Author comments on

Ms. No. esd-2010-18:
Climate change under a scenario near 1.5°C of global warming: Monsoon intensification, ocean warming and steric sea level rise
by J. Schewe, A. Levermann, M. Meinshausen

Below we answer the two referee comments published during the open discussion of the manuscript. We thank both referees for their constructive and helpful comments.

Please find below the referees' comments, quoted in *italic*, and our corresponding statements of how we address them in the revised version of our manuscript. Following that, we also indicate a minor update we performed independently of the reviews.

Referee #1

General comments

The title just focuses only on the lowest RCP. I recommend the title be changed to: Climate change in response to the new RCP scenarios: monsoon intensification, ocean warming and steric sea level rise

Referee #2 also comments on the title of the paper and suggests it be changed to "Climate change under the RCP3-PD scenario: Ocean Warming, Slow Global Cool-Down and Steric Sea-Level", focusing explicitly on the lowest RCP (see below). Because the two referees differ in their views on this issue and because the novelty in this paper relates to the lowest scenario RCP3-PD, we suggest to keep the title unchanged. We believe it becomes clear in the beginning of the abstract that the paper deals primarily with the lowest RCP, but considers as well the other RCPs as a point of reference.

Specific comments

1. *Page 299, 4 lines down – At the same time, a review by 2015 – English is awkward.*

We replaced the sentence

> "At the same time, a review by 2015 was agreed on to look into a potential tightening of this target…"

by

> "At the same time, it was agreed that a review, to be concluded by 2015, should look into a potential tightening of this target…".

2. *Page 301 – The climate sensitivity and transient climate response of Climber 3 should be given here and compared to the AR4 AOGCMs. I note that the climate sensitivity is discussed in the last section but I think the reader needs to know where this model fits into the AR4* *distribution much earlier in the paper.*

We have added, at the end of section 2, the text:

> "CLIMBER-3α's climate sensitivity is about 3.4°C, which is higher than the average climate sensitivity of the transient AOGCM emulations of 2.9°C (Meinshausen et al., 2008, Table 4), very close to the average of the slab-ocean GCMs of 3.26°C and still close to the IPCC AR4 best estimate of 3°C (Meehl et al., 2007, Box 10.2). The transient climate response is about 1.9°C for CLIMBER-3α, compared to about 1.8°C for the average of IPCC AR4 AOGCMs (Meehl et al., 2007b, Table 8.2)."

Accordingly, we have replaced the corresponding sentence in section 5, paragraph 1, by a statement referring to the earlier mention of the climate sensitivity:

> "CLIMBER-3α temperatures tend to be slightly higher than the median of the AOGCM emulations (cf. Fig. 1), owing to the difference in climate sensitivity."

3. *Page 302, 5 lines down – Why use the observed temperature trend estimated by Broham et al.? The IPCC AR4 estimate is more widely accepted.*

HadCRUT3 / Brohan et al. (2006) is cited in the IPCC AR4 (WG1, chapter 3.2) as one of the three main sources for the estimation of global warming trends (NCDC, GISS and HadCRUT3 data), and their 1961-1990 mean global surface temperature estimate serves there as reference for the comparison of different estimation methods. We therefore find it appropriate to use the same reference in our study, in order to make our results easily comparable to those presented in the AR4.

4. *Page 302, 5-6 lines down – The sentence "The warming projected . . . . of the AOGCMs." needs a reference.*

We have added a reference to Fig. 1c and f.

5. *Page 302, 10 lines down – 0.18C per decade – This needs a reference or a description of how the value was computed. What period? Linear trend?*

We thank the reviewer asking for this clarification and adapted our text now to refer to the 0.16 to 0.18°C trend per decade estimated for 1979-2004 by the IPCC AR4 WG1 (Trenberth, Jones et al. 2007, Section 3.4).

6. *Page 303, bottom, last 3 lines – More is needed. What variable(s?) in view?*

We have added an additional reference, and detail on which variables are affected, to the respective sentence. It now reads:

> "Note that changes due to direct and indirect aerosol effects are not captured by simulations with CLIMBER-3α and may have significant influence on monsoon rainfall and circulation which is likely to counter-act that of global warming (Lau and Kim, 2006; Rosenfeld et al., 2008)."

7. *Page 304, top PP – I am confused by the use of high, medium, low RCP in this discussion. Use the RCP labels (RCP8.5, RCP6, etc).*

We are now using the RCP labels throughout the paper, and have removed the terms high, medium, low where appropriate.

8. *Page 304, 7 lines up – Southern Ocean outflow – Define.*

We have added the definition thus:

> "Southern Ocean outflow, i.e. the AMOC flux across 30°S, …"

9. *Page 304, bottom – The SLR pattern should be compared to those published in Yin et al. 2010.*
Yin, J, S Griffies, and RJ Stouffer, 2010: Spatial variability of sea-level rise in 21st century projections. J Climate, 23(17), doi:10.1175/2010JCLI3533.1.

We have added at the end of section 3.4 the following text:

> "Yin et al. (2010) showed by comparison of simulated and observed present-day dynamic sea level patterns in twelve IPCC AR4 AOGCMs that their ensemble mean performs better than any of the individual models. The SLR pattern found in our analysis is in good qualitative agreement with the ensemble mean projection of those models under the SRES A1B scenario (Yin et al., 2010)."

We have also added a reference to Yin et al. (2010) earlier in this section when discussing sea level changes in the North Atlantic.

10. *Page 307 – Stouffer (2004) discusses many of the processes outlined here. It should be referenced.*
Stouffer, RJ., 2004: Time scales of climate response. J Climate, 17(1), 209-217.

We have included a reference to this paper in the corresponding section, at the end of the sentence:

> "The inertia induced by these processes delays the cooling that results from the decline in GHG concentrations (Stouffer, 2004)."

Referee #2

General comments

The paper structure could be improved to allow the material to be read more easily and to focus the reader's attention on the more important results. The results concerning the mid-ocean warming and consequent dynamic ocean effects on long-term global temperature stand out as particularly important. Section 4 refers many times to figures and results from *section 3, some restructuring of these two sections could improve the layout.*

As the referee correctly states further below, we have made a mistake in referring to figure 5 instead of figure 8. After correcting this, section 4 does not refer explicitly to figures from section 3, and refers to results from section 3 only in the first sentence. Thus, after correcting the reference mistake, we see no need for restructuring here.

Some figure panels were not referred to in the text (figure 2b, 3b) and not discussed whilst unique material was presented in the figure captions that would have been more appropriately placed in the main body of the text (e.g. figure 5 and 7).

We have added an explicit discussion of, and reference to, figure panel 2b in section 3.2:

> "In the RCP8.5 scenario (Fig. 2b), the AMOC reduction is relatively smaller compared to the warming, and has no large offsetting effect."

Figure panel 3b is referred to in the second paragraph of section 3.4.

We have moved the discussion of the relationship between global warming and the rate of sea level rise from the caption of figure 5 (figure 6 in the revised manuscript) to the main text, section 3.4:

> "During an initial phase, we find a quasi-linear relationship between the rate of steric sea level rise and the global mean surface warming (Fig. 6, inset; cf. Rahmstorf, 2007). However, the quasi-linear relation fails as soon as global warming starts to decelerate, i.e. around 2100 for RCP8.5, and some time earlier for the lower scenarios. As suggested by Vermeer and Rahmstorf (2009), validity of semi-empirical projections of sea level change based on this relation might be extended by taking rapid adjustment processes into account."

To our understanding, no unique material is presented in the caption of figure 7 (figure 8 in the revised manuscript). The effect of polar amplification and outcropping of isopycnals on oceanic warming mentioned in the caption is discussed in detail in the second paragraph of section 3.5.

There is also a mistake in that figure 8 is referred to as figure 5 in the text.

We have corrected this mistake.

There should be some expansion of the section on changes in ocean circulation and AMOC, to allow further explanation of the mechanisms and consequences. The following questions on the AMOC results should be addressed in the text or in response to this review. How does the AMOC in CLIMBER-3A compare to the AMOC in IPCC models? Is it stronger or weaker than the IPCC model average and what effect would a weaker/stronger AMOC have on the results? What are the hydrological changes (precipitation and runoff) in the North Atlantic region and what impact do these have on the AMOC results? Is the AMOC in CLIMBER-3A stable in the long run? The intensity of the AMOC increases after 2300 for the RCP3-PD, why is this?

The AMOC in CLIMBER-3α is stable over control integration timescales >10'000 years.
We have addressed the questions raised by the referee by expanding sections 2 and 3.2 as follows:

In section 2, we have added detail to the model description that is necessary to appreciate the overturning strength of the model version used:

> "The model version used here features a low background value of oceanic vertical diffusivity ($0.3*10^{-4}$ m^2/s) and an improved representation of the Indonesian throughflow as compared to the version described by Montoya et al. (2005)."

In section 3.2, first paragraph, we have added or extended the following sentences:

> "The recovery of the AMOC beyond 2200 is facilitated by the retreat of sea ice cover in the North Atlantic (Levermann et al., 2007), which in the case of RCP3-PD even leaves the AMOC stronger in the long-term than under pre-industrial conditions."
>
> "With respect to the pre-industrial overturning strength, CLIMBER-3α is comparable to the IPCC AR4 model average and consistent with observations (cf. Fig. 10.15 in Meehl et al., 2007)."
>
> "AMOC changes in response to global warming in CLIMBER-3α are dominated by changes in heat flux, as in most other CMIP3 models, while hydrological changes tend to have a minor, strengthening effect (Gregory et al., 2005)."

It does not seem necessary to include the results on the monsoon response in this paper, which draws attention away from the stronger results on the impacts of ocean warming and circulation change on global temperature and thermosteric sea-level rise. The monsoon is an important impact of climate change but perhaps this model is not the best tool to assess it, with very coarse atmospheric resolution (22.5 x 7.5) and using a statistical-dynamic atmosphere model. If this section is kept a comparison of the model with the IPCC AOGCMS for precipitation, particularly in monsoon regions would be a valuable addition. In addition the inclusion of more explicit caveats or discussion of the impacts that the low resolution and the statistical dynamical model have on the monsoon results would be of benefit.

To address these issues, we have included a new figure (figure 4 according to the numbering in the revised manuscript) that shows monsoon precipitation and winds for the control climate of our model and compares its annual rainfall cycle with reanalysis data. We refer to this figure in section 3.3 to discuss the robustness of our monsoon results, and also compare to IPCC AR4 model results. See specific comment no. 8 below for details.

The title does not reflect the focus of the paper very well and does not mention the interesting mechanism for the slow-down in global cooling after peak temperatures are reached. As a suggestion: "Climate change under the RCP3-PD scenario: Ocean Warming, Slow Global Cool-Down and Steric Sea-Level" would highlight the results that were most important from the paper and the fact that almost all the results relate to the RCP3 scenario. The slow cool down should be mentioned in the title as it seems to be the key result.

Referee #1 also comments on the title and suggests it be changed to “Climate change in response to the new RCP scenarios: monsoon intensification, ocean warming and steric sea level rise”, leaving the second part of the title unchanged. Because the two referees differ in their views on this issue, we suggest to keep the title unchanged. We believe that the wording “…a scenario near 1.5°C” already reflects the fact that many of the results focus on the RCP3-PD scenario, while also reflecting, to some extent, the nature of this scenario. The slow-down in global cooling found in this scenario is cited prominently in the abstract.

It is not clear whether the paper focuses solely on the RCP3-PD scenario or gives a broader overview of all the scenarios. Most of results are related to the RCP3-PD scenario with some comparison with the RCP8.5 scenario, however in the text some results for the other scenarios are discussed and section 2 suggests that all the scenarios were investigated.

The paper is intended to do both: Give an overview of all the scenarios with respect to some key climate variables, and lay special focus on RCP3-PD with its near-1.5C temperature rise. We think that such an approach is justified here, because (i) a comprehensive, if somewhat brief, presentation and intercomparison of the climatic effects of this relatively new set of scenarios is of high interest for a broad audience within the climate research community; and on the other hand, (ii) RCP3-PD stands out from the other three RCPs because it includes active carbon removal from the atmosphere and features a very low peak temperature, and thus represents a major innovation with respect to the SRES scenarios. We discuss this topic in the Introduction.

Further explanation of the ocean dynamic changes and how they relate to the changes in ocean mixing and regional sea-level change would be of value. For example, the second paragraph of section 3.5 could be split to allow a longer explanation and to highlight the effect of these ocean dynamic changes on the ocean-atmosphere heat exchange and the consequent slow-down in global cooling.

See our response to specific comment no. 11, below.

<u>Specific comments</u>

1. *page 298, around line 15 – helpful to compare sea level rise on the same year for both scenarios.*

In the text

> “Steric sea level rise under the RCP3-PD scenario continues for 200 years after the peak in surface air temperatures, stabilizing around 2250 at 30 cm.This contrasts with around 2 m of steric sea level rise by 2500 under the highest scenario, RCP8.5.”

we have replaced the second sentence by

> “This contrasts with around 1.3 m of steric sea level rise by 2250, and 2 m by 2500, under the highest scenario, RCP8.5.”

2. *Page 300, line 20 – Comment on precipitation and monsoon response in comparison with the CMIP3/AR4 models.*

This is done in section 3.3 – see our response to specific comment no. 8, below.

3. *Page 301, line 1 – not clear what the phrase 'compute the emulated temperature ranges for the RCP scenarios' means.*

We have deleted this part of the sentence as it is redundant, with information given in the following sentences, and apparently unclear.

4. *Page 302, line 6 – 'emulation of the AOGCMs', it would be better to use a consistent phrase throughout the text, earlier the phrase 'MAGICC 6 emulations' was used.*

We use the phrases "emulations of AOGCMs" or "AOGCM emulations" throughout the text, except for one instance (page 301, line 2 of the original paper) where we use the phrase "MAGICC6 emulations". To avoid any misunderstanding, we have replaced "MAGICC6" in that instance with "AOGCM", so that the sentence now reads:

> "Our AOGCM emulations use RCPs harmonized emission inputs…"

5. *Page 302, around line 20 – no mention of figure 2b or 3b in the text.*

See our response above, under "General comments".

6. *Page 303, line 5 – what are the effects of freshwater input from the land and from precipitation? Do these play a significant role?*

We address this question in the text now; see our response above under "General comments".

7. *Page 303, line 10 – it is not clear what the sentence beginning 'depending on the scenario: : :' refers to, which scenario? Which scenarios are the upper/lower values correlated with?*

We have restructured this sentence to make it more comprehensible:

> "Seasonal (June-August) mean rainfall associated with the South Asian summer monsoon (including India and the Bay of Bengal) strengthens by 10% (RCP3-PD) to 20% (RCP8.5) until the middle of the 21st century and, for RCP8.5, by up to 30% during the 22nd century (Fig. 5a)."

8. *Page 303, line 25 – expand on the caveats for the monsoon results. What is the effect of the coarse resolution? How dependent are the results on the use of a statisticaldynamical model?*

We have included an additional figure (figure 4 according to the numbering in the revised manuscript) that shows monsoon precipitation and winds for the control climate of our model and compares its annual rainfall cycle with reanalysis data. The caption of this figure reads:

> "Fig. 4. (a) Difference between average boreal summer (JJA) and winter (DJF) precipitation (shading, in mm/day), and average summer (JJA) near-surface winds (vectors) in the control (pre-industrial) climate of CLIMBER-3α. (b) Seasonal cycle of monthly average precipitation in the South Asian monsoon region in CLIMBER-3α's control climate (solid line) and in the NCEPNCAR reanalysis (Kistler et al., 2001), averaged over the period 1948-2007 (dashed line)."

In section 3.3, we have added discussion of caveats and the robustness of our results, using this figure, and also referring results from IPCC AR4 models. The 2nd and 3rd sentences of section 3.3 now read:

> "Within the limitations of the statistical-dynamical atmosphere model and its coarse resolution, CLIMBER-3α simulates the principal patterns of monsoon dynamics and precipitation reasonably well (Fig. 4a), and its seasonal rainfall cycle compares favourably with reanalysis data (Fig. 4b) and IPCC AR4 models (cf. Kripalani et al., 2007, Fig. 1). We find that average monsoon rainfall in Asia and Africa intensifies under global warming (Fig. 5), consistent with many studies using more complex models (e.g. Kripalani et al., 2007)."

Moreover, in response to comment no. 6 of referee #1 (see above), we have improved the discussion of aerosol effects on the monsoon.

9. *Page 304, line 26 – A sentence explaining the relationship between ocean circulation changes and local sea-level rise would be useful.*

We have added explanation to the sentence addressed here, which now reads:

> "By 2100 (Fig. 7a), the weakening of the AMOC maximum (cf. Fig. 3a) and of the North Atlantic current produces a southeast-to-northwest SLR gradient in the North Atlantic via geostrophic adjustment (Levermann et al., 2005; Yin et al., 2010)."

(Figure numbers refer to the revised version of the manuscript.)

10. *Page 305, around line 15 – Material from the caption of figure 7 may be more appropriately included at this point.*

The effects mentioned in the caption of figure 7 (figure 8 in the revised manuscript) are discussed in the subsequent paragraph, starting in line 16 of the original version of the paper. See also our response above, under "General comments".

11. *Page 305, lines15-25 – The explanation of the changes in mixing should be expanded and clarified. The explanation is clearer in the conclusion: Page 309, line 15.*

We have expanded the explanation, in line with the one in the Conclusions. The sentence now reads:

> "In general, the strong deep oceanic warming signal results from outcropping of isopycnals (black lines in Fig. 8b) at high latitudes, i. e. a lack of density stratification, which is a characteristic and robust feature of the modern ocean circulation."

(Figure numbers refer to the revised version of the manuscript.)

12. *Page 305, line 25+ - consider splitting paragraph to highlight the role of the heat anomalies at intermediate depths on the slow down in global cooling.*

We have added the following sentence at the end of section 3.5:

> "Conversely, these oceanic heat anomalies serve as a longterm reservoir that slowly discharges into the atmosphere and delays surface cooling, as discussed in the following section."

13. *Page 306, line 15 – This is the first mention of the climate sensitivity, adding this earlier when discussing global temperature trends or in the model description would be useful.*

See our response to specific comment no. 2 of referee #1, above.

14. *Page 308, line 18 – elaborate on the caveats for the statistical dynamic model and the resolution. How do these affect the results? What will their influence be on the robustness of the monsoon results? This could be addressed earlier in the text rather than here.*

We address this issue in section 3.3 – see our response to specific comment no. 8, above. In the Discussion, we remind the reader:

> "With respect to atmospheric quantities, the coarse resolution of CLIM*BER*-3α and the limitations of the statistical-dynamical representation must be kept in mind."

(This sentence was already present in the original manuscript.)

15. *Page 309, around line 20 – For the second half of the last paragraph, are the conclusions about the importance of studying mid-ocean warming specific to the results of this study?*

The risks associated with prolonged deep ocean warming discussed here are not specific to the results of our study; in fact, we refer to previous studies here. Rather, our study provides new insights as to the circumstances under which such warming could occur, and about its spatial distribution and residence time scale, and thereby might allow future studies to better analyse and quantify those risks.

16. *Page 316, figure 2 – It may be more appropriate to show the true resolution of the model and not use smoothing, as the resolution is very coarse and this may mislead the reader.*

We acknowledge the need to show the true model resolution. We have therefore left the model resolution visible in the new figure 4 (panel a). This way we can keep smoothing in figure 2 which we find more beneficial for the information we want to convey there.

17. *Page 317, figure 3 – Comment on the increased intensity of the AMOC above the modern value from 2300 onwards in the main text.*

As mentioned above under "General comments", we have added the following sentence in section 3.2, first paragraph:

> "The recovery of the AMOC beyond 2200 is facilitated by the retreat of sea ice cover in the

North Atlantic (Levermann et al., 2007), which in the case of RCP3-PD even leaves the AMOC stronger in the long-term than under pre-industrial conditions."

18. *Page 317, figure 3 – what is the longitude of the Labrador coast? "SPG" on figure 3B needed? Figure 3B is not referred to in the main text.*

We have added the longitude of the Labrador coast (62°W) in the caption.
We prefer to have the labels "AMOC" and "SPG" on the panels 3a and b to make this figure more easily accessible for the reader.
Figure panel 3b is referred to in the second paragraph of section 3.4.

19. *Page 318, figure 4 d,e,f – is the temperature reported the summer or annual value?*

We now state in the caption that it is the summer (JJA) value.

20. *Page 318, figure 4 a,b,c – How different are these results from the global average values?*

We have added a sentence in section 3.3 which discusses the difference for RCP8.5:

"In absolute terms, this means increases in JJA rainfall by up to 3-5 mm/day for RCP8.5, which far exceeds the global average increase of about 1 mm/day under this scenario."

For the other scenarios, the relative difference is similar.

21. *Page 319, figure 5 – improve the axes on the inset graph and consider using markers for certain key dates, i.e. peak emissions, etc.*

We have improved the inset by adding grid lines and additional tick marks, as well as markers for peak emissions. Note that this figure is figure 6 in the revised manuscript.

22. *Page 319, figure 5 – consider adding the Vermeer and Rahmstorf 2009 projections to the main figure.*

We thank the referee for this suggestion. However, our intention here is to place our results in the context of the semi-empirical approach by Vermeer and Rahmstorf (2009), rather than discussing that approach itself in much detail. We therefore suggest not to add any more information to figure 5 (figure 6 in the revised manuscript).

23. *Page 319, figure 5 – important information in the figure caption does not appear in the text, consider moving to main text.*

We have moved it to the main text, see our response under "General comments", above.

24. *Page 320, figure 6 – these results differ significantly in the atlantic from the IPCC WG1 results in chapter 10, figure 10.32. What are the reasons for this?*

One reason is that we present our results (figure 6 of the original manuscript, now figure 7) relative to pre-industrial, as stated in the caption, while those in the IPCC figure are presented relative to 1980-1999. Moreover, Yin et al. (2010) showed that IPCC AR4 models differ significantly in their ability to simulate present-day dynamic sea level patterns, as well as in their projections of future patterns. They show that an ensemble mean from the 12 best-performing IPCC AR4 AOGCMs outperforms any individual model in reproducing present-day patterns. Following the suggestion by referee #1, we compare our results to that ensemble mean – see our response to specific comment no. 9 of referee #1, above.

25. *Page 321, figure 7 – Move or copy the middle sentence of the caption from figure 7 to the main text.*

See our response to specific comment no. 10, above.

26. *Page 324, figure 9 – This is a very complicated figure, it needs an expanded explanation. It may also help to add markers for key dates, e.g. indicating the year of peak CO2, peak Temperature, or a marker every 25 years. This will allow the reader to follow the figure more easily.*

We have expanded the figure caption to allow a more detailed explanation of the figure. Also, we have added markers every 25 years, and some date labels to those markers.
The caption now reads:

> "Fig. 10. As Fig. 9a, but plotted versus CO2-equivalence concentration (sum of longwave absorbers) instead of time, and with the results of eq. (1) for the modified scenarios shown as dashed grey lines. This figure represents the transient "hysteresis" of global warming in RCP3-PD (blue line, marked every 25 years) and the modified peak-and-decline scenarios, i.e. how much GHG reduction it takes to cool the surface back to a given temperature that it had during the warming phase. The dashed lines show the hysteresis expected from the processes represented by eq. (1), while the solid lines show the hysteresis behaviour observed in CLIMBER-3α. The convection-related slow-down of the cooling rate (marked by a blue circle for the RCP3-PD scenario) translates into a widening of the hysteresis. The slow-down occurs at the same time under different scenarios (at the beginning of the 21st century, see thin grey lines in Fig. 9a), and at different CO2 concentrations."

(Note that figure numbering has changed due to an additional figure in the revised manuscript.)

<u>Technical Corrections</u>

1. *References – There are 2 papers matching the description: Stouffer et al. 2006, double check the references for other duplicates and mistakes.*

We have made the two references distinguishable by using letters a, b.

2. *Page 306 – all the references to figure 8 have been mistakenly made to figure 5.*

We have corrected the references. Note that figure numbering has changed due to an additional figure in the revised manuscript.

Update

In addition to the changes requested by the referees, we have updated the first sentence of the Introduction in order to reflect the situation in the international policy negotiations. Instead of referring to the *Copenhagen Accord*, we refer to the *Cancún Agreements*, where both the 2°C target and the decision to review that target have been officially adopted under the UNFCCC:

> "In December 2010, the international community agreed, under the United Nations Framework Convention on Climate Change, to limit global warming to below 2°C (Cancún Agreements, see http://unfccc.int/files/meetings/cop 16/application/pdf/cop16 lca.pdf)."

This change has no consequences for any of the results or conclusions drawn in the paper.

J. Schewe, A. Levermann, M. Meinshausen
December 20th, 2010