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Climate of the Past Discussions

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Interactive Comment

Interactive comment on "Climate and carbon-cycle variability over the last millennium" *by* J. H. Jungclaus et al.

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Climate and carbon-cycle variability over the Last Millennium

Manuscript under review for Climate of the Past by J.H. Jungclaus et al.

After the manuscript has been evaluated by four reviewers we have responded to all points raised by the reviewers, corrected shortcomings and errors and reformulated a substantial part of the manuscript. We thank all reviewers for the constructive remarks and suggestions that helped to make the manuscript more mature and to clarify misunderstandings. In the following we respond (indicated by Authors' Response: "AR") to each of the reviewer's comments (indicated by the reviewer's initials, here anonymous referee #2: "R2"). The modified passages from the manuscript indicated starting with

"MS":

R2: The authors present a set of last millennium simulations performed with a complex AOGCM coupled with a carbon cycle component. The focus of the study is on the carbon cycle variability with respect to temperature changes due to different forcings. In comparison to ice-core data the CO2 variability is still underestimated during the last millennium. General comments: General the manuscript is well written and clearly structured. The paper is scientifically very relevant and should be published. However, there are still some shortcomings (see major comments). Therefore I recommend that the manuscript should be accepted after minor to major revisions.

AR: We thank referee #2 for the positive evaluation and the constructive suggestions. In preparing the revised version of the paper we have taken all the reviewer's comments into account. We hope that shortcomings have been eliminated and that the new manuscript gives a more comprehensive account of our analyses.

Major comments: R2: I. page 1019 line 5-23: The whole paragraph should be also discussed in the light of the climate sensitivity of the model. There are several shortcomings: e.g., it is not clear which 30 yr period the authors use - is it just the warmest and coldest period in each ensemble member or is it the ensemble mean (which I would prefer as it fits better to the choice of Frank et al.)? How strongly does the timing of the periods vary compared to reconstructions? Do the authors use different period for different target variables like NH land or NH land summer, ...? Please insert the pdf of Frank et al in Fig. 3. The conclusion seems to be to strong - given the fact that the solar community heavily discuss the amplitude could be stronger, so how will the authors interpret their result if this is the case. Moreover, with the analysis presented they have not shown that differences among reconstructions are explained as a result of different spatiotemporal sampling among the records

AR: We have addressed the reviewer's comments by rewriting the entire paragraph. We provide more information on how the periods were chosen and add an extended section on the sensitivity of the simulated global surface air temperatures to changes in TSI. We prefer to keep the analysis based on individual ensemble members because this gives another estimate on the ensemble uncertainty. From Fig. 4 (left y axis) (Fig. 3 in the original manuscript) it should be clear that the symbols refer to the individual ensemble members.

We don't feel that it is necessary to include Frank et al.'s pdf as a figure. The focus of their analysis is the re-calibration of the various reconstructions and a probabilistic best estimate of the long-term temperature change. We just use this information as one of the best estimates presently available.

We have also modified our conclusion. However, we would still make the statement that, given our model's sensitivity to solar variations is not too far off and the Frank et al. temperature amplitude for the MWP-LIA cooling is realistic, a solar forcing much stronger than the present state-of-the-art is not necessary to reproduce such a cooling. In the new discussion section (see below) we have also added some remarks on the uncertainty that is still present in the external forcing reconstructions.

We agree with the reviewer on the spatio-temporal sampling. The way we formulated that in the submitted manuscript was perhaps a bit misleading. We actually wanted to express that only part of the differences in the reconstructions can be explained by the sampling. We have clarified this in the new version.

MS: Another way of characterizing the MWP-LIA overall cooling was proposed by Frank et al. (2010) who compare the warmest 30-year climatic period during the MWP epoch with the coldest 30-year period during the time of the LIA. According to their probabilistic analysis, which involved re-calibrating of nine different reconstructions, the best estimate for the difference between the coldest episode of the LIA (1601 – 1630) and the warmest pre-industrial period (1071-1100) is 0.38 K. The ensemble means of both our ensemble simulations indicate common warm eras in the 11th to the mid-13th century and the coldest epoch before the onset of anthropogenic warming in the 17th

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century. The MWP-LIA temperature change defined in this way is then calculated for each ensemble member and for different choices of regional and seasonal averages. The latter were motivated by the data available from IPCC (see Jansen et al. (2007), their table 6.1). The simulated data in Fig. 4 indicate that the choice of season and the selection of land-only or land-and-ocean data points can explain differences of up to 0.2 K where the 20°-90°N land data show the strongest response in most simulations. We note that the much larger spread seen in the reconstructions (here not re-calibrated as in Frank et al. (2010)) cannot be explained by these choices alone. In the individual simulations, the warmest MWP climatic periods occur between the end of the 11th century and the middle of the 12th century (see appendix A, Table A1) while the reconstructions suggest a slightly earlier temperature maximum. All experiments and the reconstructions have their coldest LIA period between 1580 AD and 1699 AD. The simulations show a certain ensemble spread as a result of internal variability but the E1 experiments cluster around a 0.4 K cooling whereas the E2 temperature difference is considerably larger. Regarding the Frank et al. (2010) recalibration as one of the best estimates of NH temperature evolution presently available would suggest that simulations with weak solar forcing yield a MWP-LIA cooling that is more consistent with the reconstruction-based estimate. The simulated response to solar variations certainly depends, however, on the climate sensitivity and can thus be model-dependent. Recent assessments of the global temperature change per Wm-2 (TSI) (Camp and Tung, 2007; Lean and Rind, 2008) arrive at sensitivities between 0.1 and 0.2 K/(Wm-2). Tung et al. (2008) use multiple temperature data sets including reanalysis and in situ data for the last 60 years and determine the response to the 11-year solar cycle variations to be 0.12 – 0.17 K/(Wm-2) . We carried out a regression analysis for the temperature response in the experiment where the (weak) solar variations represent the only external forcing. For the last 60 years we find a sensitivity of 0.15 K/(Wm-2) as response to the 11-year cycle. A respective analysis of low-passed-filtered data over the entire millennium gave somewhat weaker response (0.1 K/(Wm-2)) and a longer time-lag. The details of the mechanisms involved in the response at different time scales

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are presently subject of ongoing analysis. Based on recent findings of Servonnat et al. (2010), low frequency modulations in the forcing invoke, for example, long-lasting responses in the ocean circulation which could explain different sensitivities at different time scales. Nevertheless, the model's sensitivity is well in the range of observational estimates and it is unlikely that that too large a model climate sensitivity is compensating for a weak forcing. Moreover, with a larger sensitivity the model would then agree less well with the 20th century record (Fig. 2 a).

R2: II. The second major concern relates to the fact that the authors argue that the E1 simulations are well within the range of NH temperature reconstructions and E2 is off compared to the reconstructions but the results of the carbon cycle (page 1023) are mainly presented for the E2 ensemble - this is a inconsistency which need an explanation.

AR: The motivation to focus on the E2 ensemble was simply driven by the better signal-to-noise ratio owing to the stronger modulation. However, in the revised manuscript we have taken both ensembles into account. In the new figure 8 (Fig. 7 in the original MS) we have included the E1 ensemble and discuss the differences between them and the control experiment in the text. As we point out in the response to reviewer P. Friedlingstein, we have to apologize for a misinterpretation of Frank et al.'s definition of the sensitivity parameter gamma. They define it as the change in atmospheric CO2 concentration (in ppm) per $^{\circ}$C change in NORTHERN HEMISPHERE temperature, whereas we used GLOBAL temperatures in the analysis for Fig 7 in the original manuscript). We have corrected this in the revised manuscript and recalculated gamma accordingly. This leads to somewhat smaller numerical values for gamma (this is because the standard deviation of NH temperature variation is higher than the one for global means). The resulting gamma values are still well within the range given by Frank et al. (2010), but somewhat lower than their median over the 1050-1800 period (7.7 ppm/K).

R2: III. Concerning the carbon cycle sensitivity the authors could also compare directly the Fig. 3 of Frank et al. 2010 by splitting their period into 1050 -1549 and 1550 -1800.

AR: We have refrained from doing this because we wish to concentrate our analysis on the period where anthropogenic influences are small. At least in the model CO2 release from land-cover changes influence the estimate of γ in the 18th century. We discuss, however, the time-invariance of γ in the simulations and in the reconstructions in the revised paragraph. The high γ values in Frank et al's estimate come, of course, from the strong Co2 drop in the 17th century that we are not able to reproduce. We feel however, that the finding of a time-varying γ over the centuries is important for the interpretation of Frank et al's results.

We have therefore modified the paragraph considerably:

MS: Similar to the temperature sensitivity to external forcing that we have discussed with respect to TSI variations, the response of the simulated carbon-cycle to climate variations is certainly model dependent (Friedlingstein et al., 2006; Frank et al., 2010). The processes controlling carbon fluxes between the atmosphere, biosphere, and the oceans are temperature dependent and, on glacial timescales, the sensitivity of the global carbon cycle to temperature is roughly linear with a slope of about 8 ppmK-1 (Woodwell et al., 1998). While empirical estimates based on last-millennium data have reported values up to 40 ppmK-1 (Scheffer et al., 2006; Cox and Jones, 2008), a recent assessment (Frank et al., 2010) quantified γ (the sensitivity of atmospheric CO2 to Northern Hemisphere temperature changes) with a median of 7.7 ppmK-1 and a likely range of 1.7–21.4 ppmK-1. For our simulations γ falls within this range, though at the lower end (Fig. 8 a). Strikingly, however, γ is much larger for the forced as compared to the unforced simulations. The regression slopes read 2.7 ppmK-1 for the E1 ensemble and 4.3 ppmK-1 for the E2 ensemble, but it is considerably smaller for the control experiment (1.6 ppmK-1). An analysis in the frequency domain (Fig. 8 b) reveals increasing sensitivity on longer (centennial to millennial) time-scale. Moreover, running regressions for the ensemble means over the pre-industrial last millennium (Fig. 8 c, d) reveal that γ is not time-invariant but varies on multidecadal to centennial

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time-scales. High sensitivities appear at times of pronounced and sustained temperature changes (Figs. 3a, 6a) in response to strong forcing anomalies, such as the volcanic eruptions in the 13th and 14th century where the latter coincides with a maximum solar forcing anomaly (Spoerer Minimum). Both control and forced simulations indicate the strongest response of atmospheric CO_2 variations at positive time lags, but the amplitude in the forced run is much higher. Such centennial-scale variations in the sensitivity are apparently also present in the observational record. Frank et al. (2010) found considerable variations for the first (1050 – 1549 AD: mean 4.3 ppmK-1) and second (1550 – 1800 AD: mean 16.1 ppmK-1) half of the pre-industrial period. Our actual numbers are somewhat lower (Figs. 8c, d) and we do not reproduce the much higher values in the second analysis period reported by Frank et al. (2010) because those include the pronounced CO_2 drop around 1600 AD which appears not as pronounced in our simulations. Nevertheless, the finding that γ is not time-invariant and depends on external forcing strength and time-scale is important for the interpretation of the reconstruction-based estimate. The stronger response in the forced simulations may reflect non-linearities in the system, or the different spatio-temporal structure of the temperature patterns in the forced simulations. The detailed processes behind the carbon-cycle response to time-varying forcing are presently analyzed in a subsequent study. Some insight can be gained from the recent study of Brovkin et al. (2010) who, using the same millennium simulations, investigated the impact of a single strong volcanic eruption. They analyzed the time period around the eruption of the 1258 unknown volcano. They conclude that the CO_2 decrease in the atmosphere is explained mainly by reduced heterotrophic respiration on land in response to surface cooling corroborating findings by Jones and Cox (2001). Furthermore, the magnitude of the atmospheric response is determined by the land carbon storage while its duration is set-up by the marine carbon cycle. In particular, the stronger sensitivity at low frequencies (Fig 8 b) suggests that these slow processes associated with carbon storage in the biosphere and oceans determine the feedback strength. Therefore, the slowly varying solar irradiance changes and the cumulative effect of volcanoes that lead to multi-centennial climate variations provide time-scales in which the carbon-cycle response can fully develop.

R2: IV. There is no discussion of the results in Section 4, also the conclusions could be presented in a more comprehensive way.

AR: We have extended the discussion paragraph and included a more detailed account on uncertainties.

MS: Discussion and Conclusion While many of the features of the observed record appear compatible with our simulations and serve to highlight the peculiarity of the present epoch, some mysteries remain. In particular, the magnitude and rate of CO2 change during the LIA and the timing of the MWP prove difficult to reconcile with our best estimates of the climate forcing and response over the last millennium. The CO2 reconstructions show a rise by 4 ppm between 1000 AD and 1100 AD and a decrease by about 5 to 7 ppm in the following 600 years. After 1750 AD, there is a steep increase towards modern values. The CO2 decrease coincides with a period of decreasing temperatures towards the LIA, suggesting that CO2 simply follows temperature. However, the relation is probably not that simple: For example, the cooling after the volcanic eruptions in the early 19th century, that drove the climate back into almost as cold condition as in the early 17th century does not show up strongly in the CO2 records and the coincidence of the MWP with high CO2 levels around 1200 AD remains questionable. Therefore, although temperature changes certainly explain part of the observed CO2 variations, we cannot rule out that carbon-cycle variations related to mechanisms other than surface temperatures, such as redistributions in the oceanic/sediment pools, with timescales from century to millennia play a considerable role. In the simulations we start from a well-equilibrated carbon-cycle that may not exist in the real world. The simulated sensitivity of the atmospheric CO2 concentration to temperature is not time invariant in the simulations. Estimates of γ both from observations and model experiments provide an integrated quantification of climate-carbon cycle feedbacks, but the underlying processes are complex and are characterized by different time-scales and

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physical and biogeophysical mechanisms. We interpret the non-stationarity of γ in our experiments as a response to different time-scales induced by the forcings with higher sensitivity for longer time-scales. Reorganisations in the slowly varying compartments ocean and carbon storage are apparently needed for the climate-carbon cycle feedback to fully develop. The simulated climate and carbon-cycle response to variations in the external forcing is likely model-dependent. In particular, our model's sensitivity of global CO2 concentration in the atmosphere to NH temperature changes is on the lower end compared to the probabilistic estimate by Frank et al. (2010), in particular, for those estimates including the LIA CO2 drop. Frank et al. ruled out earlier findings with much greater numbers, but their estimate encompasses still a wide range (1.7 – 21.4 ppmK-1). Model-based estimates of γ reported in Frank et al. (2010) come from the short C4MIP simulations and are probably not representative for experiments with relatively weak external forcing. Carbon-cycle model intercomparison exercises over longer periods are necessary to identify the model dependency of the interchange between the carbon pools. The applied forcings, though state-of-the-art, come with a range of uncertainty. Recent estimates on the TSI increase from the Maunder Minimum to present have converged on a probable increase of about 1.3 Wm-2, but the solar community still discusses how the findings from the last three solar cycles can be related to different states of the sun (see the recent review by Gray et al., 2010). Reconstructions of volcanic eruptions (Crowley et al., 2008; Gao et al., 2008) are based on ice-core sulphate records. They differ in their transfer function, mainly deduced from recent eruptions, to the optical properties and in the screening process for deciding what is an important eruption. These choices can lead to considerable differences in the radiative forcing for individual volcanic eruption (Schmidt et al., "Climate forcing reconstructions for use in the PMIP simulations for the Last Millennium", manuscript submitted to Geosci. Model Dev., 2010). Finally, the representation of the response to external forcing and the internal interaction between modes of variability (e.g. NAO, ENSO) depend on the model resolution and complexity. Owing to the long integration times we use a relatively coarse-resolution model. Although there is no doubt that in-

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clusion of a dynamic stratosphere and UV variations on stratospheric ozone will alter the response to solar forcing (Mann et al., 2009; Spangehl et al., 2010), the details appear to be, again, model dependent (Palmer et al., 2004). The experiments presented here are among the first ESM simulations that comply with the protocols of the Paleo Modelling Intercomparison Project Phase 3 (PMIP-3, http://pmip3.lsce.ipsl.fr) and the upcoming Paleo Carbon Model Intercomparison Project (PCMIP). Analysing the role of external forcings and internal variability and the climate-carbon cycle feedbacks in a multi-model framework is a promising way to improve climate models to be used in future international assessments of climate change.

R2: V. The selection of time filtering in the figures is not clearly explained, to give you an overview: Fig. 1: 11-yr running mean; Fig. 2 & 5: 31-yr running mean; Fig 6.: unfiltered ?; Fig. 7: low-pass 50 years and 31-yr running mean

AR: Different time filtering was done for different purposes. For the 20th century, we prefer to include decadal to multidecadal variability and therefore used a 5-year running mean (erroneously described as 11-yr running mean in the figure caption of the original figure 1, we apologize for not transferring the figure caption correctly from an earlier version). Most of the data are displayed as 31-yr running means focusing on multidecadal to centennial variations and because such a filtering is very common for such applications (e.g. Jansen et al., 2007, figure 6.10). For Fig. 8 (Fig. 7 in the original MS) we use a particular filter to accommodate for the analysis in the frequency domain (Fig. 8b). Since we redid the analysis for Fig 8 anyway, we now, however used a 31-year filter.

Specific comments: 1. page 1012, line 18: There are a lot of publications of fully coupled AO-GCM & carbon cycle focusing on the last 150 yrs and the future - maybe it would be nice to mention some recent studies, e.g. Froelicher and Joos 2010 (Clim Dyn). Moreover, studies on the dynamics of the past 500-1000 yrs are also performed by several other groups: Stendel et al. (2006, Clim Dyn), Tett et al (2007, Clim Dyn), and Spangehl et al. 2010 (JGR)

AR: We have followed the reviewer's suggestion and modified the paragraph accordingly:

MS: This is a significant advance over previous efforts, which have been restricted to Energy Balance Models (Crowley, 2000) and ESMs of Intermediate Complexity (e.g., Gerber et al., 2003; Goosse et al., 2005), to single realisations of coupled models without a carbon cycle (Gonzáles-Rouco et al., 2003; Ammann et al., 2007) or to simulation that did not span the entire last millennium (Stendel et al., 2006; Tett et al., 2006; Spangehl et al., 2010). The introduction of an interactive carbon cycle is considered to be a major advance in climate modelling (Friedlingstein et al., 2006) but comprehensive climate-carbon cycle models have been applied mostly to the anthropogenic era and to study future changes in the carbon cycle-climate connection (e.g. Raddatz et al., 2007; Fröhlicher et al., 2009; Fröhlicher and Joos, 2010).

R2: 2. page 1012, line 22/23: I suggests to remove 'Readers who ... and 2.2." as this is not necessary. Some readers will do this anyway.

AR: This sentence was removed

R2: 3. page 1012, line 23/24: "... starting with a comparison of simulated and reconstructed NH temperatures, followed ..." reads better.

AR: The sentence was changed accordingly.

R2: 4. page 1015, line 20/21: The reference is misleading. Timmreck et al use the same model to understand the 1258 AD eruption so at least the authors should mention here some reconstructions they use to proof that the response to 1258 is in agreement.

AR: We have modified the paragraph to discriminate between the references for the sensitivity experiments and the reconstructions, respectively:

MS: Sensitivity experiments for the model response to the Pinatubo eruption yield an average global temperature change (0.4 K) comparable to observations. Sensitivity experiments (Timmreck et al., 2009) for the largest eruption of the last millennium (1258

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AD) demonstrate that Reff variations matter and that aerosol particle sizes substantially larger than those observed after Pinatubo yield temperature changes consistent with reconstructions (Büntgen et al., 2006; Crowley et al., manuscript in preparation, 2010).

R2: 5. page 1017, line 17: "The simulated global CO2 increase ... shows a somewhat less ..." is clearer.

AR: The sentence has been modified accordingly.

R2: 6. page 1017, line 17/18: Why do you find a less upward trend? At least present a hypothesis.

AR: Following a suggestion by reviewer P. Friedlingstein we have included a discussion on the quantitative changes in the carbon reservoirs and the sinks and sources. There is now an entire paragraph devoted to the 20th century CO2 evolution and Fig. 2 b (formerly Fig. 1b, see below) has been redrawn including a CO2 reconstruction merged from ice-core data and atmospheric measurements. In summary, we relate the fact that the simulations arrive at roughly 10 ppm smaller CO2 concentrations than the observations at the end of the 20th century mainly to an underestimation of the carbon fluxes from land-cover-changes.

MS: The simulated global atmospheric CO2 concentration in the 20th century (Fig. 2 b) stays below the observed record (a combination of ice core data and atmospheric measurements provided by the Paleo Model Intercomparison Project at https://pmip3.lsce.ipsl.fr/. By the end of the 20th century, the simulations arrive at 10 ppm lower values than the reconstructions. Part of this discrepancy can be explained by the roughly 3 ppm lower CO2 concentration at the very beginning of the experiment (800 AD). For the industrial period (1850 – 2000 AD) the simulated carbon content in the atmosphere increases by 163 Gt C in the ensemble mean, the land inventory changes by -3 Gt C and the ocean takes up 119 GT. The respective numbers given from a combination of reconstructions and model estimates (Houghton, 2007) read 175 Gt C, 40 Gt C, and 140 Gt C. However, terrestrial fluxes in particular (see table

1 in Houghton, 2007) come with a large range of uncertainty. As has been pointed out by Pongratz et al. (2009) the primary emissions from land-use change simulated by our model are similar to other studies (DeFries et al. 1999; Olofsson and Hickler, 2008), though at the lower end. Therefore we attribute the lower-than-observed CO2 concentrations in part to an underestimation of land-use change emissions that are not compensated for by a somewhat too weak ocean uptake. In addition, the turnover of soil turnover may be too slow. For the period 1990 – 2000 AD, however, the simulated carbon sources and sinks for the 1990s are well in the range of observations: atmospheric growth is 3.2 Gt C in the simulations vs. 3.1 Gt C in the observations. The ocean sink is 2.1 (2.2) Gt C, the land-atmosphere net flux is 1 (1) Gt C and the land use emissions account for 1.3 (1.6) Gt C (numbers in brackets from Le Quéré et al., 2009). Overall, the differences between simulated and observed CO2 concentration at the beginning of the 21st century are well in the range of state-of-the-art climate carbon models, such as those carried out in the framework of C4MIP (Friedlingstein et al., 2006; Raddatz et al., 2007). The CO2 increase from land-cover changes is moderate compared to contribution from fossil-fuel emissions. Over the last millennium, land-cover changes contribute roughly 20 ppm (Pongratz et al., 2009).

7. page 1018, line 25/27: Is this 'difference in spread' statistical significant - I have my doubts when looking at Fig. 2b. Please test and in the case it is not significant please remove the statement.

AR: The question if the ensemble spreads are different is, in fact, not very important. We have therefore removed the statement and reformulated the paragraph:

MS: The magnitude of the ensemble spreads is, however, considerable when compared to the multi-centennial temperature changes. In particular, the E1 ensemble exhibits spread of 0.25-0.3 K almost continuously between 1450 and 1700 AD.

8. page 1018, line 28: Give a reference for statement, that 1600-1650 is the coldest period.

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AR: We have rephrased the sentence and included a reference:

MS: During the first part of the 17th century, where the reconstructions show the coldest part of the LIA (Frank et al., 2010), a “cold” E1 realization gives a negative temperature anomaly nearly as strong as the much more strongly forced E2 simulations.

R2: 9. page 1019, line 2: ’swing’ implies a clear (periodic) process and yet there is no commonly accepted one for the MWP-LIA transition, so I suggests to you instead ’variability’.

AR: “swing” has been changed to “variation”

R2: 10. page 1019, line 16: The sentence ’Therefore it seems ..." is awkward and has to be clarified.

AR: We have reformulated the entire paragraph (see comment to Major Point I above)

11. page 1021, line 27: Maybe ’highlighting’ reads better than ’signaling’.

AR: changed

12. page 1022, line 15: As I do not have the possibility to read the Brovkin paper (as it is in review) I wonder that the long-lasting imprint is the trend of the light-blue line in Fig 5b, correct - if so it would be nice to add a sentence of two, explaining why you found such a imprint.

AT: The Brovkin et al. paper is now available online under: http://www3.interscience.wiley.com/journal/123567292/abstract

It discusses the impact of the 1258 volcanic eruption on the carbon-cycle. This is seen in Fig. 6 b (Fig. 5b of the original MS) in the atmospheric CO2-decrease in the second half of the 13th century. The CO2 decrease in the 19th century is a corresponding response to the volcanic eruptions in the early 19th century. We have redrawn the figure showing the CO2 curve until 2000 and one can see that CO2 recovers in the volcano-only experiment in the 20th century. We reformulated the paragraph in order

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to clarify the long-term response of the carbon-cycle to volcanic eruptions (see answer to Major Comment III above).

R2: 13. page 1023, Line 1: here I am puzzled - how have you estimated gamma for the unforced simulations, do you really mean the CTRL simulation?

AR: Yes, we do mean the unforced control experiment. Following Frank et al. (2010) gamma is defined as the change in CO2 concentration per 1K change in Northern Hemisphere temperature (see above). Therefore, internally-driven temperature changes in the control experiment will affect the carbon reservoirs.

R2: 14. page 1023, line 3/4: This is an interesting analysis however I miss an interpretation or a hint of an underlying process which is responsible for this time dependence

AR: Interpretation: We are presently investigating further the time-scale dependence by conducting sensitivity experiments with different forcing periods. For the present manuscript we have to speculate and our interpretation is that the slow processes (ocean, soil carbon) in the carbon cycle are important for the feedback to fully develop.

MS: The stronger response in the forced simulations may reflect non-linearities in the system, or the different spatio-temporal structure of the temperature patterns in the forced simulations. The mechanisms behind the carbon-cycle response to external forcing have been investigated in a separate study focusing on the impact of a strong volcanic eruption. Brovkin et al. (2010) analyzed the time period around the eruption of the 1258 unknown volcano in the same experiments. They conclude that the CO2 decrease in the atmosphere is explained mainly by reduced heterotrophic respiration on land in response to surface cooling corroborating findings by Jones and Cox (2001). Furthermore, the magnitude of the atmospheric response is determined by the land carbon storage while its duration is set-up by the marine carbon cycle. In particular, the stronger sensitivity at low frequencies (Fig 8 b) suggests that these slow processes associated with carbon storage in the biosphere and oceans determine the feedback strength. Therefore, the slowly varying solar irradiance changes and the cumulative

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effect of volcanoes that lead to multi-centennial climate variations provide time-scales in which the carbon-cycle response can fully develop.

R2:15. page 1026, line 17: A segment length of 1 yr seems to be awkward. I guessed that the authors use yearly data, so 1 yr segments lead only to points and thus it is impossible to estimate a linear trend. I think the method has to be clarified.

AR: The reviewer is correct, 1yr-segments do not make much sense and we therefore have redrawn figure 4 with segment lengths from 10 years to 100 years

R2: 16. page 1027, line 23-25: The sentence needs clarification, maybe splitting it into two will help.

AR: The paragraph has been rephrased

R2: 17. page 1035, Fig1a: The simulation with a weak solar forcing (E1) show during the 20th century a higher response in NH temperature than the simulation with high solar forcing (E2, dashed lines). Knowing that the solar forcing is increased during this period and shows a linear trend this behavior is counterintuitive.

AR: It is correct that the E1 ensemble arrive at somewhat higher temperatures at the end of the 20th century. However, the E2 temperatures are colder in the early 19th century so that the overall warming from the Dalton Minimum to present is greater in the runs with stronger fording. We interpret the cold deviations during the second half of the 20th century as a (delayed) response to the multidecadal variations in the solar forcing (see Fig. 1a). In addition we have to apologize and correct the statement about the time filtering: The data in Figure 2 were not smoothed by an 11-year running mean, but by a 5-year running mean. We applied this smoothing to focus on the decadal to multidecadal time scale and to exclude the ENSO variability (a plot with yearly data would be hard to read). We have included the following sentences in the manuscript:

MS: The E2 ensemble members are slightly colder at the beginning of the industrialized era (see below) and are modulated by the stronger multidecadal variations in the E2

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solar forcing. Therefore the E2 simulations arrive at somewhat colder temperatures in the second half of the 20th century.

R2: 18. page 1036, Fig3c: Please do not smooth the volcanic forcing as it might lead to a miss interpretation, e.g., a 'permanent' volcanic eruption from 1800-1830. I also cannot believe that it is a running mean - I would expect that at the beginning and the end ofthe simulation 15 yrs are missing.

AR: Both temperature data (fig. 2a in the original manuscript) and the radiative forcing (fig 2 c in the original manuscript) were smoothed with a 31-yr running mean. The last 15 years were omitted (the curves for the experiments covering 800-2005 AD end in 1990). For this reason we also noted the respective values at the end of the simulation (2005) with symbols at the right y-axis. We have, however, followed the reviewer's suggestion and display now annual values for the radiative forcing. Compared to the other forcings, the volcanic effects are very strong, but short-lived. Therefore it was necessary to split the figure into two with different vertical axes for the volcanic RF. We then reconsidered the appearance of the original Fig. 1 and now prefer to show the radiative forcing as Figure 1 together with the description and discussion of the external drivers. In the revised manuscript, we have therefore included the paragraph on the calculation of the radiative forcing (appendix B in the original manuscript) in section 2.

R2: 19. page 1038: An information which periods are shown might be useful, maybe in a table.

AR: we have followed the suggestion and have included a table in appendix A1 (see Table A1).

R2: 20. Page 1040, Fig5b: Why do we see such a strong negative trend in the light blue experiment?

AR: We have updated Fig. 6b (Fig. 5 b in the original manuscript) and now show the solar and volcano-only runs until 2000 AD. Now one can see that the negative trend is not continuing into the 20th century. The long-term deviations are the response of the climate system to the cumulative volcanic forcing that is particularly strong during the early 19th century. As explained above, the long time scales in the response to this event-like forcing are introduced by the slowly-varying components of the Earth system, the ocean and the soil in the land biosphere.

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6, C658–C680, 2010

Interactive Comment

Figure1

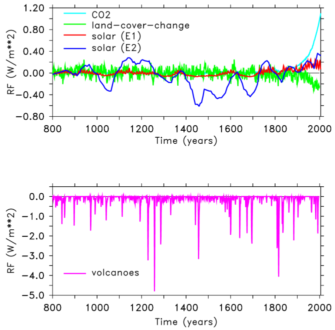

Fig.1. Radiative forcing at the top of the atmosphere displayed as annual means **(a)** for the greenhouse-gas forcing (CO_2), land-cover-change (albedo effect only), and solar forcing, and **(b)** for volcanic forcing displayed with a different axis. Anomalies from solar irradiance and CO_2 variations are calculated w.r.t. their pre-industrial control mean (1367 Wm^{-2} and 280.02 ppm, respectively). The radiative forcing from volcanic aerosol injections and land-cover-changes are calculated from single forcing experiments.

Fig. 1.

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Figure 2

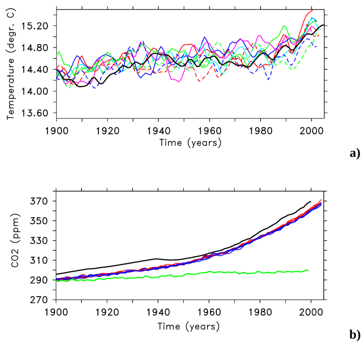

Fig. 2. NH temperature and global CO_2 concentration in the 20th century. **(a)** 20th century Northern Hemisphere (land and ocean) 2m air temperatures (11-year running means) simulated in ensemble E1 (solid coloured lines) and E2 (dashed coloured lines) in comparison with the HadCRUT3v dataset (obtained from the Climatic Research Unit, http://www.cru.uea.ac.uk/cru/data/temperature), **(b)** 20th century global CO_2 concentration (yearly data) simulated in ensemble E1 (red) and E2 (blue) in comparison with a combination of ice core data and atmospheric measurements (black) provided by the Paleo Model Intercomparison Project at **http://pmip3.lsce.ipsl.fr**. The green line is the respective curve for the land-cover-change-only experiment.

Fig. 2.

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Figure 6

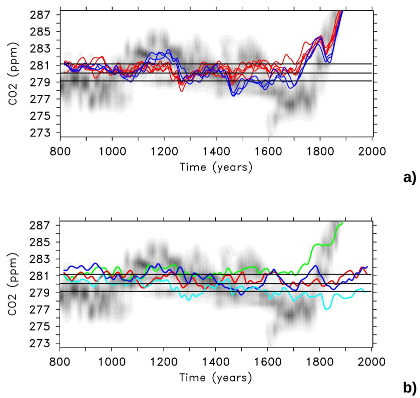

Fig. 6. CO_2 concentrations (31-year running mean) from **(a)** ensembles E1 (red) and E2 (blue) in comparison with a compilation of ice core reconstructions (grey shading, see Appendix A). Black horizontal lines denote the control experiment mean and its 5th-95th percentile range, **(b)** the respective CO_2 concentrations from the experiments forced by one single component, i.e. standard solar forcing (red), strong solar forcing (blue), land-cover change (green), and volcanic aerosols (light-blue).

Fig. 3.

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Figure 8

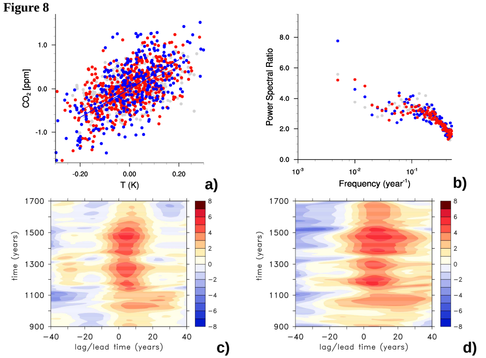

Fig. 8. Climate carbon-cycle sensitivity: **(a)** Co-variability of annually averaged NH temperature anomalies with globally and annually averaged CO_2 anomalies for the ensemble E1 (red dots), the ensemble E2 (blue dots) and control (grey dots) experiments. Data points are taken by randomly sampling the low-pass (31-year) filtered data with a mean sample stride of 25 years. Correlations are significant at greater than the 99% level given an equivalent sample size of 68 and 140 for the experiments with strongly-varying solar forcing and the control experiments, respectively (see Appendix C), **(b)** Ratio of power spectra as a function of wave-number for the E1 (red) and E2 (blue) ensembles and the control (grey) simulations. In both panels the forced experiments were only analyzed for the period between 800 and 1700, during which time the anthropogenic influence on the carbon cycle was negligible, **(c),** and **(d)** running regressions (slopes in ppm/K) between NH temperature anomalies and globally and annually averaged CO_2 anomalies for different time lags (positive lags mean that temperature is leading) for one the ensemble means of ensemble E1 (left) and E2 (right). Running regressions were performed for 200-yr chunks based on the 31-yr low-passed filtered data.

Fig. 4.

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Appendix Tables:

Table A1: Timing of occurrence of the warmest MWP and coldest LIA 30-year climatological periods in (left) the simulations, and (right) the reconstructions (Jansen et al., 2007).

Table A1:

Experiment	Warmest MWP period	Coldest LIA period	Reconstruction	Warmest MWP period	Coldest LIA period
E1_1	1070 - 1099	1670 - 1699	JBB1988	1030 - 1059	1600 - 1629
E1_2	1100 - 1129	1670 - 1699	MBH1999	1150 -1169	1660 - 1689
E1_3	1190 -1219	1580 - 1609	ECS2002	980 - 1009	1600 - 1629
E1_4	1250 -1279	1640 -1669	B2000	980 - 1009	1670 - 1699
E1_5	1250 - 1279	1640 - 1669	MJ2003	950 - 989	1640 - 1679
E2_1	1220 - 1249	1640 - 1669	MSH2005	1100 - 1129	1580 - 1609
E2_2	1130 - 1159	1670 - 1699	DWJ2006	980 - 1009	1670 - 1699
E2_3	1190 - 1219	1670 - 1699	HCA2006	950 - 979	1640 - 1679

Fig. 5.