Clim. Past Discuss., 8, C2777–C2790, 2012
www.clim-past-discuss.net/8/C2777/2012/

Climate of the Past Discussions

CPD

8, C2777–C2790, 2012

Interactive Comment

Interactive comment on "Variability of the ocean heat content during the last millennium – an assessment with the ECHO-g Model" *by* P. Ortega et al.

P. Ortega et al.

pablo.ortega@lsce.ipsl.fr

Received and published: 14 December 2012

The authors are grateful to the four anonymous referees for their helpful and constructive comments. We think that the new version of the article benefits substantially from the changes that have been proposed. All suggestions were carefully considered and most of them were included in the new manuscript. Some long comments were divided into different sub-points to better organise the response and to ease readability. We have also tried to reply in detail each of the major and minor comments. The full text of the review is reproduced below, with an answer following each comment. A pdf file highlighting changes (deletions/addition) to the previous version of the manuscript is also sent to the editorial office in order to facilitate a detailed screening of changes. Additional figures and tables have been included in a supplementary file to attend the reviewers concerns.

Reply to Reviewer 2

General Comment: *In this paper, the authors address a relevant research question. The variability of ocean heat content needs to be further assessed in order to compare it against the observed trends. It is also important to understand the development of the regional structure of ocean heat uptake further. In these respects the submitted ms. is timely.*

My concern is, however, whether it was a wise choice to use ECHO-G for the purpose of this study. As the authors discuss, the drift in ocean temperature is strong. In Fig. 4c, they have to go great lengths (for details see below) to explain the the large discrepancy between the trends of their model and the data.

3 Moreover, the model uses flux corrections, which affects the surface heat fluxes and therefore certainly the ocean heat uptake. I acknowledge that in the CMIP3 class of models some still used flux corrections, but I expect that ocean heat uptake and its regional patterns will be affected by the flux corrections particularly strongly.

In addition, in a recent model intercomparison study (Kuhlbrodt and Gregory, 2012, GRL), ECHO-G stands out with an exceptionally small ocean heat uptake efficiency, actually by far the smallest of all CMIP3 and CMIP5 models. I am aware that the authors could not have seen this study upon submission of their ms., but perhaps they would still like to discuss this feature.

In another intercomparison study, ECHO-G stands out as well. Wang et al. (2011, JGR 116) found that in the A1B scenario it has the strongest wind stress change of all CMIP3 models, but no consequent increase in ACC volume transport, which could point to an unusual response of the ocean stratification to the wind stress.

In conclusion, I would suggest that the authors (1) discuss the results of their model in

CPD
8, C2777–C2790, 2012

the context of other AOGCMs, and (2) if possible, repeat at least a few of the analyses with another AOGCM, to be sure that their results are of general relevance, and not particular to ECHO-G alone. Therefore, my recommendation is to return the ms. to the authors for a major revision.

General reply: The authors understand the reviewer's concern about the model. We agree that the fact that ECHO-G requires flux corrections, together with the important drifts in deep ocean temperature present at the beginning of FOR1 and FOR2 (the first two GCM simulations ever made for the last millennium) can cast doubt on the general relevance of our results. Other state-of-the-art AOGCMs without flux adjustments are now available, and many of them have been used to generate new millennial simulations. Most of these simulations would be probably more suitable for this particular analysis. However, we will like to discuss, and hopefully convince the reviewer, that even if ECHO-G is not a-priori the wisest choice, it can still provide new valid insight on the variability of ocean heat content. Indeed, in our particular case, the use of these ECHO-G simulations suppose an advantage to us, since many aspects of their variability, their specific shortcomings, the experimental setup and the model components are well known to us. In the following, we will answer in detail the different points raised by the reviewer:

Ocean trends and comparison with proxy data: section 3.2 has been restructured and simplified. It now simply discusses the simulated OHC700 variability in the context of the radiative forcing and the proxy evidence available. A special focus is set on the instabilities introduced in each simulation by the initial thermal imbalance, with the final goal of determining under which conditions their impact can be neglected. We conclude that by focusing on the upper 700 m of the ocean, and restricting the analysis to FOR2 when the focus is set on the whole millennium, the effect of this drift is minimized. The former part on the simulated thermal expansion, the hypotheses to correct the drift from 1700 onwards, and the final comparison with SL trends has been removed for various reasons: first, that thermal imbalance has a considerable effect on variables defined integrating through the whole depth of the ocean like the global thermal expansion; second, that the model is unable to represent other contributions to sea level rise than this thermosteric component; third, that the assumptions made for the drift correction are not reliable enough to guarantee that final trends are exclusively attributable to the forcing; and finally, and maybe more importantly, that these results were somewhat less related to the rest of the analysis, which only focus on the OHC700.

The effect of flux corrections: Flux corrections are controversial due to their inherent non-physical nature (Shackley et al., 1999). Yet, in the case of ECHO-G an other CMIP3 type of models, they are important to reduce some biases in the mean distributions of ocean surface temperature, salinity and precipitation. Regarding their impact on the heat uptake by the ocean, particularly at the regions where the influence of climate indices has been studied, we believe that flux adjustments will have a minor effect as long as they remain small when compared to the actual fluxes (Sausen et al., 1988). In the following we will illustrate to what extent this is true for the ECHO-G simulations. In Sup. Fig. 2 the climatological net fluxes at the ocean surface in CTRL are compared with the heat flux corrections. We can see that these correction terms are generally smaller than the actual fluxes, and this is more evident when we average over the areas where the OHC700 has been analysed regionally (Sup. Table 1), in particular for those related to ENSO, the AMO and the NAO. We can expect therefore that the local distortion on ocean heat uptake from these heat flux adjustments is not particularly strong. We further note that flux adjustments by construction have global averages equal to zero. This implies that global OHC values should not be affected by them. At regional scales, flux corrections remain constant in time, thus not directly affecting the results from correlation and regression analyses, nor the linear trends. However, they will have an indirect effect, as they introduce systematic biases in the model's base state, thus affecting the feedback mechanisms,

CPD
8, C2777–C2790, 2012

Interactive Comment

and probably the representation of the climate modes themselves. In this respect, the model performance for ENSO and the NAO was discussed in (Min et al., 2005b) and also now throughout the text (from line 7 to line 17 in page 23[1]). To conclude, in a recent study, Pardaens et al. (2011) compared the spread in sea level projections between two different ensembles within the QUMP (Quantifying Uncertainty in Model Projections) project, and found comparable results for the experiments with and without flux adjustments. Although no specific details on the regional aspects were provided, their result gives us more confidence to believe that the overall impact of flux adjustments on the ocean heat content (that is directly related with the thermosteric component of SL) will remain relatively small. The effect of flux corrections is now discussed in the last paragraph of the conclusions (starting in Page 28, line 27).

Inclusion of other models in the analysis: Authors agree that if similar results were obtained in other model simulations of the last millennium, that would doubtlessly help to support the general relevance of our findings. However, we believe this would radically change the extent (as the number of figures and subfigures would multiply) and scope of the paper (as a comprehensive evaluation of the similarities and, more importantly, the discrepancies among the models would be desirable). This is clearly not feasible for us at the moment. In either case, we believe that our results remain valuable by themselves, as long as our model is properly put in the context of other AOGCM (as also suggested in the general comment). We hope, nevertheless, that our work can inspire other groups, which will be able to assess the reproducibility of our results.

Intercomparison with other models (is it really an outlier?): Given the limitations previously discussed for the model, and in particular the fact that it requires flux

[1]We will always refer to the manuscript with deletions and additions since page numbering in the clean final version will change after the journal's online edition.

adjustments, it seems unavoidable to discuss the overall model performance in the context of other simulations with state-of-the-art models. In the first comparisons with other AOGCMs, the main drawback was related to the anomalously warm temperatures in FOR1 at the beginning of the millennium (Goosse et al., 2005; Osborn et al., 2006). This problem was overcome when FOR2 was completed, as its more equilibrated initial conditions place its simulated Northern Hemisphere mean temperature well within the range of more recent models (Ammann et al., 2007; Zorita et al., 2007; Fernández-Donado et al., 2012). Indeed, a model intercomparison study by Fernández-Donado et al. (2012) shows that the equilibrium climate sensitivity, the transient climate response and the temperature change in the MCA-LIA transition for ECHO-G compare well with those of the other simulations, most of them not using flux corrections. Regarding the comparatively small value of its heat uptake efficiency reported in (Kuhlbrodt and Gregory, 2012), we admit that the ECHO-G value for this quantity stands out when compared to the other CMIP models. However, it it is also important to note that Kuhlbrodt and Gregory (2012) also argue that models tend to overestimate this heat uptake efficiency, which depends on how fast heat is transported downward, and this in turn is controlled by the ocean stratification. And this ocean stratification is comparatively good for the ECHO-G simulation (see Sup. Fig. 3). Moreover, in their Fig. 2, Kuhlbrodt and Gregory (2012) compare the model ensemble with the WOA05 climatology, finding a rather realistic vertical temperature structure for the HadGEM2-ES model, that has a value for heat uptake efficiency not too far from that for ECHO-G model. Other point raised in the general review is the relationship between the ACC and the Southern Hemisphere winds in the ECHO-G model discussed in Wang et al. (2011). Their analysis shows evidence that the theoretical direct link proposed by Wang (1994) between the ACC transport and the intensity of westerlies is not reproduced in 9 models out of 19 used in the IPCC AR4. ECHO-G stands out because it simulates a small decrease in the ACC simultaneously to the largest increase in westerlies. But there are other 7 models showing much larger decreases in the ACC while the intensity of the westerlies keep rising, and other three for which no significant trends in the ACC transport are observed. This only reflects that the ACC response to the magnitude of the zonal wind stress is not coherent among the simulations. Indeed, the actual role of wind-stress is still under debate (e.g. Gnanadesikan and Hallberg, 2000; Böning et al., 2008). Furthermore, recent hydrographic data suggests that ACC has been insensitive to significant intensifications of Southern Hemisphere westerlies during the last few decades (Böning et al., 2008). To conclude, and more in relationship with our variable of study (i.e. OHC), we can consider the model intercomparison study by Pardaens et al. (2011), focused on projections of sea level change. By comparing the Figures 1 and 2a in that article we can conclude that SL changes in ECHO-G show a great degree of coherence with the model ensemble, reproducing most of the local SL changes that remains significant and of similar sign for at least two thirds of all the ensemble members. This includes, among other things, a SL dipole in the North Atlantic with negative values South of the Gulf stream and positive values in the Labrador Sea (but whose thermosteric components show an opposite contribution), a strong meridional gradient in the Southern ocean with negative changes near 60°N and positive further north, and finally positive SL anomalies in the North Pacific. Similar features are also recognizable in our analysis of the OHC700 response to the radiative forcing (Fig. 7a), thus giving confidence on the further validity of our results. A summarised discussion of all these aspects has been also included in the final paragraph of the conclusions (starting in Page 28, line 27).

Finally, please note that most figures in the manuscript have been redone after realizing that the removal of the linear trends in CTRL is no longer valid (See Comment 1.2 of the 4th reviewer). Fortunately, changes in the figures are almost imperceptible as the impact of this incorrect detrending is really small in the upper ocean, where the analysis is focused.

SPECIFIC COMMENTS:

<u>Comment 1:</u> *(p.4225, l.23 and p.4231, l.15) Inconsistent discussion. Does the shutdown of convection lead to deep warming (p.4225) or to deep cooling (p. 4231)? This might well depend on the surrounding stratification, but that should be discussed here.*

Reply: The reviewer is right. Explanations given on both pages were contradictory. Under normal stratification conditions convection activates the vertical mixing, substituting cold dense waters at the surface with relatively lighter and warmer waters from the bottom. Thus, it leads to both a net warming at the surface and a net cooling at depth. A reduction (and in a extreme case a shutdown) of convection will diminish this vertical heat transfer, thus producing a relative cooling at the surface (and in turn on the OHC700) and a relative warming in the deeper ocean, both with respect to the normal convection conditions. Therefore, a decrease in convection activity reduces the net upward (and not downward as stated in page 4231) heat transport. Both paragraphs have been rephrased in the new manuscript.

Rephrased version: The deeper ocean warming can be associated with a decrease in convection in the North Atlantic, which will diminish the vertical transfer of surface cold water thus leading to an anomalous warming at depth and a cooling in the upper levels. [It starts in Page 3, line 23]

Rephrased version: Yet, a local OHC700 cooling south of Greenland is also seen, in line with a local decrease in deep convection that reduces vertical heat mixing and thus the replacement of dense cold waters at the surface with relatively lighter and warmer waters from deeper levels. [It starts in Page 11, line 26]

<u>Comment 2:</u> *(section 2.3) I can see why the authors use proxies of total sea level rise for its thermosteric component. However, in the North Atlantic the thermosteric and halosteric components can cancel each other out (e.g. Pardaens et al., 2011, Clim.*

Dyn.). What does that imply for using the Kemp et al. record here?.

Reply: The proxy from Kemp et al. (2011) represents relative sea level variations that account for the combined contributions of the halosteric and thermosteric components (that can locally cancel out), and also of non-steric sources (e.g. melting of ice-caps). Their proxy, despite being estimated from two local sediment cores near North Carolina, compares well with global tide-gauge data in the last three hundred years. They estimate that their index can represent the global mean sea level changes in the last 2 millennia within an uncertainty of $\pm$10 cm. And it is under this assumption, i.e. that their proxy captures the global SL signal within the given uncertainty range, that we establish our comparison with the simulations. We believe the effect of local cancelations between the thermosteric and halosteric components will be smoothed in this global SL estimate. Note also that now the comparison is made with the simulated global OHC700 means.

Comment 3: *(p.4233, upper half) As said before, the authors have to make a really great effort to discuss the large discrepancy between their model and the data. Still, I don't find the discussion convincing. The model trends are dominated by the model drift. That's why their trends have the wrong sign up until 1600. They also don't capture the trend after 1850. According to Church et al., 2011, GRL, the thermosteric contribution to the total is about 40% in the late 20th century, not one sixth as the authors claim. Using the years 1800 to 1900 to de-trend the model simulations appears as a very ad-hoc approach, and from Fig. 4c it cannot be assessed how the trends in that time compare with the data.*

We also think that the previous analysis was probably too ambitious given the important drift in simulated thermal expansion and the model misrepresentation of ice-sheet melting contributions. For all these reasons, as we already advanced in the general reply, we have reconsidered the main purpose for this section, and simplify the corresponding discussion. Proxy records are now considered just as a reference framework

Full Screen / Esc
Printer-friendly Version
Interactive Discussion
Discussion Paper

to assess the potential reach of the initial thermal imbalance. In the new analysis we conclude that the effect of this imbalance is probably negligible in the upper 700 m of FOR2. Also, given the limitations previously discussed, no final quantification of the thermosteric contribution to the total SLR (40% according to Church et al., 2011, and one sixth that is what we obtained when we compared the model with SL estimates from Jev08) has been included in the revised manuscript.

Comment 4: *(Fig. 2/new Fig. 3) Please discuss the big patch of ocean heat loss in the Pacific sector of the Southern Ocean. What is happening there? There is no similar feature in the observations, but this patch dominates some of the regression patterns in Fig. 6 (new Fig. 7).*

Reply: This local patch of negative OHC700 anomalies North of the Ross Sea is directly related to local changes in convection, as we will try to illustrate in the following. In FOR2, convection activity over the Ross Sea is particularly sensitive to changes in the radiative forcing (Sup. Fig. 4a), which tends to warm (and thereby lighten) the surface waters, thus damping convection. During the last millennium the Ross Sea, unlike the whole Southern Ocean, is characterised by climatologically colder waters in the upper 700 m than in the immediate levels below (Sup. Fig. 4b). These are favourable conditions for convection. Furthermore, as the transition from cold to warm waters takes place near 700 m, the vertical mixing fostered by convection will probably inverse the thermal conditions above and below this level. Therefore, whenever convection activity is reduced (like in response to a larger radiative forcing) the vertical mixing will also diminish and in this way lead to a local cooling of the upper 700 m. Likewise, the rest of the Southern Ocean, and in particular the regions where convection is not important, will tend to warm following the increase in the radiative forcing. We believe that this is what explains the local cooling and the Southern Ocean warming in Fig. 7a-c.

Something similar can be discussed regarding the trends in Fig. 3. Two different as-

CPD
8, C2777–C2790, 2012

Interactive Comment

pects will deserve some attention: first, that no cooling near the Ross Sea is evidenced in the observations, nor in the period 1955-1990 of the simulations; and second, that in the simulations, the cooling only appears in the period 1991-2010, and thereby not from 1955-1990 nor from 2011-2100. Regarding the first point, the climatological temperature profile over the Ross Sea from the observations (WOA05 Locarnini et al., 2006) is not exactly the same as in FOR2, since only the upper 250 m remain clearly colder than the rest, while the warmer waters lay between 300 and 1500 m depth. In these conditions, it is not clear which would be the net effect of convection on the upper 700 as a whole. In either case, the signal should be considerably smaller than for the simulations (which is in line with Fig. 3). Regarding the other point, two different reasons are proposed to explain the absence of the cooling patch in each case. During the period 1955-1990 the radiative forcing does experience a net increase (see Fig. 2e), although with important decreases due to volcanic activity, which can probably reactivate convection due to its large cooling effect on surface and subsurface temperature. In contrast in the last period (2011-2100) the radiative forcing increases monotonically, yet, the Southern Ocean undergoes a wide-spread OHC700 warming. In this case what we see is that the vertical temperature profile in the Ross Sea has changed substantially (red line in ??b) under the increasing GHGs concentrations, which have warmed up the subsurface waters, thus reducing the temperature contrast between the upper 700 m and the waters underneath (similarly to the temperature profile for observations). As these conditions enhance throughout the 21st century, the cooling effect of convection on the OHC700 will tend to disappear.
The main points of this discussion have been included in the text when both Fig. 3 and Fig. 7 are commented.

New text: Both simulations also show a patch of ocean heat loss to the North of the Ross Sea, which relates to a local decrease in convection over the region that will be further discussed in Section 4.2. [It starts in Page 11, line 13]

Rephrased version: Within the last millennium, the pattern of response to an increase in the total radiative forcing (Figure 7a) corresponds to a generalised warming of the upper ocean, with larger values in the extratropics, and some local coolings in regions of deep water formation convection, like the Labrador and Ross Seas. In this latter region both convection and the OHC700 respond differently to the radiative forcing than in the rest of the Southern Ocean, due to its particular stratification conditions. The Ross Sea is characterised by climatologically colder waters in the upper 700 m than in the levels underneath (not shown), so that a corresponding decrease in convection will reduce vertical heat mixing between both layers, thus producing the local cooling in OHC700. By contrast, the rest of the Southern Ocean, and in particular the regions where convection is not important, will tend to warm following the increase in the radiative forcing. [It starts in Page 17, line 26]

New text: In either case, both forcings factors (i.e. GHGs and solar irradiance) are the only to exhibit the local cooling in the Ross Sea, which might therefore require a gradual adjustment of convection to the changes in the radiative forcing. [It starts in Page 18, line 14]

References

AchutaRao K, Sperber K (2002) Simulation of the el niño southern oscillation: Results from the coupled model intercomparison project. Climate Dynamics 19: 191–209

Ammann CM, Joos F, Schimel D, Otto-Bliesner BL, Tomas RA (2007) Solar influence on climate during the past millennium: Results from transient simulations with the ncar climate system model. Proc Natl Acad Sci 104: 3713–3718

Böning C, Dispert A, Visbeck M, Rintoul S, Schwarzkopf F (2008) The response of the antarctic circumpolar current to recent climate change. Nature Geoscience 1: 864–869

Church JA, White NJ, Konikow LF, Domingues CM, Cogley JG, Rignot E, Gregory JM, Broeke MRVD, Monaghan AJ, Velicogna I (2011) Revisiting the earth's sea-level and energy budgets from 1961 to 2008. Geophys Res Lett 38: L18,601

CPD

8, C2777–C2790, 2012

Interactive Comment

Danabasoglu G (2008) On Multidecadal Variability of the Atlantic Meridional Overturning Circulation in the Community Climate System Model Version 3. J Clim 21: 5524

Fernández-Donado L, González-Rouco J, Raible C, Ammann C, Barriopedro D, García-Bustamante E, Jungclaus J, Lorenz S, Luterbacher J, Phipps S, et al. (2012) Temperature response to external forcing in simulations and reconstructions of the last millennium. Climate of the Past Discussions 8: 4003–4073

Gnanadesikan A, Hallberg RW (2000) On the relationship of the Circumpolar Current to Southern Ocean Winds in coarse-resolution ocean models. J Phys Oceanogr 30: 2013–2034

Goosse H, Crowley T, Zorita E, Ammann C, Renssen H, Driesschaert E (2005) Modelling the climate of the last millennium: What causes the differences between simulations? Geophys Res Lett 32: L06,710

Kemp A, Horton B, Donnelly J, Mann ME, Vermeer M, Rahmstorf S (2011) Climate related sea-level variations over the past two millennia. Proc Natl Acad Sci published online: 1–6

Kuhlbrodt T, Gregory JM (2012) Ocean heat uptake and its consequences for the magnitude of sea level rise and climate change. Geophysical Research Letters 39: L18,608

Latif M, Sperber K, Arblaster J, Braconnot P, Chen D, Colman A, Cubasch U, Cooper C, Delecluse P, DeWitt D, Fairhead L, Flato G, Hogan T, Ji M, Kimoto M, Kitoh A, Knutson T, Treut HL, Li T, Manabe S, Marti O, Mechoso C, Meehl G, Power S, Roeckner E, Sirven J, Terray L, Vintzileos A, Voû R, Wang B, Washington W, Yoshikawa I, Yu J, Zebiak S (2001) Ensip: the el nino simulation intercomparison project. Climate Dynamics 18: 255–276

Locarnini R, Mishonov A, Antonov J, Boyer T, Garcia H, Levitus S, et al. (2006) World ocean atlas 2005 volume 1: Temperature. NOAA, Silver Spring, Md., 182 pp.

Min S, Legutke S, Hense A, Kwon W (2005b) Internal variability in a 1000-yr control simulation with the coupled climate model ECHO-G -II. El Niño Sourthern Oscillation and North Atlantic Oscillation. Tellus 57A: 622–640

Olbers D, Völker C (1996) Steady states and variability in oceanic zonal flows. NATO ASI SERIES I GLOBAL ENVIRONMENTAL CHANGE 44: 407–444

Osborn TJ, Raper SCB, Briffa KR (2006) Simulated climate change during the last 1000 years: comparing the ECHO-G general circulation model with the MAGICC simple climate model. Clim Dyn 27: 185–197

Pardaens AK, Lowe JA, Brown S, Nicholls RJ, Gusmão DD (2011) Sea-level rise and impacts projections under a future scenario with large greenhouse gas emission reductions. Geophys Res Lett 38: L12,604

Sausen R, Barthel K, Hasselmann K (1988) Coupled ocean-atmosphere models with flux correction. Climate Dynamics 2: 145–163

Shackley S, Risbey J, Stone P, Wynne B (1999) Adjusting to policy expectations in climate change modeling. Climatic Change 43: 413–454

Stommel H (1957) A survey of ocean current theory. Deep Sea Research Part II: Topical Studies in Oceanography 4: 149–184

Wang L (1994) A linear homogeneous model for topographic control of the antarctic circumpolar current. Journal of marine research 52: 649–685

Wang Z, Kuhlbrodt T, Meredith MP (2011) On the response of the antarctic circumpolar current transport to climate change in coupled climate models. Journal of geophysical research 116: C08,011

Warren B, LaCasce J, Robbins P (1996) On the obscurantist physics of “form drag” in theorizing about the circumpolar current. Journal of physical oceanography 26: 2297–2302

Zorita E, Gonzalez-Rouco F, von Storch H (2007) Comments on “Testing the fidelity of methods used in proxy-based reconstructions of past climate”. J Clim 20: 3693–3698