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Climate of the Past Discussions

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

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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 "HW"). The modified passages from the manuscript indicated starting with "MS":

Review by Heinz Wanner (HW): General comments: For the first time the Hamburg MPI for Meteorology Earth system model (ESM) ECHAM5 is used to study the role of external climate forcing and internal climate variability by also including a fully interactive carbon-cycle. The study was performed for the last 1200 years. By using state-of-the-art data for the different forcings the authors were able to successfully simulate the Northern Hemisphere temperature as it was reconstructed based on different proxy time series. Similar to other authors they demonstrate that groups of volcanic events in combination with solar irradiance minima (e.g. Wolf, Spörer, Maunder, Dalton) are substantial for the formation of multidecadal-scale Little Ice Age cold relapses. The authors discuss some aspects of the MWP-LIA transition but do not touch the question of changing circulation modes or regimes. In more detail they discuss the role of the carbon cycle and point to the problem that the simulated multi-centennial CO2 concentrations are smaller than in the observed records. The MS gives an important new insight into the climate dynamics of the last millennium. I therefore recommend to accept it after minor revisions.

AR: We thank Heinz Wanner for his positive evaluation and the comments and recommendations. As we have pointed out also in the response to the other reviewers, we have included additional information, reconsidered part of our analyses and added a more extended discussion section in particular on the CO2 evolution in the simulations and the reconstructions, respectively. We have, indeed not touched extensively on the role of changing climate regimes or modes. The detailed response of the climate system to individual forcings is subject of another study that we are preparing. We have mentioned the ongoing discussion on the role of changing “atmospheric modes”, however, in the discussion section.

Specific comments: HW: Page 1012, line 1: The expression Medieval Warm Period MWP is widely used. Because of the large heterogeneity of the spatiotemporal structure several authors prefer to use the expression Medieval Climate Anomaly MCA (e.g. Mann et al. 2009, Science, 326, 1256-1260).

AR: We have included a sentence on the different expressions for the MWP/MCA. For the manuscript, however, we want to keep the name MWP as we discuss almost entirely northern hemisphere climate change:

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MS: Northern Hemisphere (NH) temperature reconstructions (Jansen et al., 2007; Mann et al., 2008; Mann et al., 2009) for the last millennium differ substantially among each other, raising questions (Trouet et al., 2009; Mann et al., 2009) about the spatial and temporal extent of climatic epochs such as the Medieval Warm Period (MWP) and the Little Ice Age (LIA, ca. 1500-1850 AD). The large heterogeneity in space and time has lead several authors to prefer the expression Medieval Climate Anomaly (MCA, e.g., Mann et al., 2009).

HW: Page 1014 and 1015, solar and volcanic forcing: My impression is that the uncertainties related to the reconstruction of both forcings are still huge because we do neither have good reconstruction data nor do we satisfactorily understand the specific dynamics. A joint effort is needed to get to better reconstructions of solar and volcanic forcing.

AR:We have pointed to these uncertainties now more extensively in several parts of the manuscript and, in particular, in the discussion:

MS: Third, 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). . . . 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 Intercom-

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parison 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.

HW: Page 1018, line 17: I looked through about 50 significant time series around the globe. Their warmest peaks occur at a different time. This fact was already demonstrated by Bradley et al. (Science 302/2003, 404 – 405).

AR: We acknowledge the hint to the Bradley's perspective papers and we have changed the respective paragraph accordingly. For the NH, where most of our study focuses on, at least the reconstructions compiled in Jansen et al. (2007) show their warmest peak earlier than 1200. We have rephrased the corresponding sentences:

MS: While the world-wide distributed data compiled by Bradley et al. (2003) showed their warmest 30-year period anywhere between 1000 and 1200, most NH temperature reconstructions (Jansen et al., 2007; Mann et al., 2008; Mann et al., 2009), however, indicate a MWP centred on the turn of the millennium and decreasing temperatures from 1150 onwards.

AR: We have also taken up a suggestion by reviewer #2 regarding Figure 3 and included the actual timing of the warmest and coldest climate periods for both the reconstruction and the simulations as a table in appendix A1. We have modified the respective paragraph accordingly.

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

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and the coldest epoch before the onset of anthropogenic warming in the 17th 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), table 6.1). Figure 3 indicates 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 20-90N 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.

HW: Page 1019, line 2-4: I am convinced both aspects are important: a) the superposition of a group of volcanic events with solar activity minima; b) internal variability. I am not convinced that only one mode (e.g. NAO) was responsible for the MCA-NAO transition. It was likely a combination of different processes, e.g. represented by the complex interaction between NAO and ENSO.

AR: We agree with this interpretation and have extended the section by a short discussion to include some remarks on the ongoing discussion on sustained changes of atmospheric modes during the last millennium:

MS: Therefore, multi-century climate variations such as the MWP-LIA transition may not require particular strong solar forcing but can be attributed, at least in parts, to internal variability on centennial time-scales. Trouet et al. (2009) interpret the warm MWP conditions over Europe and North America as expression of a positive NAO/AO anomaly that results from a dynamical response to the solar forcing anomaly and occurs sustained over several centuries. In our simulations, we cannot identify such a long-term response of atmospheric regimes to the external forcing. Mann et al. (2009) compare two general circulation model simulations, one of them including a well-resolved stratosphere and the effects of ozone photochemistry (based on the model of Shindell et al., 2001). They find that only the latter reproduces the observed pattern of enhanced North-American, North Atlantic, and Arctic-Eurasian warming as a result of a positive NAO/AO response. While it must be stated that other models with resolved stratospheric dynamics and ozone chemistry do not show the same projection onto the leading atmospheric modes (e.g., the UK Unified Model, Palmer et al., 2004)) it is possible that our model does not adequately represent complex interactions between variability modes, such as NAO and ENSO.

HW: Typographic errors: Page 1024, line 12: Intersomparison Page 1040, legend Fig. 5: Also

AR: The errors have been corrected

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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

Table A1: Timing of the warmest 30-year climatic period during the MWP (900 – 1300 AD) and the coldest 30-year climatic period during the LIA (1550-1750). The left part of the table refers to the individual ensemble members from the E1 and E2 ensemble. The right part of the table refers to the reconstructions using the same acronyms as in Fig. 3 (see appendix A1).

Fig. 1. Table A1

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