differences in background climatic conditions.

P2L31-P3L11 Revised to: Comparing CO_2 changes on millennial time scales during the past two glacial periods, MIS 3 (MIS 3, 60–27 kyr BP) and early MIS 6 (early MIS 6, 185–160 kyr BP) can provide us with a better understanding of the carbon mechanisms at work, due to the similarities but also differences in climate conditions and events during the last two glacial periods (see Figure S1 in SI (Supplement Information)). Proxy evidence indicates that several important components of the climate-carbon cycle were not entirely analogous between MIS 3 and MIS 6. Sea ice cover in the South Atlantic was more extensive during MIS 6, and sea surface temperature in the South Atlantic is thought to have been lower (Gottschalk et al., 2020). The bipolar see-saw phenomenon also has been observed to be active during the early MIS 6 period (Cheng et al., 2016; Jouzel et al., 2007; Margari et al., 2010). However, the bipolar see-saw events during MIS 6 are longer than MIS 3. Events of iceberg discharge into the NA, which are thought to have driven millennial-scale changes in the meridional overturning circulation during MIS 3 (de Abreu et al., 2003; McManus et al., 1999) appear to be much more frequent during MIS 3 than during MIS 6. During the early MIS 6, iceberg discharge was muted (de Abreu et al., 2003; McManus et al., 1999),.

During the time period around 175 kyr BP, summer insolation levels in the Northern Hemisphere approached interglacial values (Berger, 1978). Due to the stronger Northern Hemisphere insolation, the intertropical convergence zone (ITCZ) is thought to have shifted northward, intensifying monsoon systems in low latitude regions, such as in Asia, the Appenine Peninsula and the Levant (Ayalon et al., 2002; Bard et al., 2002; Cheng et al., 2016). This may have led to a weaker overturning circulation due to the reduction of the density of the North Atlantic surface water, making the AMOC cell shallower during MIS 6 than during MIS 3 (Margari et al., 2010). Thus, this intensified hydrological cycle may help explain a shallower AMOC cell with a limited iceberg discharge in NA and the prolonged bipolar see-saw events during the early MIS 6 (Gottschalk et al., 2020; Margari et al., 2010).

Due to the historical convention the last ice age is actually MIS2-4, rather than just MIS3. So a more meaningful comparison would be MIS2-4 to MIS6. Also, the authors also include MIS5 in their analysis (Fig. 8). I think the paper would be a lot simpler if the authors just claim to be studying millennial-scale CO2 variability, rather than focus on Marine Isotope Stage distinctions that may not be relevant.

The last glacial period covers MIS 2 to MIS 4. MIS 2 and 4 are full glacial periods but MIS 3 is an interstadial period, i.e. a less cold period during a glacial period.
MIS 6 covers the penultimate glacial period, and can be divided into 3 parts according to the magnitude of climate variability and climate characteristics observed in proxy data (Margari et al., 2014): early (185.2─157.7 kyr BP), transition (157.7─151 kyr BP) and late MIS 6 (151─135 kyr BP). Each part shows similarities to a specific period of the last Ice Age. Climate change on millennial time scales during the late MIS 6 (the penultimate glacial maximum) is subdued, similar to MIS 2 (the last glacial maximum). Climate variations on millennial time scales during the earlier MIS 6 (185-157 kyr BP) are more prominent, similar to those during MIS 3. Accordingly, similarities and differences of climate variations during MIS 3 and the earlier MIS 6 were chosen to understand similarities/differences in atmospheric CO_2 variations on millennial time scale during the past two glacial periods.

MIS 5, the interglacial period, was mentioned as a reference for our analysis of lags of CO_2 variations with respect to Northern Hemisphere warming. The paper by Bereiter et al. (2012) shows two modes of atmospheric CO_2 variations on millennial time scales with respect to abrupt warming in NA during MIS 3 and MIS 5. These modes might be caused by different configurations of oceanic circulation during MIS 5 and 3. We similarly observed two modes of lags of CO_2 variations with respect to abrupt warming in NA during MIS 6.

In all figures I would appreciate a more clear demarcation of the sub-sections. I am not very familiar with the MIS6a-6e definitions. Do they follow precession/Benthic sequences like in MIS5, and who has defined these? We used the MIS timescale developed by Railsback et al. (2015).

Could you please add the MIS5 and MIS6 (and MIS7?) sub-stage numbering into figures 1, 4 and 5. Also, for consistency you should mark the H-events of stage 6 in Fig 1. Where does the event numbering 6.e1 etc. come from? I have seen alternative numberings elsewhere in the literature.

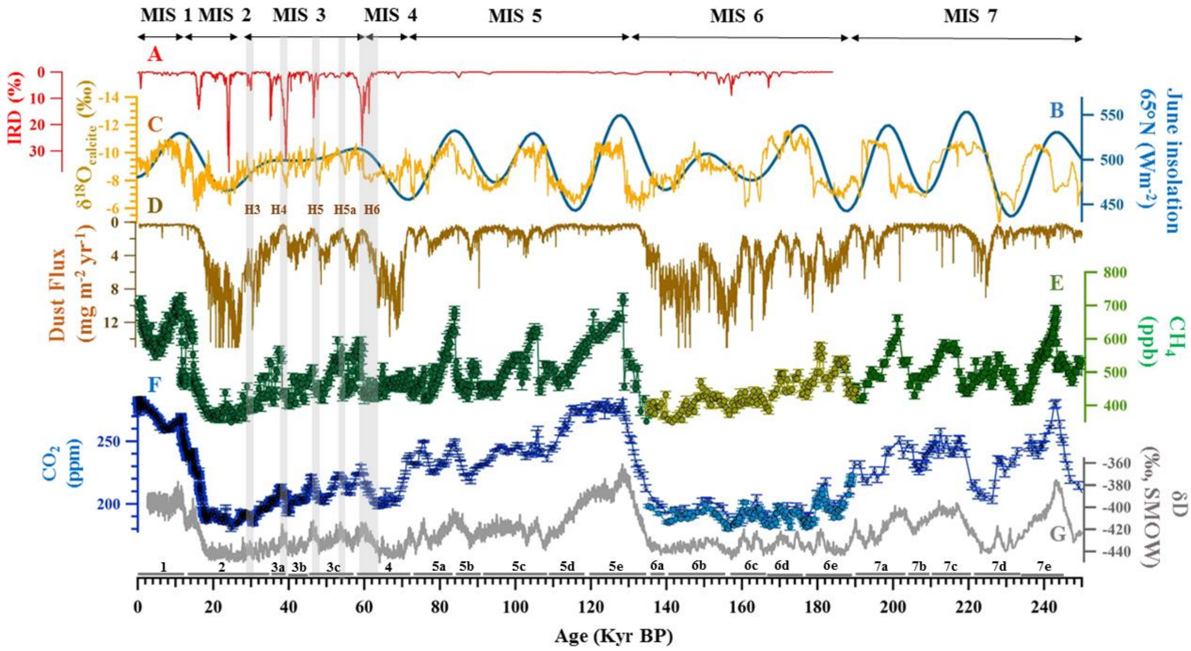

Figure 1: Proxy data during 250 kyr BP. A: Ice-rafted debris (IRD) input in the Iberian margin core MD95–2040 (de Abreu et al., 2003). B: 21 June insolation for 65°N (Berger, 1978). C: $\delta^{18}O_{calcite}$ from Sanbao cave, corresponding with the strength of the East Asian monsoon (Cheng et al., 2016). D: Dust flux in EDC (Lambert et al., 2012). E: Atmospheric CH_4 in EDC (green dots) (Loulergue et al., 2008) and Atmospheric CH_4 in EDC in this study (light yellow dots). F: Atmospheric CO_2 from EDC in this study (light blue dots) and composite CO_2 from Antarctic ice cores (dark blue dots) (Bereiter et al., 2015). G: δD composition in EDC, Antarctica (Jouzel et al., 2007). Vertical grey bars indicate the timing of Heinrich events. The sub-stage numbers are written at the bottom (Railsback et al., 2015).

Carbon Dioxide Maxima (CDM) are named according to the MIS timescale developed by Railsback et al. (2015) (Figure 5). This sentence written to the Section, 3.5 Atmospheric CO2 variability on millennial time scale.

Could you please add the synthetic Greenland reconstruction from Barker et al. 2011 to Figure 3, to see how it compares?

Accepted

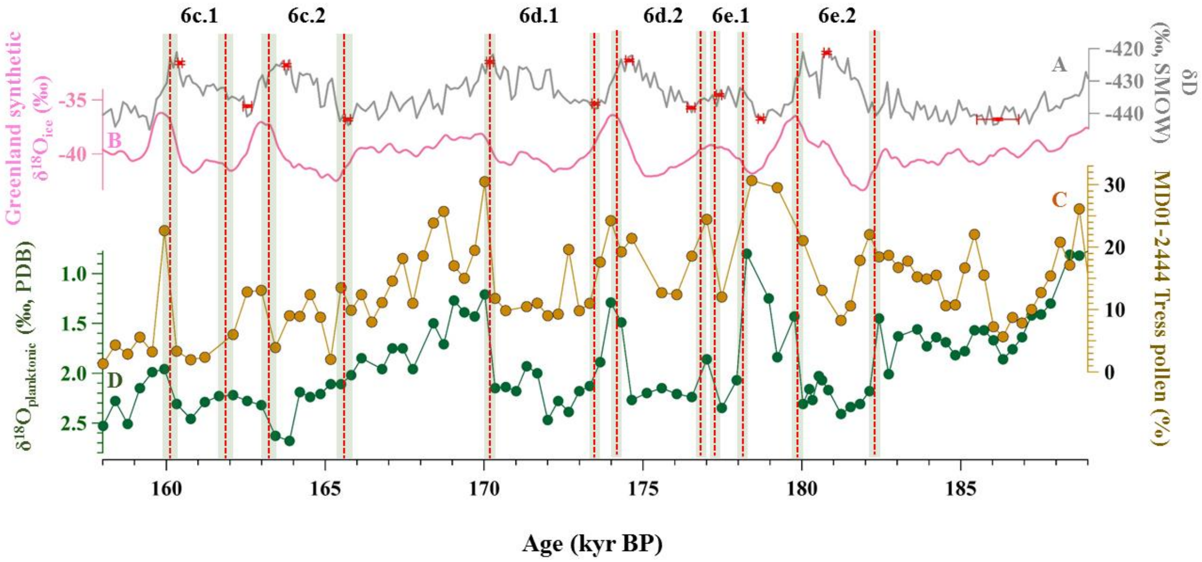

Figure 3 (in the text). The durations of the six NA stadials during MIS 6 defined by Margari et al. (2010). A: δD composition of the EDC ice core (Jouzel et al., 2007). B: Greenland synthetic $\delta^{18}O$ composition of ice (Barker et al., 2011). C: Tree pollen percentage in the MD01-2444 (Margari et al., 2010) D: $\delta^{18}O$ of planktonic foraminifera in the MD01-2444 (Margari et al., 2010). Proxy data shown here are given on the AICC2012 age scale. Red lines indicate the midpoints of the stadial transition of both $\delta^{18}O$ of planktonic foraminifera and tree pollen in MD01–2444. Light green bars indicate the uncertainty of the duration of each stadial estimated as half of the temporal difference between maxima and minima of $\delta^{18}O$ of planktonic foraminifera. Red dots indicate minima and maxima of δD composition of the EDC ice core selected in this study.

The authors do not address the CO2 offset between the records enough. It is up to 10 ppm with Vostok, which is quite large. They explain this as due to the blank correction, which is only around 1.7 ppm and therefore insufficient. Such offsets are seen more often in comparing CO2 from different cores, and may actually be in the ice. Can you explain the EDC CO2 offset between this work and Lourantou?

The ball mill system has a different extraction efficiency depending on the presence of bubbles and/or clathrates in the ice sample, which may cause an accuracy for reconstructing absolute mean CO_2 level. When the air is extracted from an ice core sample where bubble and clathrates co-exist, different dry extraction methods with different extraction efficiencies on bubbly and clathrate ice may lead to biased CO_2 concentrations (Lüthi et al., 2010; Schaefer et al., 2011b). During clathrate formation, the gas is partitioned into clathrates due to the different gas diffusivities and solubilities (Salamatin et al., 2001). CO_2 has consistently been observed to be depleted in bubbles and enriched in clathrates (Schaefer et al., 2011a). Degassing from clathrates during extraction takes much longer than air release from bubbles; thus, if air from the clathrate ice is not extracted entirely, CO_2 measurement will be lower than the true value.

The ball mill shows extraction efficiencies of ~62% for bubbles and ~52% for clathrates on average (Schaefer et al., 2011a). If the ball mill is used to reconstruct CO_2 in Bubble–Clathrate Transformation Zone (BTCZ), CO_2 concentrations can be biased.

CO_2 concentrations from EDC were reconstructed from 150 depth intervals that cover 2036.7 to 1787.5 m along the EDC ice core, which consist of clathrate ice. There exists true small scale variability in CO_2 concentrations in the ice below the Clathrate Zone (Lüthi et al., 2010). Due to the diffusion effect, this small variation of atmospheric CO_2 is smoothed. Thus, CO_2 concentrations in these depth intervals might represent the initial mean atmospheric concentration. However, the EDC ice core for MIS 6 was drilled in 1999 and, the ice core has been stored for ~20 years in cold rooms at -22.5 ± 2.5°C before the gas is analysed. More than 50% of the initial hydrates present in the freshly drilled ice may have been decomposed and transformed into secondary bubbles, or gas cavities (Lipenkov, *Pers. Comm.*). We expect the same fractionation as during the clathrate formation process, hence bubbles would be depleted in CO_2. Thus, CO_2 concentrations from EDC may be lower. The portion of the Vostok ice core covering MIS 6 is also clathrate ice, but it was drilled in 1998 and measured immediately (Petit et al., 1999), and less clathrates may have transformed into secondary bubbles. Thus CO_2 concentrations from Vostok during MIS 6 may be higher and potentially reflect the true atmospheric concentration more closely. In our study we concentrate on the relative millennial changes of CO_2 around the mean glacial concentration, which are the same in all the CO_2 records available so far, Thus, our conclusion in this paper are independent of which absolute mean CO_2 level is correct. As the new data in this study are currently the best quality data in terms of repeatability, we use our new data as the reference record and correct for any inter-core offsets. We, however, state explicitly in the text that the absolute mean CO_2 level during MIS6 is not known better than 5 ppm.

The estimated offset between the existing CO_2 dataset from EDC by Lourantou et al. (2010) and our new dataset is ~2.4±2.1 ppm. The CO_2 data from EDC by Lourantou et al. (2010) were also reconstructed using the ball mill system. However, this dataset was not corrected for the CO_2 contamination caused by the analytical procedure. We estimated the level of CO_2 contamination to be between 1 and 2 ppm for our study. Considering that the previous dataset was not corrected for, the offset between the two data sets is small when compared to their uncertainties.

This is written to Section 3.1 The new high-resolution and high precision CO_2 record during MIS 6

Specific line-by-line comments:

P1L16: I don’t think you can argue that the background conditions are different. That hasn’t been established.

The detailed information about background conditions during the last two glacial periods is re-written for greater clarity on Page 3. We already mentioned before, please see the response to first question on Page 2 in this document.

P2L11: Broecker does not talk about the bipolar seesaw, but a seesaw in deepwater formation. Other references to consider are Blunier & Brook (2001); Pedro et al. (2018).

Blunier & Brook (2001); Pedro et al. (2018) added, Broecker, 1998 removed

P3L6: Normally a stronger monsoon is not associated with a weaker AMOC. How does this work?

This paragraph re-written. Please see the response to the first question on Page 2 in this document.

P6L9: Add or replace with Etheridge et al (1992); this idea is much older.

Added

P5L5: The “assumption” that the bipolar seesaw was present is a pretty obvious one, and I don’t think it needs to be questioned. My personal choice would have been to use Antarctic isotopes to define the stadials and interstadials (see e.g. Kawamura et al., 2017), rather than NA sediments that have much poorer age control.

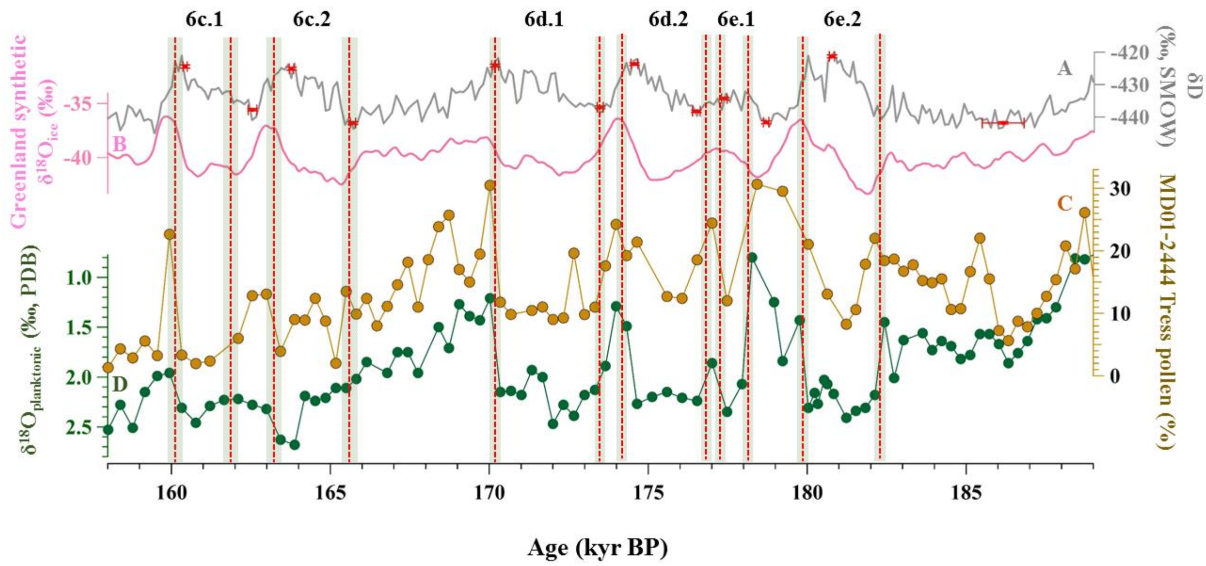

Figure 3 (in the text): The durations of the six NA stadials during MIS 6 defined by Margari et al. (2010). A: δD composition of the EDC ice core (Jouzel et al., 2007). B: Greenland synthetic δ^{18}O composition of ice (Barker et al., 2011). C: Tree pollen percentage in the MD01-2444 (Margari et al., 2010) D: δ^{18}O of planktonic foraminifera in the MD01-2444 (Margari et al., 2010). Proxy data shown here is on the AICC2012 age scale. Red lines indicate the midpoint between the midpoints of the stadial transition of both δ^{18}O of planktonic foraminifera and tree pollen in MD01–2444. Light green bars indicate the uncertainty of the duration of each stadial estimated as half of the temporal difference between maxima and minima of δ^{18}O of planktonic foraminifera. Red dots indicate minima and maxima of δD composition of the EDC ice core selected in this study.

In our study, the durations of the six NA stadials were originally defined as the interval between the midpoints of the stadial transition of both δ^{18}O of planktonic foraminifera and tree pollen in MD01–2444 (C and D in figure 3) which was suggested by Margari et al. (2010). With this data we observed that the magnitude of atmospheric CO_2 change is generally correlated with the NA stadial duration (r=0.7, n=6) during the early MIS 6 period.

As the reviewer mentioned, not all of the stadial durations during MIS 6 are entirely clear using this method. As suggested by the reviewer, a synthetic Greenland $\delta^{18}O_{ice}$ record (Barker et al., 2011) and Antarctic (δD) variations in Antarctic ice core are plotted in Figure 3 as references, on the AICC2012 age scale. The interval between the maximum and the preceding minimum of δD in the EDC record can also be used to estimate the duration of the stadial transitions (Gottschalk et al., 2020; Margari et al., 2010). In most cases, the synthetic Greenland $\delta^{18}O_{ice}$

record and the interval between the maximum and the preceding minimum of δD in the EDC record confirm the definition of NA stadials selected by $\delta^{18}O$ of planktonic foraminifera in MD01–2444 and tree pollen in MD01–2444. However, the duration of the NA stadial in MIS 6d.2 is not clearly confirmed by Greenland $\delta^{18}O_{ice}$ and δD in the EDC (Figure 3 (in the text)).

We recalculated the durations of the six NA stadials using the interval between the stadial transitions as recorded in the EDC δD record (Gottschalk et al., 2020; Kawamura et al., 2017; Margari et al., 2010). Minima and maxima were selected by finding zero values in the second Savitsky–Golay filtered derivative of the data (the same method we used to pick minima and maxima of atmospheric CO_2; P9 in SI and Figure 1 in this text).

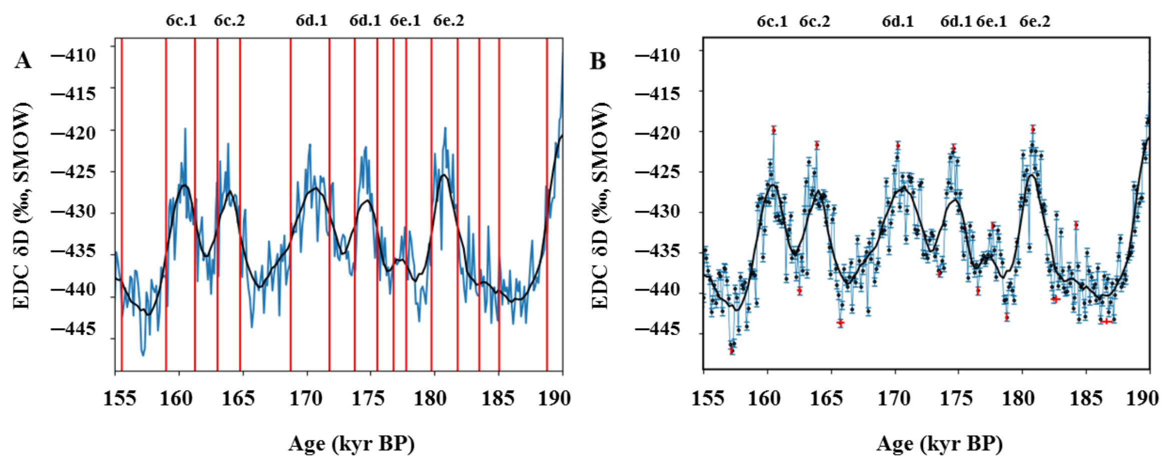

Figure 1: Temperature records from EDC during MIS 6. The black curve in both panels shows the Savitsky-Golay filtered δD series, and the blue curve shows the original data. (A) Red vertical lines mark inflection points. (B) Blue vertical lines show the minima and maxima, the blue shading illustrates the estimated uncertainties of their timing. The event numbers are written at the top.

The red dots and error bars on δD in the EDC record in Figure 3 of the main text show the estimated minima and maxima of temperature corresponding to stadial transitions using this method, along with their uncertainties. However, using this tool, durations of 6e.1 and 6e.2 are apparently overestimated due to ambiguity concerning of maximum in 6e.1 and minimum in 6e.2. Neither our method nor that of Margari et al. (2010) can be considered absolutely correct. To account for the differences between the two methods, we took the stadial duration to be the mean of the duration estimated by both $\delta^{18}O$ of planktonic foraminifera and tree pollen in MD01–2444 and dD definitions. The correlation coefficient between the magnitude of atmospheric CO_2 change and the NA stadial duration remains high ($r=0.93$, $n=6$) during the early MIS 6 period.

This new calculation added to Section 2.6. Section 2.6 Definition of NA stadial duration re-written: Due to the absence of a Greenland temperature record for MIS 6, the durations of the six NA stadials were defined using $\delta^{18}O$ of planktonic foraminifera and tree pollen in MD01–2444, which reflect temperature variability in the NH (Margari et al., 2010). The midpoint of the stadial transitions in both $\delta^{18}O$ of planktonic foraminifera and tree pollen in MD01–2444 were used to identify the NH stadial stadial transitions. The time interval between two stadial transition points were defined as the NA stadial duration. In this approach, small variations of the two records may bias the calculation of the duration of short stadials in the NH. However, the average age difference between the durations identified using the two methods is only 205 years, which is less than the sampling resolution of MD01–2444 during MIS 6. The stadials identified for MIS 6 are shown in Figure 3. The uncertainty of the duration of each stadial was estimated as half of the temporal difference between maxima and minima of $\delta^{18}O$ of planktonic foraminifera. However, not all of the the stadial durations during MIS 6 are entirely clear using this method. Figure 3 shows synthetic Greenland $\delta^{18}O_{ice}$ record (Barker et al., 2011) and Antarctic (δD) variations in Antarctic ice core on the AICC2012 age scale. The interval between the maximum and the preceding minimum of δD in the EDC record can also be used to estimate the duration of the stadial transitions (Gottschalk et al., 2020; Margari et al., 2010). In most cases, the synthetic Greenland $\delta^{18}O_{ice}$ record and the interval between the maximum and the preceding minimum of δD in the EDC record confirm the definition of NA stadials selected by $\delta^{18}O$ of planktonic foraminifera in MD01–2444 and tree pollen in MD01–2444. However, the duration of the NA stadial in MIS 6d.2 is not clearly confirmed by Greenland $\delta^{18}O_{ice}$ and δD in the EDC.

We recalculated the durations of the six NA stadials identified during the MIS 6 period were previously defined by Margari et al. (2010). Between the maximum and the preceding minimum of δD in the EDC record is defined as the stadial durations (Gottschalk et al., 2020; Kawamura et al., 2017; Margari et al., 2010). Minima and maxima were selected by finding zero values in the second Savitsky–Golay filtered derivative of the data (the same method we used to pick minima and maxima of atmospheric CO_2; Figure S11 in SI). The red dots and error bars on δD in the EDC record in Figure 3 show the estimated minima and maxima of temperature corresponding to stadial transitions using this method, along with their uncertainties. However, using this tool, durations of 6e.1 and 6e.2 are apparently overestimated due to ambiguity concerning of maximum in 6e.1 and minimum in 6e.2. Neither our method nor that of Margari et al. (2010) can be considered absolutely correct. To account for the differences between the two methods, we took the stadial duration to be the mean of the duration estimated by both $\delta^{18}O$ of planktonic foraminifera and tree pollen in MD01–2444 and dD definitions (Table 2).

P7L31: the offsets persist in periods of stable CO2, suggesting there is more than chronological error going on. Please discuss offsets between the cores.

Accepted, Re-written. We mentioned about CO_2 offset on Page 4 in this document. Please see Page 4 in this document.

P10L19: again, the link between monsoon and AMOC does not make sense to me

This paragraph re-written: These two CDM events occurred during MIS 6d, when iceberg discharge was muted and the intertropical convergence zone (ITCZ) is thought to have shifted northward, intensifying monsoon systems in low latitude Northern Hemisphere regions, such as in Asia, the Appenine Peninsula and the Levant (Ayalon et al., 2002; Bard et al., 2002; Cheng et al., 2016). This shift may have led to a weaker overturning circulation due to the reduction of the density of the North Atlantic surface water, making the AMOC cell shallower with limited iceberg discharge in NA during MIS 6 as compared to MIS 3 (Margari et al., 2010). The two apparent CO_2 lag timescales with respect to abrupt warming in NH during MIS 6 might be related to this difference.

P12L7: upwelling or ventilation /de-stratification?

Upwelling or ventilation

P12L15-16: Anderson does not cover MIS6, plus those records lack the resolution to investigate short stadials.

Two sentences removed: “During the short stadial in MIS 6 (AIM 6e.1) and the short stadials in MIS 3, the duration and strength of AMOC disruption are similar (Margari et al., 2010). This is supported by the marine proxy data for upwelling in the Southern Ocean which do not show strong variations during short stadials for both MIS periods (Anderson et al., 2009).”

P13L22: yet the CO2 variations of MIS5 are larger than those in MIS3?

The sentence at P13L22 is about CO_2 outgassing from the Ocean.

P14L22: remove “unprecedented”. Some ice core CO2 records have decadal precision.

Removed

P21: Could you add the H-events of Stage 6 also (or perhaps an IRD record that spans the full period)? Could you mark the MIS6a-6e substage numbering? (I am not familiar with this nomeclature).

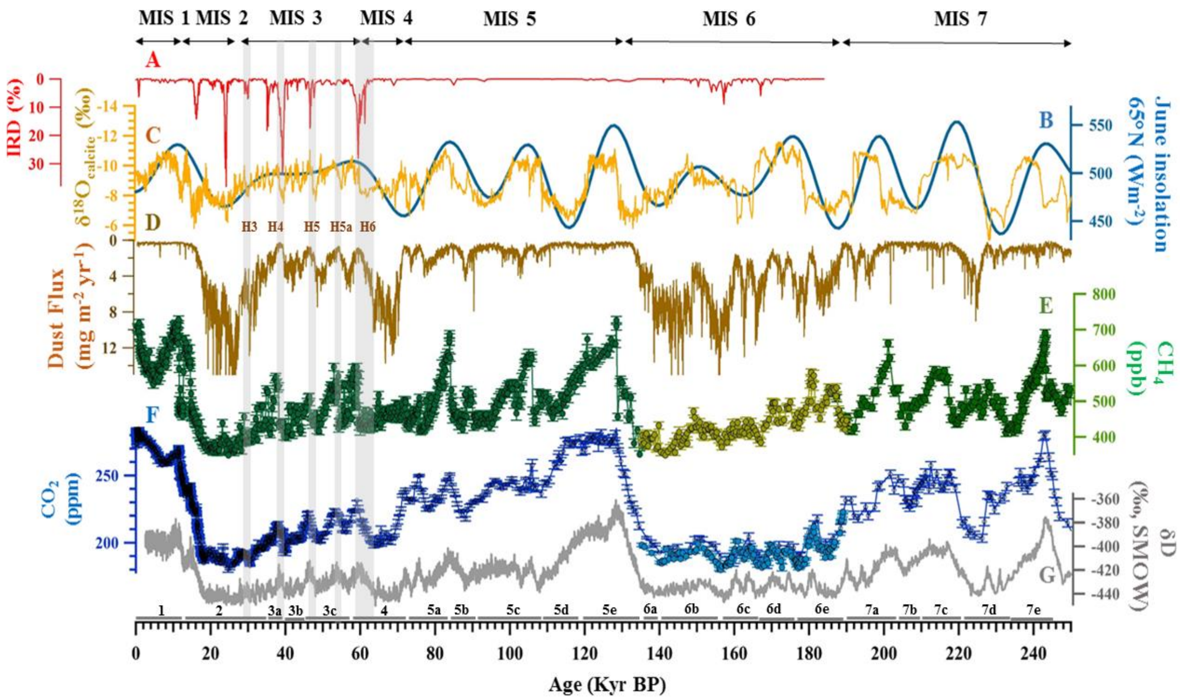

Figure 1: Proxy data during 250 kyr BP. A: Ice-rafted debris (IRD) input in the Iberian margin core MD95–2040 (de Abreu et al., 2003). B: 21 June insolation for 65°N (Berger, 1978). C: $\delta^{18}O_{calcite}$ from Sanbao cave, corresponding with the strength of the East Asian monsoon (Cheng et al., 2016). D: Dust flux in EDC (Lambert et al., 2012). E: Atmospheric CH_4 in EDC (green dots) (Loulergue et al., 2008) and atmospheric CH_4 in EDC in this study (light yellow dots). F: Atmospheric CO_2 from EDC in this study (light blue dots) and composite CO_2 from Antarctic ice cores (dark blue dots) (Bereiter et al., 2015). G: δD composition in EDC, Antarctica (Jouzel et al., 2007). Vertical grey bars indicate the timing of Heinrich events. The sub-stage numbers are written at the bottom (Railsback et al., 2015).

Although the IRD dataset added in Figure 1 does not cover the whole 250 kyr period shown in figure 1, it is in our opinion the most appropriate to show North Atlantic events during MIS 6, and is thus used for our analysis. We prefer to not include any additional IRD datasets in the figure to avoid confusion for the reader.

P26: could you add the DO onsets you infer from CH4 as vertical bands?

It would be better to add vertical lines for CDM because there are 6 variations of atmospheric CO_2 but we could find only three abrupt CH_4 increases indicating the onset of DO events with the CH_4 data set. Vertical lines for CDMs added in Figure 6.

P27: Why did you not add the Stage 5 events here?

In this study we focused on atmospheric CO_2 variations on millennial time scales during the past two glacial periods, thus, the stage 5 was not included in Figure 7. In section 3.4 and 4.2, the stage 5 is mentioned, but only to discuss the factors that can influence the lag of atmospheric CO_2 with respect to abrupt warming in NH.

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