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

Review by N. Krakauer (NK): This manuscript describes experiments with a coupled atmosphere-ocean general circulation model that included an interactive carbon cycle, aimed at understanding changes in surface temperature and CO2 concentration over the last millennium. The modeled temperature fluctuations are found to be qualitatively consistent with available records, while the modeled preindustrial CO2 fluctuations and industrial CO2 surge are too small. The manuscript is generally clear and well-presented, although the description of the modeling details is rather abbreviated. The work reported is of interest to climate scientists, and I recommend publication.

AR: We thank reviewer N. Krakauer for the positive evaluation and the suggestions. As can be seen also from our responses to the other reviewers, we have taken all suggestions into account and modified the manuscript accordingly. We have also extended the discussion section and elaborate in more detail possible model shortcomings and uncertainties (see answer to remark 3 below).

NK: 1. Information on the fossil fuel emissions assumed as forcing should be provided.

AR: A reference to Marland et al. (2003) is now included in section 2.2.5

NK: 2. It would be useful to describe the model representation of sea and land snow and ice, and how important albedo changes are for the temperature response.

AR: We have extended the model description to the representation of sea-ice, snow on sea ice, and snow on land. Our model does not include an interactive ice-sheet model or variable glacier mask.

NK: 3. The discussion could be extended slightly to consider why the modeled preindustrial CO2 fluctuations might be too small (e.g., not enough soil carbon in long-lived pools?).

AR: We have discussed this issue in more detail in the discussion section of the revised manuscript. We point out (also in another manuscript that has been recently published online in Tellus: Reick et al. “Contribution of anthropogenic land cover emissions to pre-industrial CO2, Tellus, B, published online, doi:10.1111/j.1600-0889.2010.00479.x, 2010) that the origin of the observed CO2 fluctuation is far from being well understood. It may well be that there are long-term variations in the climate-carbon-cycle

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system that we cannot include in our simulation which we start from a well equilibrated state. Following also recommendations by reviewer Pierre Friedlingstein we have re-evaluated our estimate of the atmospheric CO2 concentration sensitivity to temperature and corrected the gamma estimate for Northern Hemisphere temperatures (as in Frank et al. (2010)). We conclude that our model's sensitivity is in the range of Frank's estimate for the last millennium, but probably on the lower end. The determination of the exact reason for the magnitude of gamma is, however, beyond the scope of the present manuscript. Joint effort analysing different models will be necessary to identify the different responses to external forcing in different models. Here the upcoming PCMIP exercise will certainly be useful.

MS: 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 (see section). Therefore, although temperature changes certainly explain part of the observed CO2 variations, we cannot rule out that carbon-cycle variations, 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. Second, as we discussed in the previous sections, the simulated climate and carbon-cycle response to variations in the external forcing is model-dependent. In particular, the sensitivity of global CO2 concentration in the atmosphere to NH temperature changes could be on the lower end. The probabilistic estimate of Frank et al. (2010)

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ruled out earlier findings with much greater numbers, but encompasses still a wide range (1.7 – 21.4 ppmK-1). Model-based estimates of γ 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. Third, the applied forcings, though state-of-the-art, come with a range of uncertainty. For TSI, the centennial variations are uncertain. Recent estimates on the 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). 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 inclusion 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. 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.

NK: 4. Another good diagnostic for whether the modelled sensitivity to solar variability is reasonable would be to compare the modelled amplitude of the temperature response to the 11-year solar cycle with that derived from observations (cf. Tung et al., Constraining model transient climate response using independent observations of solar-cycle forcing and response, GRL, 2008).

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AR: We have followed NK's suggestion and carried out a regression analysis between the TSI variations and global temperatures for the last 60 years, as in Tung et al. (2008). For this we used an experiment, where the solar forcing that includes an 11-yr cycle is the only external forcing. We arrived at a sensitivity of 0.15 K/(Wm-2). Reviewer #2 also wanted a more comprehensive discussion on temperature sensitivity and we therefore extended the paragraph in section 3.2:

MS: 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 is 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 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. 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. 1).

NK: Typographic comments: 1. p. 1027:18-19 "Regression slopes varied by _0.07 for the control and 0.06 ppm for the forced simulations." – should the units be ppm/K? 2. p. 1043, figure caption: "the strongly forced and controlled experiments" – should be something like "the strong-solar-variability and the control experiment".

AR: The typos have been corrected.

Interactive comment on Clim. Past Discuss., 6, 1009, 2010.