Response to Reviewers

I very much thank the two Reviewers for insightful and constructive comments. The comments by Anonymous Reviewer #1 are repeated in blue and the comments by Prof. Cronin are repeated in dark red. My replies are typeset in black.

Please note that line numbers in the "revised manuscript" actually refer to the track changes version. This revised version including track changes is found directly after the point-by-point replies in this document.

In case I fell short of some of your expectations, I would very much appreciate a chance for further improvements.

Response to Anonymous Reviewer #1

Major issues:

1) differences between RAD and ctrl runs and temporal evolution
Going back and forth between results from both types of runs at times becomes confusing for the reader. I suggest a more explicit discussion of the use of both runs and why one of them would be more reliable for a certain analysis than the other in the methods section. Are results that are not robust between these two sets of runs robust enough to be mentioned at all? To the extent that the RAD re-run mostly triggers a new realisation, I would doubt that. Especially for the temporal evolution section, the robustness of the results has to be demonstrated.

Unfortunately, the RAD re-runs are needed for the budget analysis. On the whole, the original runs and the RAD-reruns are similar, and in the revised manuscript, I have tried to make this clearer and also to more clearly point out where differences exist and to better explain them.

The following sentences have been added to page 4, lines 14ff of the revised manuscript in order to more explicitly explain why two sets of runs are used:

"The advantage of the RAD re-runs is that the PRP analysis is more exact which makes them more suitable for a budget analysis. The advantage of the base model setup is that it is computationally cheaper to run and thus is better suited for longer integrations."

On page 7 in lines 31f of the revised manuscript (please see appended track changes version at the end of the responses) it has been stressed that the RAD re-runs are sufficiently similar to the original runs for the budget analysis based on the RAD re-runs to be useful. This point is discussed in more detail in the reply to the major point 4 by the other reviewer Prof. Timothy Cronin.

On page 7 in lines 26f of the revised manuscript the sentence:

"This result is based on the original coupled runs and differs from the corresponding result of the RAD re-runs since the temporal evolution of the surface temperature differs."

has been amended as follows:

"This result is based on the original coupled runs, and differs from the corresponding result of the RAD re-runs since the temporal evolution of the surface temperature differs although the finding that polar amplification asymmetry decreases markedly in the flat AA model setup holds in the RAD re-runs as well"

Furthermore, Fig. R1 of this reply was added as Fig. 5 to the revised manuscript in order to better explain a result that is not robust across the sets of runs and minor clarifications have been added to the description of the result (on page 8 lines 7 to 10 of the revised manuscript). Fig. R1 should be compared to Fig. 5 of the original (Fig. 4 of the revised) manuscript.

The point that the OHT changes are not robust has also been re-iterated in

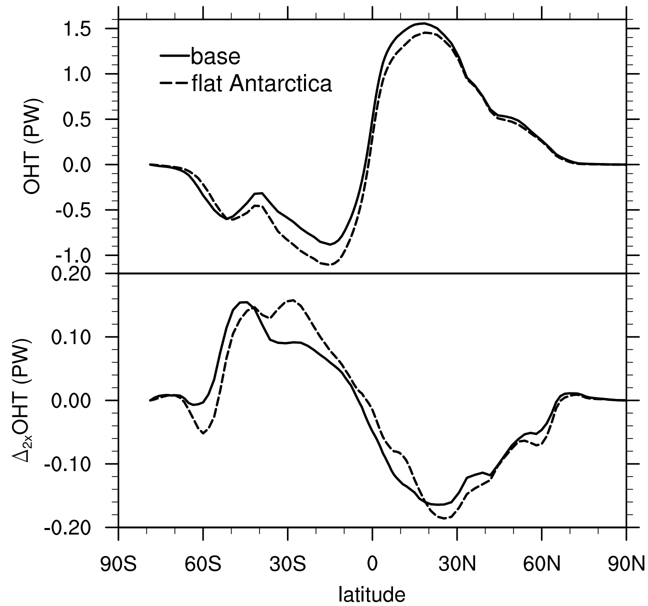

Figure R1: Oceanic heat transport (OHT) as in Fig. 5 of the original manuscript but for the original run.

Sect. 3.6 on page 11 lines 17ff of the revised manuscript as follows:

"Finally, in Sect. 3.3 it was shown that small OHT changes in response to doubling CO_2 *across the Arctic Circle that contribute to the OHT difference in Fig. 12 depend on the whether the original runs or the RAD re-runs are analyzed."*

Please note that the non-robustness of this result is reflected by a difference between Fig. R1 and Fig. 5 of the original manuscript that appears to be very small.

Although a set of two runs (i.e. the original and the RAD re-runs) is a very small "ensemble", and although the RAD re-runs are short since they are much slower to run due to increased I/O and more computationally expensive than the original runs, the general similarities between the results of the RAD-

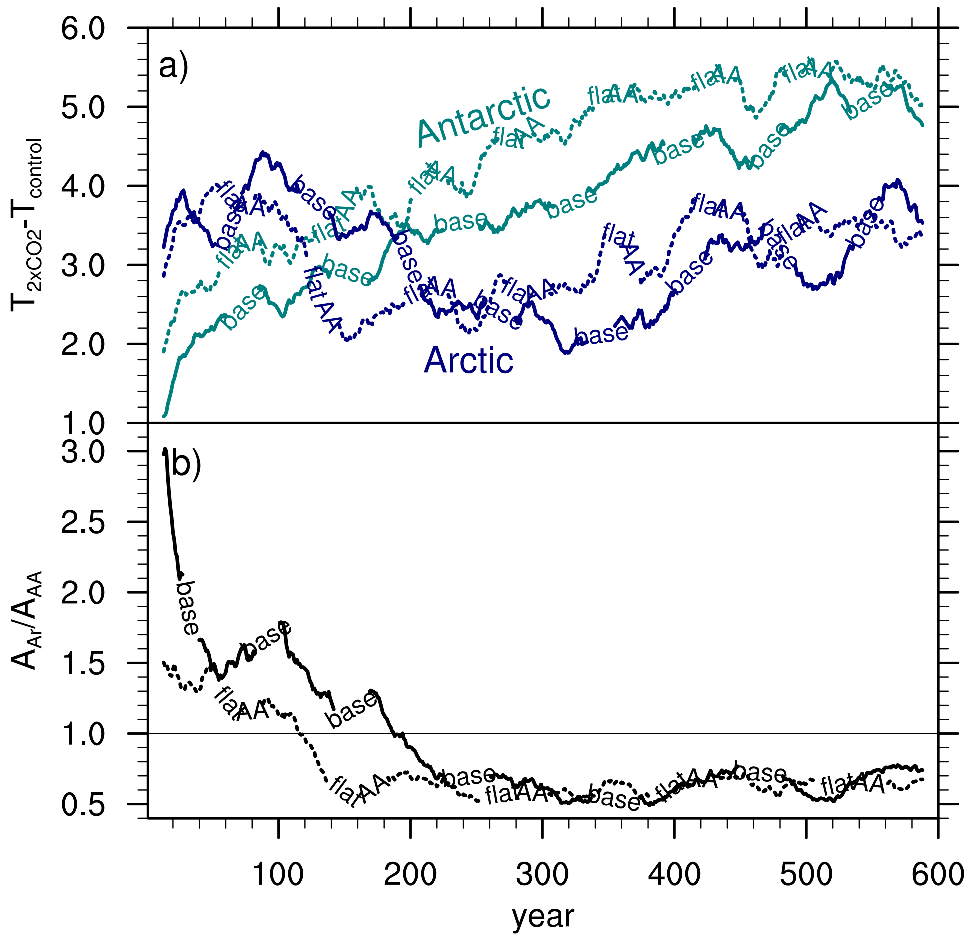

Figure R2: (a) 25-year running mean of the temperature difference between the 2xCO2 and the control runs for the arctic and the antarctic region in the base and the flat AA model setup and (b) ratio of arctic to antarctic amplification based on 25 year running mean time series.

reuruns and the original coupled runs indicate that the main conclusions are robust between these two sets of runs. At the same time a comparison between the two sets of runs gives a first indication as to where the robustness is limited.

In order to investigate whether the stronger (or faster) antarctic warming in the flat AA run is mainly related to ocean transients, the base control and

2xCO2 runs and the corresponding two flat AA runs from 200 to 600 years and Sect. 3.7 has been expanded to discuss these runs. Fig R2a (which corresponds to Fig. 14a of the revised manuscript) shows that antarctic warming in the flat AA run is stronger than arctic warming almost throughout the entire 600 year period. The figure also shows that the antarctic temperature increase eventually becomes larger than the arctic temperature increase in both model setups. This point (which is in part explained by a MOC slowdown in both model setups and in part by a steady antarctic warming in both model setups) is discussed in Sect. 3.7 of the revised manuscript (page 12, lines 23ff) and also in Section 2 (page 3, lines 28ff).

Furthermore, the revised manuscript discusses potential improvements of the current model setup in Sect. 3.7 which are re-iterated in lines 16ff of the the abstract and at the end of the conclusion section. One of the improvements that is suggested is to use a proper ensemble (if possible of several high resolution models).

2) Discussion of the role of sfc vs. atmospheric temperatures The author convincingly shows that the change in sfc temperature and its relationship to atmospheric warming is causing changes in the lapse rate feedback, rather than the warming profile within the atmosphere. However, it is not clear to me that the temperature feedback should therefore be regarded as a single mechanism. This point might benefit from either rethinking or more detailed discussion.

I partially agree with this criticism and I have adapted a corresponding statement in the conclusion section and added a discussion to the end of Section 3.5 (see details below).

Here, the main reason for lumping the two feedbacks is simply that the change of the LR feedback was not associated with a difference in atmospheric temperature. Furthermore, as you have noted above, the lumped feedback has a simple physical interpretation as it corresponds to the the total thermal feedback.

In order to point out that lumping the feedbacks is not uncommon, I have added the sentence

"The definition of the TA feedback is identical to the definition of the long-wave feedback in a study by Winton et al. (2006) and to the definition of the temperature feedback in a study by Block and Mauritsen (2013)."

to page 10, lines 20ff of the revised manuscript.

On the other hand, decomposing the total thermal feedback into LR and PL feedbacks is indeed very useful for understanding polar climate change, and I appreciate that your comment gives me the opportunity to clarify this point.

I have replaced the following sentence of the conclusions:

"On the other hand, unlike for the tropics in the polar regions there appears to be no clear rationale for separating the total temperature feedback into the Planck and the lapse rate feedback."

by:

"Although the rationale for decomposing the total temperature feedback into the Planck and the lapse rate feedback is less clear in the polar regions than in the tropics, such a decomposition is nevertheless useful for understanding polar climate change (see e.g. Pithan and Mauritsen, 2014; Payne et al., 2015). A more detailed discussion of this issue was given at the end of Sect. 3.5."

The newly added discussion at the end of Section 3.5 reads as follows:

"The usual decomposition of the total temperature feedback into PL and LR feedbacks is nevetheless useful for understanding polar climate change. As explained above, the PL feedback is defined as the hypothetical feedback that would be expected if the atmosphere would warm at the same rate as the sur-

face. However, the polar atmosphere generally warms less than the surface due to a lack of vertical mixing (e.g. Manabe and Wetherald, 1975). The tropical atmosphere, on the other hand, warms more than the surface. Therefore, in order to radiate away a given amount of energy a larger surface warming is required in the polar regions compared to the tropics (Pithan and Mauritsen, 2014). The lack of atmospheric warming in the polar atmosphere relative to the surface is reflected in the large positive polar lapse rate feedback."

Furthermore, I have changed the following sentence on page 9, lines 12ff of the original manuscript (page 10, lines 16ff of the revised manuscript) that describes the rationale for lumping the LR and the PL feedback.

"The rationale for this is that the sum LR+PL is mainly sensitive to changes in surface temperature and not to changes in the atmospheric lapse rate above the surface layer."

to:

"The rationale for this is that in the present study setup the sum LR+PL in the antarctic region is mainly sensitive to changes in surface temperature and not to changes in the atmospheric lapse rate above the surface layer."

Minor issues:

l. 5 if→when (If + past tense triggers would in main clause, and indicates a hypothetical case) This issue reappears in the manuscript.

Changed "if" to "when" in on page 1, line 5, page 6, line 29, and on page 7, line 20 of the revised manuscript.

l.6 (and elsewhere): please reserve "significant" for its statistical meaning, and specify the statistical test.

"Significantly" was replaced by "notably" on page 1, line 6, page 2, line 2, and page 13, line 7 of the revised manuscript. On page 1 in line 11 "significant" was replaced by "considerable".

p.2 l1 ff: What is the baseline for warming?

Added *"relative to a 1986-2005 reference period"*.

p.2 l.23 Arctic or Antarctic?

Corrected. Thank you very much.

p. 2 l.32, general issue: I would suggest to consistently speak of either polar amplification symmetry or asymmetry to avoid confusion.

Changed "increasing polar amplification symmetry" to "decreasing polar amplification asymmetry' throughout the revised manuscript. I also corrected "decrease" to "increase" on p. 15, l. 17.

p. 6 l.27 explained by what?

Added *"by the antarctic surface height"*.

p. 11 l. 15 Arctic or Antarctic?

Corrected. Thank you very much.

Figure 1 and 2: I suggest combining these into one Figure, or at least using the same axes to facilitate comparisons.

Figure R3 of this reply shows Figures 1 and 2 of the original manuscript combined into a single plot and Figure R4 shows a panel containing Figures 1 and 2 with identical y-axis scaling. Figure R3 shows that in the northern hemisphere more solar radiation is absorbed and terrestrial radiation emitted in the low-resolution CESM v1.0.6 run compared to CERES SYN1deg Edition 3A. A part (but certainly not all) of this difference is probably due to comparing

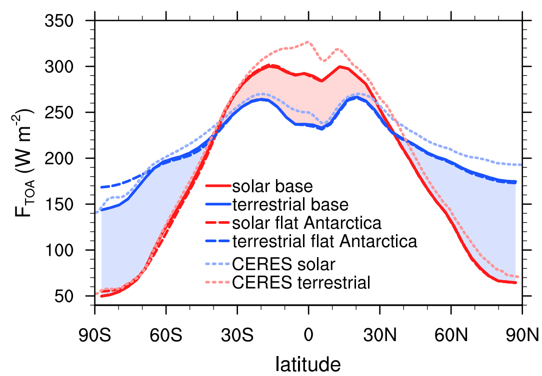

Figure R3: Single plot

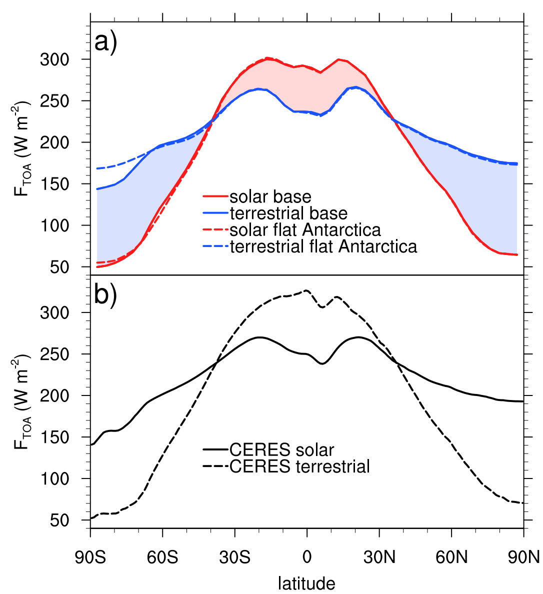

Figure R4: Panel plot

a pre-industrial run to near present day observations (which are influenced by higher aerosol concentrations in the northern hemisphere and also land use changes). Nevertheless, based on the magnitude of the difference, other model biases almost certainly dominate. In particular, one could speculate that the model bias might be related to the representation of clouds over land and sea ice. Regardless of what the reason for this bias might be, a discussion of this bias seems not overly relevant to the arctic/antarctic asymmetry discussed in the manuscript. The bias does, however, make Figure R3 look rather busy. Consequently, the simulated decrease in asymmetry between the two polar regions when Antarctica is assumed to be flat is easier to see in Figure R4 than in Figure R3. Therefore, unless you strongly prefer Figure R3, I would rather replace Figures 1 and 2 by Figure R4.

Response to Prof. Timothy Cronin

Major Comments:

1) One major issue is that the ocean circulation may change considerably between flat-AA and base setups, and it may not be in pre-industrial equilibrium in either case. A hint of this is seen in Figure 5, and a trace of its implications may also emerge in figure 10. How long was the model run for to get a stable "preindustrial climate" in both the flat-AA and base setups? If the ocean is not equilibrated and I doubt it would be given that most runs appear to occur for ∼100-200 years and this is an order of magnitude less time than required for equilibration how do we definitively interpret differences between flat-AA and base setups as being results of changes in terrain and not ocean transients? Some issues with this are hinted at in section 3.6, where southern hemispheric heat content changes are noted as large, and also in section 3.7, where the MOC starts to collapse in the 2xCO_2 run and leads to changes in Arctic temperature that may be purely due to internal variability rather than forcing or changes in topography.

The control base run was started from a spun-up state. As indicated in Fig. 13c of the original manuscript, the surface temperature in the noAA control run changed little after the initial decades (as expected based on several studies that showed that a large part of the surface temperature response to an initial perturbation occurs in the first decades while the gradual adjustment of the deep ocean takes much longer). Furthermore, there is a flat AA control run and a flat AA 2xCO2 run in which the deep ocean was still adjusting gradually to the change in surface height, so that taking the difference is expected to remove most of this effect.

In order to investigate whether the stronger antarctic warming in the flat AA runs is due to ocean transients, the original coupled sensitivity runs have been extended from 200 to 600 years. The results are shown in Figs. R5 and R6 of this response which correspond to Figs. 13 and 14 of the revised manuscript.

The extended coupled sensitivity runs show that the antarctic warming is stronger in the flat AA setup compared to the standard setup almost throughout the entire 600 year period (Fig. R6a). Based on this result, I find it very unlikely that the stronger antarctic warming in the flat AA run is due to ocean transients. Note also, that abrupt CO_2 doubling experiments have often been used in climate research even though the models were very seldomly run to equilibrium.

Regarding the MOC slowdown it was noted in the original manuscript that a slowdown of the MOC due to CO_2 doubling was also found in other climate models. The results from the extended runs in Figs. R5 and R6 further illustrate the point that such a slowdown is fairly common.

In the extended base 2xCO2 model run, the MOC starts to slow down around year 200 and then starts to gradually recover during the last 200 years of the 600 year run (Fig. R5b). In the flat AA model run the slowdown occurs earlier (moderate weakening starts around year 100 and the strongest slowdown occurs after year 120, see Fig. R5d). After 200 years antarctic warming is larger than arctic warming not only in the flat AA but also in the base model setup. While this does not contradict present-day observations or CMIP5 model re-

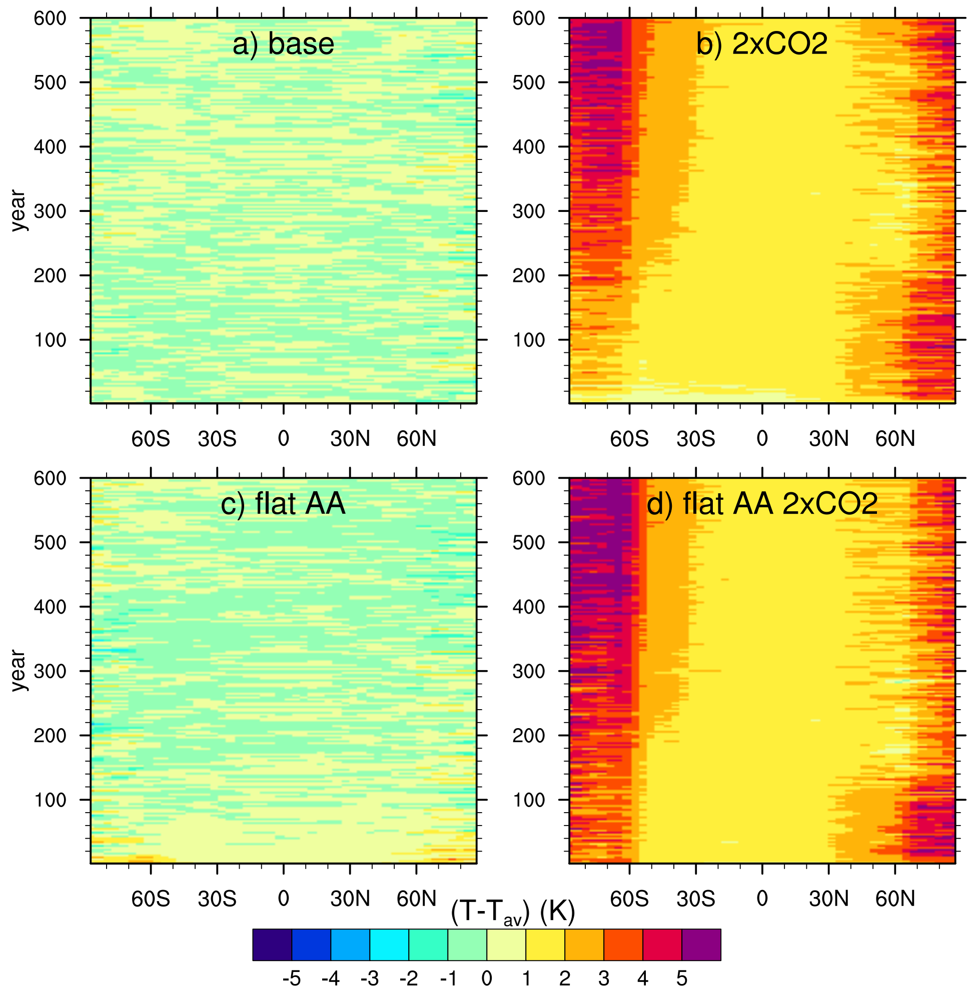

Figure R5: As Fig 13 of the original manuscript, but for extended runs.

sults, it clearly differs from present-day observations of a stronger polar amplification in the arctic compared to the antarctic region and also from results of shorter CMIP5 future scenario runs. As explained in the original manuscript, the findings regarding MOC slowdown should not be overinterpreted since the MOC tends to react more sensitively to CO_2 increases in low-resolution models compared to high-resolution models, and additional caveats with respect to using this setup for projecting future antarctic climate change (especially the

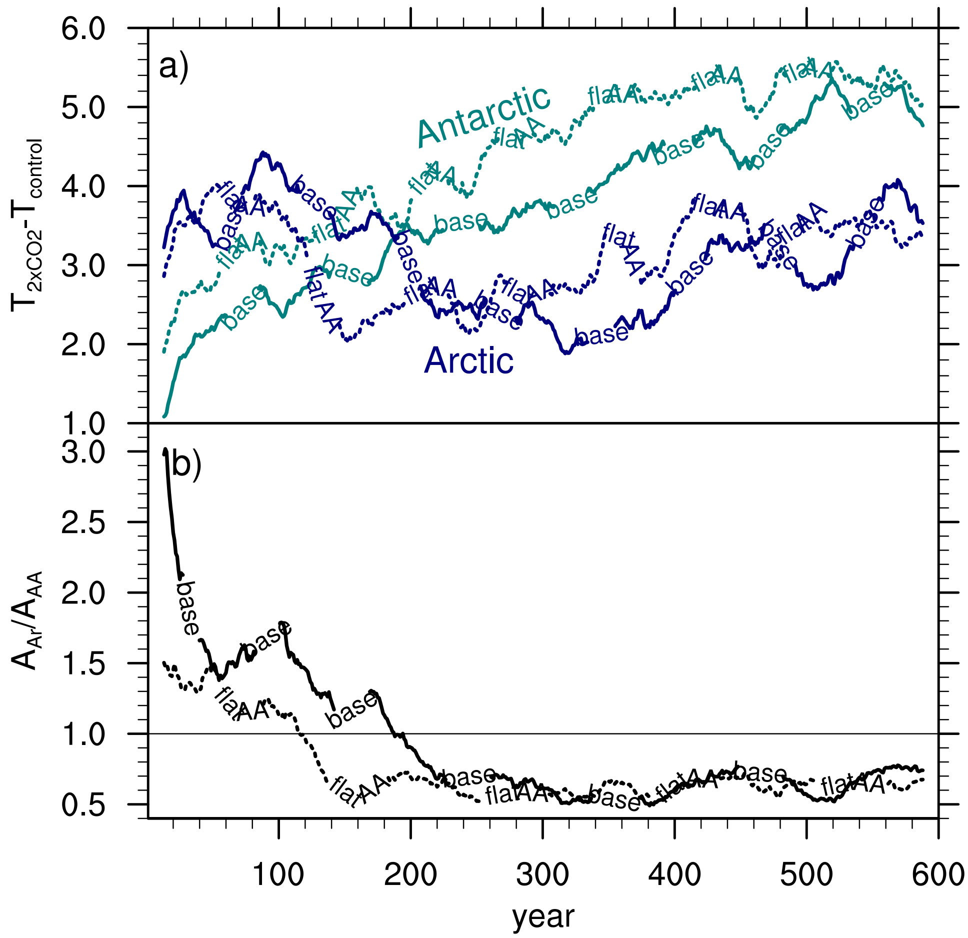

Figure R6: (identical to Fig. R2) (a) 25-year running mean of the temperature difference between the 2xCO2 and the control runs for the arctic and the antarctic region in the base and the flat AA model setup and (b) ratio of arctic to antarctic amplification based on 25 year running mean time series.

lack of an ice sheet model) have been highlighted in Sect. 3.7 of the revised manuscript.

The choice of time slices has been better motivated in the methods section of the revised manuscript as follows (see also my response to point C below):

The analysis focuses on the transient response to CO_2 *doubling during the* *years 76 to 125 and especially during the years 80 to 109 for which the model was re-run and PRP calculations were performed. While most of the temperature response in the upper ocean to the CO_2 perturbation takes place during the initial decades of a 2xCO2 perturbation experiment the deep ocean has not yet reached equilibrium during this period which is similar to the situation in present-day climate and transient future climate change. In the base 2xCO2 run antarctic warming (see Sect. 3.7) became stronger than arctic warming around year 200 (and around year 120 for the flat AA 2xCO2 run) which differs from present-day observations of a stronger polar amplification in the arctic compared to the antarctic region and from the results of shorter CMIP5 simulations which the present study aims to help explain.*

Sect. 3.7 has been partially re-written and extended to describe the extended runs and to include the main arguments from above. Potential improvements to the model setup have also been proposed in Sect. 3.7. It now reads as follows (please see the appended manuscript for complete track changes):

"Fig. 13 shows the temporal evolution of the zonal mean surface temperature in the control runs and the 2xCO2 runs for the original coupled runs. As expected, the largest surface temperature response to assuming Antarctica to be flat occurred during the first decades of the flat AA control run (Fig. 13c). These decades were not taken onto account in the preceding analysis. After this, the surface temperatures remained fairly stable in the flat AA control run, although the deep ocean was still adjusting. Taking the difference between the flat AA 2xCO2 run and the flat AA control run (as was done in the preceding sections) is expected to remove most of the latter effect.

Fig. 13b and d show that antarctic surface temperatures increased faster in the flat AA 2xCO2 run than in the base 2xCO2 run as expected based on the previous sections. The arctic temperatures varied strongly due to internal variability, which helps to explain the differences between the original coupled *run and the coupled re-runs with half-hourly radiation calls which have been pointed out in the discussion of the ocean heat transport in Sect. 3.3.*

The weaker arctic warming in the middle of the 2xCO2 base run (Fig. 13b) is an indication of a slowing of the ocean's meridional overturning circulation (MOC). Such a slowdown has often been found in CO_2 *perturbation experiments, and it tended to be stronger in low-resolution low-complexity models compared to state-of-the art high-resolution models. Since the CESM was run at a low resolution in this study, this finding should also not be overinterpreted. In the 2xCO2 flat AA run, the MOC started to slow down earlier than in the 2xCO2 base run (Fig. 13d), which might indicate that assuming a flat Antarctica did not only influence the Antarctic region but also the arctic region. For a more reliable estimate of this effect coupled runs at a higher resolution and an ensemble of model runs with slightly perturbed initial conditions would be required.*

Fig. 14a shows the evolution of the arctic and antarctic surface temperature for the base and the flat AA model setup and Fig. 14b shows ratios of the arctic to the antarctic amplification which are computed as:

$$f = \frac{A_{Ar}}{A_{AA}} = \frac{\hat{T}_{Ar,2xCO2} - \hat{T}_{Ar,Control}}{\hat{T}_{AA,2xCO2} - \hat{T}_{AA,Control}} \tag{1}$$

where $\hat{T}$ *is a regional average 25-year running mean temperature.*

It should be noted that antarctic warming relative to the respective control run (Fig. 14a) was stronger in the flat AA than in the base model setup almost throughout the entire 600 year period. However, even though the temperature in the flat AA control run stabilized after a moderate initial warming and even though the temperature evolution from the control run was subtracted in this analysis, it can not be completely ruled out that this moderate initial warming could have also played a role in the later development in the 2xCO2 flat AA *run. Therefore, in retrospect, starting the flat AA 2xCO2 from a separate long flat AA spinup run and prescribing a more realistic gradual increase of the CO_2 concentration which would allow to also inspect the first decades of the CO2 perturbation experiments would have been better.*

After 250 years, f was lower than unity in the base and the flat AA model setup which indicates that the antarctic temperature increase was stronger than the arctic temperature increase in both model setups. This finding is related to a slowdown of the north Atlantic MOC in both of the runs which could in part be a transient feature as the MOC recovery times are known to be extremely long. Again, in order to gain confidence in this result, additional ensemble model runs at higher resolution and ideally also a comparison with results from a multi-model ensemble would be necessary. Since the aim of the various model sensitivity runs has been to investigate the sensitivity of the polar amplification asymmetry to antarctic surface height (and not to provide a future projection of antarctic climate change under global warming), the runs were performed without an ice sheet model. In order to arrive at a more credible projection of antarctic climate change, state-of-the art high resolution models that include state-of-the art ice sheet dynamics models should be used.

The suggestions for improving the model setup have been re-iterated at the end of the conclusion section of the revised manuscript as follows:

"Potential future studies based on coupled climate model runs that aim to study the influence of surface elevation on the polar amplification asymmetry which is found in present-day observations and also in future climate projections (which often span only one or one and a half centuries) would benefit from a separate long flat AA spinup run and from prescribing a more realistic gradual increase of the CO_2 concentration."

And the following sentence was added to the end of the abstract of the revised manuscript:

"In order to arrive at a more reliable estimate of the role of land height for the observed polar amplification asymmetry, additional studies based on ensemble runs from higher resolution models and an improved model setup with a more realistic gradual increase of the CO_2 concentration are required."

Based on the newly extended flat AA control run, performing an additional CO2 doubling run would take two or three additional weeks (depending on availability of computing resources). The PRP runs, on the other hand take several months to run.

2) I find the multiple layers of differences to make some figures, discussion, and notation very confusing. There are essentially three sets of differences used in this paper: a climate change difference (2xCO2 − 1xCO2), a hemispheric difference (Arctic – Antarctic), and a model setup difference (Flat-AA - base). Each of these is at some point annotated as Δ: in Figures 3-5 and 10, a single Δ means a climate change signal, in Figures 7 and 11, a single Δ refers to a Arctic-Antarctic difference, and in figure 9 a single Δ refers to Flat-AA minus base difference. In the worst case, all three are used together in figure 12 as $\Delta(\Delta F)$, or the difference (flat-AA – base) between Arctic and Antarctic feedbacks (with feedbacks F being in turn a difference between 1x and 2x CO2 radiative fluxes). I would suggest using subscripts for all but one of these differences, e.g., T2x-T1x for climate change in response to doubling CO2, and FA-FAA for hemispheric difference, and reserving Δ for Flat-AA minus base, as it is least-easily subscripted (though $F_{\_}$ - $F^{\hat{}}$ could serve here too).

I have replaced ΔF in the y-axis label of Fig. 6 of the revised manuscript (which is also Fig. 6 of the original manuscript) by F_{Ar}-F_{AA} and adapted the labels in Figs. 6, 11, and 12 of the revised manuscript accordingly. For the differences 2xCO2 minus 1xCO2, I have added the index "2x" to the Δ

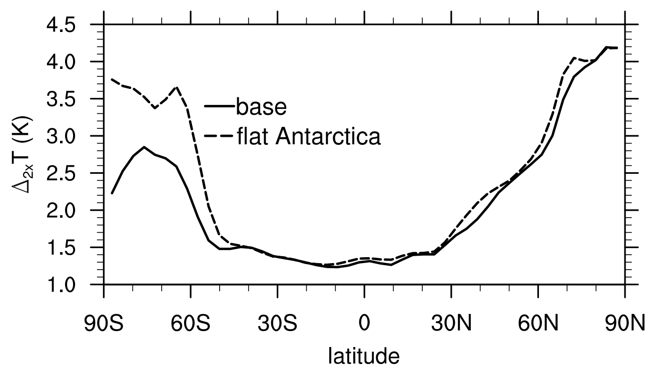

Figure R7: Modified y-axis label in Fig. 2 of the revised manuscript (Fig. 3 of the original manuscript).

in the y-axis labels of the corresponding plots except in the new figure 14 (for an example see Fig. R7). In this case, I found that spelling out the differences does not increase readability very much (see Figs. R8 and R9). I have also replaced the ΔT in the color bar label of Fig. 12 of the revised manuscript by $(T - T_{av})$ and explained that "av" denotes a time average in the caption. Δ (without index) is now reserved for flat AA minus base as suggested.

The caption of Fig. 11 of the revised manuscript was also modified to better explain the plot. The original caption

Lapse rate (LR) and Planck (PL) feedback in the base and the flat AA model setup and for the sensitivity calculations described in Table 2.

was changed to (see also comment regarding 73-hourly output below):

Arctic minus Antarctic difference of the lapse rate (LR) and Planck (PL) feedback in the base and the flat AA model setup and for the sensitivity calculations described in Table 2 (based on PRP calculations using 73-hourly instantaneous model output).

3) The definition of "feedbacks" as changes in TOA radiative fluxes, un-

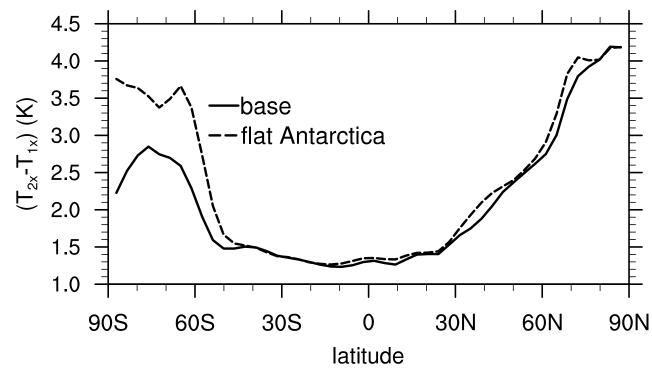

Figure R8: Using differences in the y-axis label in Fig. 2 of the revised manuscript.

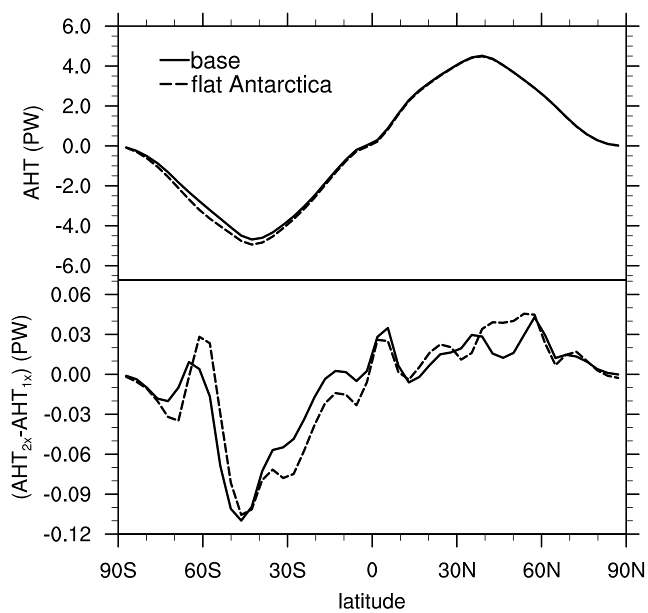

Figure R9: Using differences in the y-axis label in Fig. 2 of the revised manuscript.

normalized by surface temperature changes, complicates interpretation of findings in this paper for me. I am not sure what the basis is for this choice is, and I think it could be better explained if there is some strong reason for using these changes rather than the standard of feedbacks being normalized by temperature change e.g., λ = (R2x R1x)/(T2x T1x) (units of W m-2 K-1). In Figures 6 and 7, especially, I find that use of changes in TOA fluxes rather than standard feedbacks convolutes changes in polar warming with changes in the true per-unit warming feedbacks λ. For example, do the Planck and lapse-rate "feedbacks" in Figure 6 change just because there is more warming in the Antarctic in the flat-AA case, or because each λ has also changed? Use of the conventional feedback metric normalized by surface temperature change would also allow for more straightforward comparison to previous work.

Radiative feedbacks in general circulation models (GCMs) are most commonly defined as TOA flux changes which are normalized by the global mean surface temperature change and not by the local temperature change. Because the entire forcing/feedback formalism is usually based on an equation for the global mean energy budget, normalization by the local temperature change would induce major conceptual problems in a GCM context. In this case, horizontal advection terms would have to be included in the budget equation. These terms are not negligible especially in the polar regions and they are not constant under climate change (and they might also depend on the nature of the forcing). Therefore, in GCM studies TOA radiation flux changes are usually normalized by global mean temperature even when plotting maps. Fig. 1 shows that unlike the tropics, the polar regions are nowhere near to either radiative or radiative-convective equilibrium and that instead a radiative-advective equilibrium assumption as in Payne et al., GRL, 2015, Cronin and Jansen, GRL, 2016, clearly is more appropriate.

Here, the feedbacks are defined per CO_2 doubling with respect to 1850. Thus, one can directly compare the magnitudes of the forcing and the feedbacks. Furthermore, both magnitudes can then also be compared to transport and heat storage terms. As stated in the sentence starting in the last line on page 4 of the original manuscript, this choice also facilitates a straight forward comparison of the actual TOA energy flux differences associated with the base and the flat AA model setup. Since the sole purpose of the PRP analysis is to try to find out what causes differences in warming between the arctic and antarctic region in the different model setups, to me it seems reasonable to compare the actual TOA flux differences without normalizing by the global mean temperature change. Furthermore, even though instantaneous 2xCO2 perturbations are used, the manuscript focuses on the transient response. As noted in on page 5 in lines 2f of the original manuscript, a normalization by surface temperature change is not appropriate in this case.

4) The reasons for the RAD re-runs are not made completely clear, and it is not clear where they are used and where they are not used. This is a particular issue around line 30 on page 6, where you say "the original coupled runs were chosen for this analysis" but then in the next paragraph, you say that the simulations behind figure 3 will be analyzed in more detail but the caption of figure 3 says that they are RAD re-runs.

The following sentences have been added to page 4, lines 14ff of the revised manuscript in order to more explicitly explain why two sets of runs are used:

"The advantage of the RAD re-runs is that the PRP analysis is more exact which makes them more suitable for a budget analysis. The advantage of the base model setup is that it is computationally cheaper to run and thus is better suited for longer integrations."

The fact that the rad re-runs instead of the original coupled runs are used in several of the following sections was addressed by adding the following statement on page 7, lines 31f of the revised manuscript:

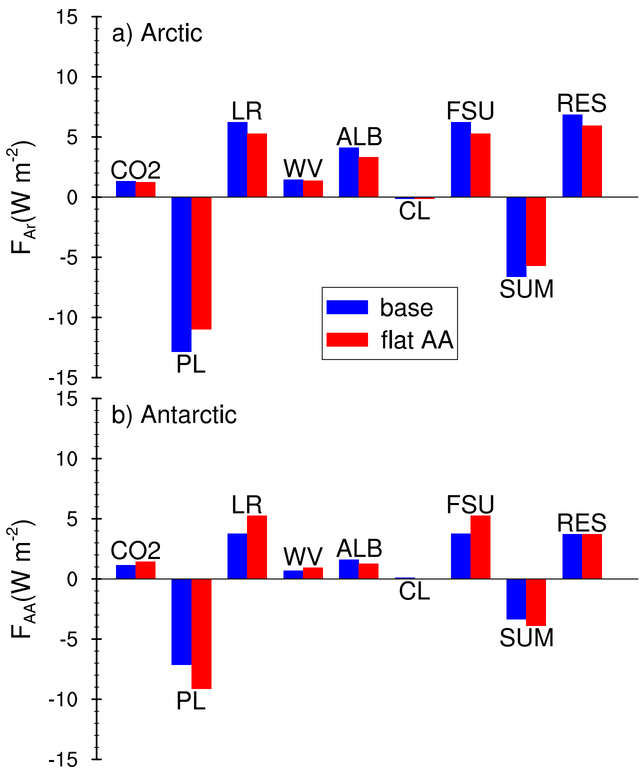

Figure R10: As Fig. 6 of the original (and the revised) manuscript, but based on the original coupled runs with 73-hourly instantaneous model output.

"... based on the RAD-reruns which yield sufficiently similar results to the original runs for this analysis to be useful."

The captions of Figs. 3 and 11 have been augmented by stating which runs were used.

Fig. R10 is based on the original runs with 73-hourly instantaneous output. Originally, I had hoped that performing the PRP offline radiation computations at this low frequency for a fairly long period would yield sufficiently exact results (which would have meant much quicker runs, much smaller amounts of data, and consequently also a much smaller logistic challenge). Only later I found out that not only the output frequency was to low but that also the frequency of the radiation calls had to be increased in order to increase the accuracy of the PRP computations.

The differences between Fig. R10 and Fig. 6 of the original (and also the revised) manuscript are due to a combination of internal variability (as the RAD-reruns trigger new realizations) and the more exact budgets (for which the radiation has been called every time step instead of every other time step and the PRP computations have been performed for three-hourly instead of 73-hourly instantaneous model output). The decision to perform the RAD-reruns was triggered by an analysis of the reasons behind the large "RES" term in Fig. R10.

Although two sets of runs (i.e. the original and the RAD re-runs) is not a very impressive ensemble, the general similarities between the results indicate that the main conclusions are robust and at the same time to some extend also suggests where the robustness is limited. In order to better explain one of the results that differs between the RAD-reruns and the original coupled runs, Fig. R11 of this reply was added as Fig. 5 to the revised manuscript (see also my response to major comment #1 by reviewer #1.

5) [Self-promotion disclosure!] Some work that I have been involved with recently has, I think, helped provide a better understanding of the high-latitude lapse-rate feedback. You might want to look at Payne, Jansen, and Cronin (2015), GRL, "Conceptual model analysis of the influence of temperature feedbacks on polar amplification" and Cronin & Jansen (2016), GRL, "Analytic radiative-advective equilibrium as a model for high-latitude climate". Both papers attempt to develop a better prognostic understanding of the high-latitude lapse-rate feedback, which, as you note in section 3.5, is mostly con-

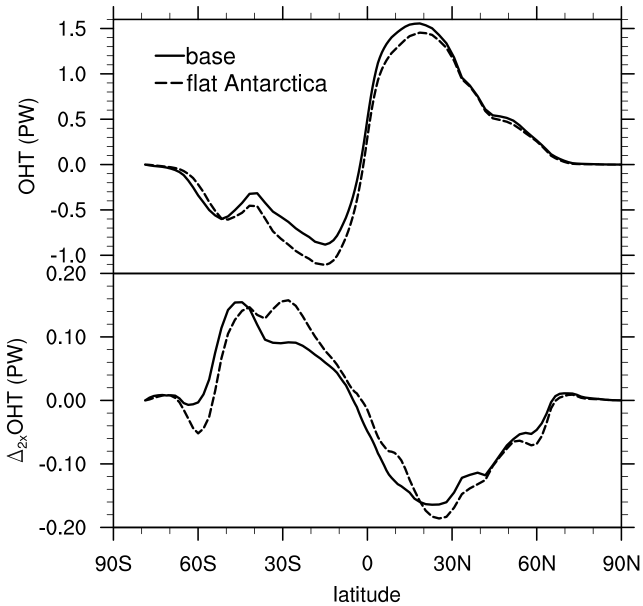

Figure R11: (identical to Fig. R1) Oceanic heat transport (OHT) as in Fig. 5 of the original manuscript but for the original coupled runs.

nected to near-surface temperature changes being larger than mid- and upper-tropospheric temperature changes. Figures 3 and 4 of Payne et al (2015) are similar to your Figure 10, except that we focused on low-latitude/high-latitude differences and not polar asymmetries, and we were using simpler column models to get a sense of temperature structure changes. I have also done some preliminary work on polar amplification asymmetry due to surface height with a radiative-advective equilibrium model (nowhere near publication, so certainly nothing to cite!). If you plan to work on the subject more, it might be good to talk outside the review process, and potentially collaborate.

The two published studies mentioned above are clearly relevant for the general discussion regarding polar feedbacks. In the revised manuscript both are cited in the introduction. The Payne et al., 2015 paper is also in the "conclusions" section of the revised manuscript (see details below).

I am currently not planning to work much more on this particular topic (i.e. the polar amplification asymmetry), but I have done some very limited initial work on another question regarding polar warming. I would certainly appreciate a discussion either on the polar amplification asymmetry or on some other topic related to polar warming outside the review process in case you are interested.

Other specific comments:

A) On page 5, lines 8 and 10 what are the respective polar circles, exactly? Its not obvious that you can choose 66.55 N and S when the models resolution is only T31 so exact limits of integration and averaging should be noted more clearly.

I added the following sentence on page 5, lines 31f of the revised manuscript:

> *"The corresponding grid cell edges of the atmosphere grid are located at 66.8°North and South. Oceanic heat transport is diagnosed at 66.6°North and South."*

B) I suggest combining Figures 1 and 2; it is difficult to compare the simulations to observations at present and an additional set of black lines in 1) should be completely readable.

A similar suggestion was made by the other reviewer (although the other reviewer also indicated that using identical axis on the two plots might be sufficient). Please refer to my answer to the last comment by Anonymous Reviewer #1 on page 8 of this document.

C) Regarding the three time slices and standard deviations in Table 3 and p6, lines 17–27. I dont understand why these three time slices were chosen, or what the % of warming difference explained by topography means, exactly. And how are the +/- standard deviations determined based on three points (the means of the three time slices), or based on each year treated as an independent point?

In order to better motivate the choice of the analysis time the following sentences were added to the methods section of the revised manuscript (compare also my response to major comment 1 above):

The analysis focuses on the transient response to CO_2 doubling during the years 76 to 125 and especially during the years 80 to 109 for which the model was re-run and PRP calculations were performed. While most of the temperature response in the upper ocean to the CO_2 perturbation takes place during the initial decades of a 2xCO2 perturbation experiment the deep ocean has not yet reached equilibrium during this period which is similar to the situation in present-day climate and transient future climate change. In the base 2xCO2 run antarctic warming (see Sect. 3.7) became stronger than arctic warming around year 200 (and around year 120 for the flat AA 2xCO2 run) which differs from present-day observations of a stronger polar amplification in the arctic compared to the antarctic region and from the results of shorter CMIP5 simulations which the present study aims to help explain.

In order to clarify that the mean and standard deviation refer to the mean and standard deviation of the three time slices and also in order to better explain how the fraction of the warming difference that is explained by surface height is computed, the following sentences:

In the base run, the arctic region warmed on average by 1.40 ± 0.29 K (mean ± one standard deviation) more than the antarctic region. In the flat AA run, on the other hand, the difference between the Arctic and the antarctic warming was reduced to 0.59 ± 0.32 K. On average, about 56 ± 30% of the difference in warming was explained for the three time slices.

were changed to:

In the base run, the arctic region warmed on average by 1.40 ± 0.29 K *(mean of three time slices ± one standard deviation) more than the antarctic region. In the flat AA run, on the other hand, the difference between the arctic and the antarctic warming was reduced to 0.59 ± 0.32 K. Thus, on average, about 56 ± 30% of the difference in warming between the arctic and the antarctic region (i.e. 0.81 ± 0.46 K of 1.40 ± 0.29 K) was explained by the antarctic surface height for the three time slices.*

The sentence:

If only antarctic temperature change were taken into account, 73%, 26%, and 42% were explained by antarctic surface height.

was replaced by:

When only antarctic temperature change was taken into account (i.e. the arctic temperature increase was taken from the base setup while the antarctic temperature increase was taken from the flat AA setup), 73%, 26%, and 42% were explained by antarctic surface height.

A correction replacing "time" by "time slices" was added to the caption of table 3.

D) In Figures 6 and 7: whether or not you stick to calling changes in radiative fluxes feedbacks or you decide to normalize them by temperature changes and make them true feedbacks, I think it would help to include changes in AHT and OHT convergences here, as well as storage if it is significant. Or, you could mention that the SUM term in each plot adds up to the sum of changes in AHT convergence, OHT convergence, and storage. It surprises me that the changes in heat flux convergence would be so small relative to local feedbacks. I do appreciate your note on p8 L5 that the values should not be over-interpreted as heat transports vary rapidly near the margins of the Arctic and Antarctic caps

I have added sentences regarding the magnitude of the AHT and OHT convergence and heat storage relative to the SUM term to the revised manuscript (see below).

One reason for not including the changes in AHT and OHT convergence and the heat storage term in figure 6 of the original manuscript (which is also figure 6 of the revised manuscript) was that they are individually of the same order of magnitude as the sum of the feedbacks (SUM) and that the bars would thus be very short. Furthermore, as mentioned on page 5 in lines 16 to 22 of the original manuscript and then re-iterated in on page 9 in lines 20 to 24 of the original manuscript, the changes in AHT convergence, OHT convergence, and heat storage which are diagnosed as described in Section 2 do not add up to the sum of the SUM and the RES term in Fig. 6 as one might expect. Since this "budget imbalance" (which might be either due to inaccuracies in the analysis method or in the model's energy balance as discussed in Section 2) does not depend strongly on the model setup, it cancels out in the analysis presented in Section 3.6 (as indicated by the small RES term in Fig. 12 of the original and the revised manuscript). This is why I decided to include the analysis in Section 3.6 in spite of the problems with computing a closed budget that are mentioned in Section 3.6 and in Section 2.

The following sentences were added to page 8, lines 26ff of the revised manuscript:

"The SUM and the RES terms in Fig. 6 are expected to balance contributions from changes in AHT convergence, OHT convergence, and heat storage. The corresponding individual contributions were diagnosed separately as explained in Section 2 and they were found to be of the same order of magnitude as the SUM term which is much smaller than the individual contributions of the major feedbacks except CL (not shown). Unfortunately, however, as explained in Section 2, the diagnosed contributions do not add up to the SUM+RES term as expected."

Because the polar regions are approximately in advective-radiative equilibrium

(Payne et al., GRL, 2015, Cronin and Jansen, GRL, 2016, see also Fig. 1), it is indeed interesting to see the large degree of cancellation between the contributions from the individual feedbacks suggested by Fig. 6 of the revised manuscript. On the other hand, it is also well understood that a decreasing meridional temperature gradient that is associated with polar amplification acts to decrease meridional heat transport convergence.

Even though the SUM term is small compared to the individual feedbacks, the subsequent analysis in Section 3.6 suggests that contributions from ocean and atmosphere heat transport convergence and heat storage are important for explaining the polar amplification asymmetry.

In addition to the changes outlined above, where appropriate I have also changed "*transport*" to "*change in transport convergence*" since the reviewer used the term "transport convergence" in his comments and since I also find it useful to make this distinction. Transport is often used to describe either a (net) flux (which with respect to an arbitrary region could in principle also mean "transit") or a flux divergence and it had previously been used for both.

E) Figure 10: The mismatch between the profiles and dots/crosses is confusing here. Why is there so much less change in the crosses in b) and d) than in the profiles at lowest-levels? Why is the red dot in c) warmer than the profile at lowest levels? And why are the base and flat-AA profiles so different in c)?

The following sentences explaining the reason for the mismatch were added to page 9, lines 28ff of the revised manuscript:

"The apparent mismatch between the dots and crosses and the profiles at the lowest atmospheric levels in Fig. 9 (b) and (d) is explained by the condition that all pressure levels where more than 20% of the grid points are above ground are shown in the profiles. Consequently, only a limited number of grid points entered the average temperature for the lowest atmospheric levels

while the average surface temperature was computed as an average over all grid points."

F) Page 8, paragraph around line 25: I suggest eliminating Table 2 I found it more confusing than helpful and relocating the paragraph from the methods section describing these simulations to this point in section 3.5 (paragraph from p4 L20-25). The information is not necessary when presented at the time in section 2, and will be more helpful in this section if the reader does not need to flip back to the earlier description.

I disagree on this point. I find that the methods section is right the place to consult when looking up information on the methods. I also think Table 2 is useful.

G) Page 8 Line 34-Page 9 line 2, re: "weaker LR feedback in the flat AA model setup" I thought Figure 6 showed the LR feedback was stronger in the flat-AA model setup? Do you mean that the LR feedback asymmetry is smaller in the flat-AA model setup (shown in Figure 7)?

Indeed. It must read *stronger* and not *weaker*. Thank you very much.

H) Page 9, lines 3-9. I'm a little puzzled by these assertions and the choice to lump the Planck and LR feedbacks together. I agree that your sensitivity tests have shown that the lapse rate feedback is dominated by changes in surface temperature rather than atmospheric temperature, or that the "lapse-rate feedback" is a feedback related to how surface temperatures and near-surface temperatures change relative to the mid- and upper-troposphere (essentially, the lapse rate feedback relates to changes in the strength of surface inversions). Thus, it still seems meaningful to me to separate the lapse rate and Planck feedbacks, since the Planck feedback could be calculated given the models control state alone, whereas changes in inversion strength are a complicated result of changes in many linked model processes. [Also, note: I do not see any references to Figure 11 in this section (or elsewhere). Perhaps the reference disappeared at the end of p9 L5? Figure 11 did not seem like the most compelling support for your argument; I think looking at each feedback by itself rather than their hemispheric asymmetry would make a stronger point]

A similar concern was raised by Anonymous Reviewer #1. For a detailed discussion of the arguments, please refer to my reply to point 2 by Anonymous Reviewer #1 on page 5 of this reply.

The main reason for lumping the two feedbacks is simply that the change of the LR feedback was not associated with a difference in atmospheric temperature. Furthermore, the lumped feedback has a simple physical interpretation as it corresponds to the the total thermal feedback (see page 9 lines 14f of the original manuscript).

Based on the first paragraph of the discussion and conclusion section in Cronin and Jansen (2016), I have the impression that separating the thermal feedback into LR and PL feedback might be related to what you call the "nonuniquess of the lapse rate feedback". But I am not sure whether I am interpreting this right?

Regarding the reference to Fig. 11: thank you for spotting this missing reference. I have added a reference to this figure on page 10 in line 2 of the revised manuscript.

I) Relatedly, on p 11, lines 1-4: I dont really follow this argument, as noted above. I also disagree with this assertion that there is no reason to separate the high-latitude Planck and lapse rate feedbacks. The reason for low-latitude separation is that we can calculate them separately, basically from first principles, if stratification follows a moist adiabat and we know the control-state climate and further, that there is cancellation between water vapor and LR feedbacks in the tropics. That we don't understand the high-latitude lapse rate feedback fully seems to be a very good reason not to lump it in with a feedback that we do understand better (the Planck feedback).

I have addressed this issue in my response to point H above. Please refer to this response.

Line-by line comments:

p1 L 6; p6 L13; p7 L10 should be "led to" if in the past tense

Changed from "lead to" to "led to" following the access review. I hope that this is what you meant.

p1, and then recurring: I am unsure of the correct style guidelines for capitalization of "Arctic", "Antarctic", and phrases containing these two terms. I have (perhaps) erred on the side of always capitalizing. Super minor issue, will presumably be fixed at the proof level, but I am interested in the "right" answer!

Merriam-Webster appears to be fine with either spelling for the adjective. It seems that except in some place names like "Arctic Ocean" they default to the lower case version (e.g. "arctic sea smoke", "arctic air"). The online version of the Cambridge Dictionary suggests that the adjective is "Arctic" in British English and "arctic" in American English. The Associated Press web site says that they have a new entry for "arctic char" in the food section of their style guide, but they might actually be more concerned about the correct spelling of the "char(r)" than the "arctic". Several American newspapers capitalize the adjective and based on a quick Google search it could even be that capitalization is more common in "Arctic amplification" than in "arctic air mass" (no real statistics here). I certainly don't have an opinion on this and I am fine with whatever the copy editors or the reviewers suggest.

p 1 L19 may want to put numbers on "substantially", e.g., "2-3 times as much as the global average"

The *substantially* refers to the absolute warming. It is quantified on page 2 in line 1 of the original manuscript (page 2, line 5 of the revised manuscript).

p2 L4 suggest rewording to "The focus in explaining arctic . . . has long been on the . . ." (rather than starting sentence with "For long")

Done.

p2 L9; p8 L17 You could mention work from point 5) above at either of these locations.

I have mentioned both studies in the introduction on page 2, line 14 of the revised manuscript. Furthermore, I have mentioned the Payne et al., 2015 study in the "Conclusions" section on page 13 in lines 23f of the revised manuscript.

p2 L26 should be "water vapor feedback" (not just "vapor feedback")

Changed.

p2 L27 should be "Antarctic" and "land-sea distribution"

Changed.

p2 L28 suggest changing "play a role for. . ." to "play a role in . . ."

Done. I also changed "role for" to "role in" on page 3 in line 5 and on page 13 in line 4 of the revised manuscript.

p3 L19-21 suggest changing "every second time step" to "every other time step" (as seconds are units of time

Done.

p4 L16 suggest hyphenating three-hourly

Done (following access review).

p4 L21-22 what does "73 hourly instantaneous model output" mean? (This looks like a typo to me)

A lower output frequency was used. I have replaced "73 hourly" by 73-hourly" on page 5 line 8 of the revised manuscript and also added the following sentence to page 5, line 12ff of the revised manuscript:

"The lower output frequency in the additional sensitivity computations was used since it significantly reduces storage requirements and run time although the PRP computations become less accurate."

The lower accuracy is evidenced by the larger residual (RES) in Figure R10 of this reply and also by the larger PL difference in Fig. 11 of the original and the revised manuscript compared to Fig. 6.

Please note, that unlike the standard model runs, the PRP method is very I/O intensive. Compared to running the model in its standard configuration with standard I/O, running the model with increased I/O frequency and then performing offline PRP computations using takes many times as long. The PRP runs presented in this manuscript were performed on two dedicated multi-core dual processor servers with standard external SAS storage raids attached via a file server over a period of several months.

p5 eqn 2 use lower-case ds in dλ dϕ ? Also suggest using a for Earths radius, as R has been used to indicate radiative fluxes

Done.

p5 L 16-18 I believe I had heard, though I am not sure where from, that there is a small added ocean heat source in some variants of CCSM, to keep sea ice from growing too thick. This might contribute to your Arctic energy imbalance, though I am not sure about its magnitude you might want to reassure the reader here by saying something about the size of the imbalance.

I have looked around the available documentation and also inspected parts of the code, but I did not find an indication of an added heat source in the Arctic. One feature that could in principle cause a local energy imbalance in the model are the energy and mass fixers that are applied in the atmosphere model which are meant to ensure global energy and mass balance. As a side effect, these mass and energy fixers induce something like a non-local transport that can cause local budgets to be out off balance. Then again, it is not clear that the present problem is indeed related to a local energy imbalance inside the model. If it is, it would certainly require a major model development effort to to pin down the root cause(s) and to devise alternative formulations to ensure local conservation. A number of potential candidates for explaining such an energy imbalance exist and as far as I know it would be much more difficult to ensure local conservation in a spectral model compared to a grid point model. In fact, the prospect of more readily achieving local energy balance (which requires that the transport of water vapor and hydrometeor mass is locally mass conserving) is one reason behind the move toward grid point models in climate research, although at low resolution spectral models still maintain advantages. The very existence of global mass and energy fixers in the low resolution atmosphere model used in this study provide a hint of the difficulties that are associated with ensuring local mass and energy conservation (because local conservation implies global conservation).

Regarding the magnitude of the budget deficit, the following sentence has been added to page 6 lines 14ff of the revised manuscript:

"The imbalance between net radiation deficit in the polar regions and the sum of the other budget terms (dominated by poleward heat transports) varies between 2 and 5% of the net radiation deficit."

When analyzing the differences between the 2xCO2 and the control runs, the imbalance (included in the SUM term in Fig. 6) is of comparable magnitude to the change of the transport terms (also included in the SUM term in Fig. 6; compare my response to specific point D above). Both are much smaller than the main local feedbacks which are also shown in Fig. 6. When looking at these differences, the contribution from the imbalance for the Arctic is larger than that for Antarctica (which cannot be seen in Fig. 6). However, because the imbalance appears to be systematic (i.e. the contribution from the imbalance is independent of whether the base or the flat AA model setup is used), the budget analysis is nevertheless considered useful. In particular, the residual that is shown in Fig. 12 of the revised manuscript (which is also Fig 12 of the original manuscript) is small compared to the other terms.

p5 L31; p6 L4 suggest deleting "rather" in these sentences, as similar is already qualitative

Deleted rather on page 6 in lines 25 and 30 of the revised manuscript where it was used together with similar and also on page 9 in line 25 of the revised manuscript.

p7 L7-9 re: "Poleward OHT increased in the southern hemisphere and also slightly increased in the northern hemisphere" and subsequent sentence Figure 5 seems to me to show a decrease in poleward OHT in the NH. . . are you showing the "original coupled run" results in Figure 5? (this ties to comment 4 above)

Thank you for pointing this out. The sentence has been revised as follows:

"Poleward OHT across the polar circles increased in the southern hemisphere and also slightly increased in the northern hemisphere."

In order to illustrate the difference between the original runs and the RAD reruns, Fig. 5 was added to the revised manuscript.

p7 L13 No comma after "Both"

Removed comma after "Both" on page 8 line 14 of the revised manuscript.

p7 L29-30 The interpretation of reduced polar feedback asymmetry is complicated by the feedbacks being expressed as radiative flux changes rather than true feedbacks per unit temperature change (see point 3 above)

Please refer to my reply to point #3 above.

p8 L3 suggest changing to "was not directly affected by. . ."

Changed *"not affected"* to *"not directly affected"* on page 9 in line 9 of the revised manuscript.

p9 L 30 Paragraph around here makes an excellent point about the semi-arbitrary extent of polar caps.

Thank you very much.

p10 L8, 12 suggest hyphenating "half-hourly" "low-complexity", and "high-resolution"

Done. For consistency, I also hyphenated "low-resolution" throughout the revised manuscript.

The polar amplification asymmetry: Role of antarctic surface height

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Abstract. Previous studies have attributed an overall weaker (or slower) polar amplification in Antarctica compared to the Arctic to a weaker antarctic surface albedo feedback and also to more efficient ocean heat uptake in the Southern Ocean in combination with antarctic ozone depletion. Here, the role of the antarctic surface height for meridional heat transport and local radiative feedbacks including the surface albedo feedback was investigated based on CO_2 doubling experiments in a low[T. Cronin]-resolution coupled climate model. [Anonym. Rev. #1]When~~If~~ Antarctica was assumed to be flat, the north-south asymmetry of the zonal mean top of the atmosphere radiation budget was [Anonym. Rev. #1]notably~~significantly~~ reduced. Doubling CO_2 in a flat Antarctica ("flat AA") model setup led to a stronger increase of southern hemispheric poleward atmospheric and oceanic heat transport compared to the base model setup. Based on partial radiative perturbation (PRP) computations it was shown that local radiative feedbacks and an increase of the CO_2 forcing in the deeper atmospheric column also contributed to stronger antarctic warming in the flat AA model setup, and the roles of the individual radiative feedbacks are discussed in some detail. A [Anonym. Rev. #1]considerable~~significant~~ fraction (between 24 and 80% for three consecutive 25-year time slices starting in year 51 and ending in year 126 after CO_2 doubling) of the polar amplification asymmetry was explained by the difference in surface height, but the fraction was subject to transient changes, and might to some extent also depend on model uncertainties. [A.Rev. #1 and T.C.]In order to arrive at a more reliable estimate of the role of land height for the observed polar amplification asymmetry, additional studies based on ensemble runs from higher resolution models and an improved model setup with a more realistic gradual increase of the CO_2 concentration are required.

1 Introduction

Surface temperature changes in response to radiative forcings are far from spatially uniform due to local radiative feedbacks and due to atmosphere and ocean dynamics. While anthropogenic greenhouse gases exert the largest radiative forcing at low and mid latitudes, the largest surface temperature increase is observed in the arctic region. Currently, the arctic surface temperature is increasing at more than twice the rate of lower latitudes (Jeffries et al., 2015), and global climate models suggest that by the end of the century the Arctic will have warmed substantially not only in absolute terms, but also compared to the rest of the globe (Collins et al., 2013). Polar amplification of surface temperature change has also been detected based on arctic proxies for past glacial and warm periods (Miller et al., 2010), and it is not limited to the Arctic. In CO_2 perturbation experiments for the early Eocene, Lunt et al. (2012) found that several models consistently simulate the greatest warming in the antarctic region due to the lower topography via the lapse rate effect and the change in albedo.

However, in recent time the Arctic has been warming faster than Antarctica, and based on climate model projections it is also expected that arctic amplification will still be [Anonym. Rev. #1]notably~~significantly~~ stronger than antarctic amplification by the end of this century. According to the fifth assessment report (AR5) by the Intergovernmental Panel on Climate Change (IPCC), coupled climate models from the Coupled Model Intercomparison Project phase 5 (CMIP5) yielded an arctic warming of 4.2±1.6 K compared to an antarctic warming of only 1.5±0.7 K for the years 2081-2100 [Anonym. Rev. #1]relative to a 1986—2005 reference period in the RCP4.5 radiative forcing stabilization scenario (Collins et al., 2013). The corresponding tropical warming under this scenario was 1.6±0.4 K.

[T. Cronin]T~~For long, t~~he focus in explaining arctic amplification has [T. Cronin]long been on the surface albedo feedback and lack of vertical mixing (e.g. Manabe and Wetherald, 1975; Manabe and Stouffer, 1980; Serreze and Francis, 2006). However, several studies have found that arctic amplification was simulated even in models in which the ice albedo feedback is suppressed (Hall, 2004; Alexeev et al., 2005; Graversen and Wang, 2009). While the surface albedo feedback is still considered to be an important contribution to arctic amplification, more recently, other processes have also been identified as being important. In particular, atmospheric feedbacks (e.g. Winton, 2006; Graversen and Wang, 2009; Serreze and Barry, 2011; Pithan and Mauritsen, 2014, [T. Cronin]Payne et al., 2015, Cronin and Jansen, 2016) and changes in heat transport from lower latitudes to the Arctic (cooling lower latitudes and warming the Arctic) (e.g. Holland and Bitz, 2003; Hall, 2004; Graversen et al., 2008) have both been suggested to be important contributors to arctic amplification.

Since the average antarctic surface height exceeds 2 km mainly due to the presence of thick ice sheets and a compensation of above sea level (positive) and below sea level (negative) bed rock elevation (Fretwell et al., 2013), the ice is thick enough and the surface temperature is low enough so that in many areas melting from above is expected to play a minor role unless temperatures increase dramatically. Even for a fairly substantial CO_2 increase, simulated arctic amplification was found to be larger than antarctic amplification due to a weaker antarctic surface albedo feedback already in the early climate model study by Manabe and Stouffer (1980).

Melting from below associated with increased sea surface temperature, on the other hand, is a major concern in part because of the sea level rise associated with pieces breaking off the antarctic ice shield and sliding into the sea (DeConto and Pollard, 2016), although regions which are located far inland and in which the bedrock remains above sea level are not immediately affected. The sea ice in the Southern Ocean, on the other hand, induces a surface albedo feedback in climate change simulations, and in association with the transition from glacials to interglacials it has long been proposed that melting at the edges of ice sheets and glacier flow can successively lower the altitude of the [Anonym. Rev. #1]antarctic ice to where it becomes more prone to melting (Hughes, 1975). The corresponding processes are difficult to represent in climate models, and at present, not all climate models include them.

In addition to the surface albedo feedback (Manabe and Stouffer, 1980), the antarctic surface height is expected to influence atmospheric heat transport. Atmospheric feedbacks such as the [T. Cronin]water vapor feedback are also expected to differ between the Arctic and Antarctic[T. Cronin]~~a~~ due to the differences in surface elevation. Furthermore, the asymmetric land[T. Cronin]-sea distribution with more land in the northern hemisphere could potentially play a role [T. Cronin]in~~for~~ the polar amplification asymmetry.

Another reason for the polar amplification asymmetry that has recently been investigated by Marshall et al. (2014) is an asymmetric response of the ocean heat transport to ozone and greenhouse gas forcing. Masson-Delmotte et al. (2013) have also indicated that asymmetric warming between the Arctic and Southern Ocean in climate models might be linked to asymmetries in ocean heat uptake and ozone depletion over Antarctica.

Here, the role of the antarctic surface height [T. Cronin]in~~for~~ the temperature response to an abrupt carbon dioxide doubling is investigated based on idealized sensitivity simulations with a low[T. Cronin]-resolution three dimensional coupled global climate model in which the surface height was artificially set to 1 m above mean sea level for the entire antarctic continent.

The model, the PRP computations, and the analysis methods are described in the next section. In Sect. 3.1, the zonal mean radiation budget is investigated. The surface temperature response to doubling CO_2 is discussed in Sect. 3.2. Changes in meridional heat transport are analyzed in Sect. 3.3 and local radiative feedbacks are analyzed in Sections 3.4 and 3.5. In Sect. 3.6 an attempt is made to compare contributions from local feedbacks, heat transport, and heat storage. The temporal evolution of the coupled runs [A.Rev. #1 and T.C.]and potential improvements to the model setup used in the present study are~~is briefly~~ discussed in Sect. 3.7.

2 Methods

The Community Earth System Model (CESM) (Hurrell et al., 2013) version 1.0.6 was used in the Community Climate System Model Version 4 (CCSM4) configuration (Gent et al., 2011) to perform a set of idealized [A.Rev. #1 and T.C.]600~~200~~ year coupled model sensitivity runs. The atmospheric component (using the Community Atmosphere Model (CAM4) physics package) was run at spectral truncation T31 (approximately 3.75 degree horizontal resolution) with 26 vertical layers (due to computational constraints). The ocean component (based on the Parallel Ocean Program version 2 (POP2), Smith et al., 2010) was run in the so-called gx3v7 setup with three degree horizontal resolution and 60 vertical layers. Land ice and snow were simulated by the land surface model (Community Land Model version 4, Lawrence et al., 2011) which includes glacier as a land cover type. Sea ice was simulated using a modified version of the Los Alamos Sea Ice Model version 4 (CICE4, Hunke and Lipscomb, 2008). The coupled model was run in a standard configuration without a dynamic ice sheet model.

In the base control run, the atmospheric carbon dioxide concentration was kept fixed at 284.7 ppmv (for the year 1850). In the base 2xCO2 run, the CO_2 concentration was doubled. In addition, two coupled sensitivity runs were performed for which Antarctica was assumed to be flat. These runs are usually referred to as flat AA control run and flat AA 2xCO2 run. Table 1 provides an overview of these coupled runs.

[A.Rev. #1 and T.C.]The analysis focuses on the transient response to CO_2 doubling during the years 76 to 125 and especially during the years 80 to 109 for which the model was re-run and PRP calculations were performed. While most of the temperature response in the upper ocean to the CO_2 perturbation takes place during the initial decades of a 2xCO2 perturbation experiment the deep ocean has not yet reached equilibrium during this period which is similar to the situation in present-day climate and transient future climate change. In the base 2xCO2 run antarctic warming (see Sect. 3.7) became stronger than arctic warming around year 200 (and around year 120 for the flat AA 2xCO2 run) which differs from present-day observations of a stronger polar amplification in the arctic compared to the antarctic region and from the results of shorter CMIP5 simulations which the present study aims to help explain.

In the standard model setup, the radiation subroutine was called every [T. Cronin]other~~second~~ time step. In order to increase the accuracy of the PRP computations (described below), the coupled model was re-run for the years 76 to 125 calling radiation every (half hour) time step instead of every [T. Cronin]other~~second~~ time step. This ensured that the net top of the atmosphere radiation in the offline PRP and the coupled runs were consistent, although closing the budgets including atmospheric and oceanic transport and heat storage remained challenging (this point is further discussed below). The results from these radiation (RAD) re-runs are not identical to the original coupled runs because the more frequent radiation computations trigger a new realization. Many of the main findings of this study are, however, independent of this choice and re-running the entire period would have been computationally expensive. The re-runs differ mainly in their temporal evolution, but the PRP analysis based on these runs~~this run~~ yields qualitatively similar results, except that the sum of all feedbacks (which is a small term compared to the individual feedbacks) is closer to TOA net radiation change in the coupled run and that the contributions of the individual feedbacks and transport terms to the [Anonym. Rev. #1]de~~in~~creasing polar amplification [Anonym. Rev. #1]asymmetry differ. [A.Rev. #1 and T.C.]The advantage of the RAD re-runs is that the PRP analysis is more exact which makes them more suitable for the budget analysis. The advantage of the base model setup is that it is computationally cheaper to run and thus is better suited for longer integrations.

In addition to these coupled simulations, the radiation code was run in an offline setup to perform a set of standard two-sided PRP computations as well as several sensitivity computations in order to investigate contributions of local radiative feedbacks. The offline version of the radiative code that is included in the the CESM v1.0.6 distribution was described by Conley et al. (2013). In the original PRP method (Wetherald and Manabe, 1988), radiative feedbacks are estimated by substituting individual fields (such as atmospheric water vapor) from the perturbed (2xCO2) simulation into an offline radiation calculation that takes all other fields from the unperturbed (control) run. In the two-sided PRP method (Colman and McAvaney, 1997), in addition individual fields from the unperturbed control run are substituted into the offline radiation calculation for the perturbed run. The resulting radiation perturbations are then combined according to:

$$\frac{\delta_{2-1}(R)_x - \delta_{1-2}(R)_x}{2} \qquad (1)$$

where R is the net radiation flux at the top of the atmosphere (TOA), i.e. the difference between incoming solar and outgoing solar and terrestrial radiation, δ_{2-1} is the radiation perturbation from the first (2xCO2 into Control) and δ_{1-2} from the second (Control into 2xCO2) substitution for variable x (or variables x for feedbacks in which contributions from several model variables such as cloud liquid and cloud ice concentration are combined into a single feedback).

Here, the surface albedo (ALB), the water vapor (WV), the cloud (CL), and the lapse rate (LR) feedback were computed. Furthermore, the CO_2 radiative forcing and the Planck (PL) feedback were computed using the two-sided PRP method. The PL feedback was computed by substituting the surface temperature and adding the surface air temperature difference $\Delta T_s(\lambda, \phi)$ to the atmospheric temperatures $T_s(\lambda, \phi, z)$ at each model layer (where ΔT_s depends on longitude λ and latitude ϕ). The LR feedback was defined as the difference LR=TA-PL, where TA is the perturbation that is obtained by substituting the surface as well as the atmospheric temperatures.

The radiation code was run offline based on three-hourly instantaneous model output for years 80 to 109 of the coupled simulations. This fairly high temporal sampling frequency in combination with a fairly long period of 30 years led to a rather smooth and less noisy geographical distribution of cloud feedbacks compared to lower sampling rates and also ensured that the top of the atmosphere energy budget in the PRP runs was consistent with the corresponding coupled runs.

In order to study differences of the LR feedback between the base and the flat AA model setup, a set of additional 30-year PRP sensitivity computations was performed (in addition to the standard PRP computations) based on 73[T. Cronin]-hourly instantaneous model output. In these sensitivity computations, individual variables from the flat AA setup were substituted in PRP computations for the base setup. For example, a PRP calculation was performed in the base model setup using T_s from the flat AA control and the flat AA 2xCO2 run instead of from the base control and the base 2xCO2 run. An overview of the additional sensitivity computations is given in Table 2. [Anonym. Rev. #1]The lower output frequency in the additional sensitivity computations was used since it significantly reduces storage requirements and run time although the PRP computations become less accurate.

Strictly speaking, the cloud radiative response to CO_2 doubling and surface warming that is computed using the PRP method is not a "pure feedback" since it is not only modulated by surface temperature changes. Instead, the cloud radiative response also contains contributions from fast cloud responses to the CO_2 increase which are independent from surface temperature changes. Since the focus here is not on clouds, the historical term "feedback" is nevertheless used for convenience, even though "response" would be more correct. Furthermore, the feedbacks were not normalized by the surface temperature change which facilitates a straight forward comparison of the actual TOA energy flux differences associated with each of the feedbacks between the base and the flat AA model setup. NFurthermore, normalization by the surface temperature change without taking into account heat storage is only appropriate when two equilibrium states are compared.

In analyzing the model output, meridional atmospheric heat transport (AHT) at latitude ϕ was computed by meridionally integrating the difference between the net radiative flux at the TOA (R) and the net energy flux at the surface (F_s, here also defined as positive downward) from the South Pole to latitude ϕ:

$$AHT(\phi) = \int_{-\frac{\pi}{2}}^{\phi} \int_{0}^{2\pi} \left(R(\lambda,\phi') - F_s(\lambda,\phi')\right)^{\text{T. Cronin}} a^2 \cos(\phi')^{\text{T. Cronin}} d\lambda^{\text{T. Cronin}} d\phi' \quad (2)$$

where the net downward surface flux $F_s = R_s - SHF - LHF - SN$ is the sum of the net downward surface radiation flux (R_s), and the sensible and the latent heat flux, and SN is a contribution from snowfall[T. Cronin]; a. R_e is the Earth radius. Ocean heat transport (OHT) is available as a standard diagnostic in the CESM. When computing AHT to the polar regions the integral in Eq. 2 was evaluated individually for each pole, integrating from the pole across all latitudes inside the respective polar circle. [T. Cronin]The corresponding grid cell edges of the atmosphere grid are located at 66.8°North and South. Oceanic heat transport is diagnosed at 66.6°North and South.

The arctic and antarctic region averages were defined as averages over model grid points that are centered poleward of the respective polar circle. In order to roughly compare local radiative feedbacks and changes of heat transport convergence, the meridional heat transport at the edge of the polar region was simply divided by the area of the polar region.

In the flat Antarctica runs, the land height over Antarctica was set to 1 m for the entire continent.

Heat storage terms (here mainly due to changing ocean heat content and a smaller contribution from sea ice and also a minor contribution from snow) were estimated based on the difference in model state during the first and the last month of the period under investigation. The regional heat storage term should be balanced by changes of net meridional heat transport convergence and TOA net radiation flux. However, after taking into account heat storage, atmospheric and oceanic transport, and TOA radiation fluxes, the energy budgets were still not balanced especially in the Arctic, and it appears that this difficulty is only in part caused by different atmospheric and oceanic grids. Instead, it could in principle either have been caused by a energy conservation issue in the model (which can not easily be confirmed based on the present analysis) or else by inaccuracies in the analysis methods used here. However, the (mainly arctic) imbalance was found to be of similar magnitude in the base and the flat AA run, so that the residual terms in the differences between the base and the flat AA model setup were small. Therefore, the energy budget analysis was still considered useful. [T. Cronin]The imbalance between the net radiation deficit and the sum of the other budget terms (dominated by poleward heat transports) varies between 2 and 5% of the net radiation deficit in the polar regions.

For model evaluation purposes, solar and terrestrial radiation fluxes derived from satellite observations for years 2001 to 2014 were taken from the NASA CERES (Clouds and the Earth's Radiant Energy System, Wielicki et al., 1996) SYN1deg Edition 3A. The orbit covers latitudes up to about 80°.

3 Results

3.1 Zonal mean radiation budget

In the polar regions, more energy is emitted to space via long-wave (terrestrial) radiation than supplied by the absorption of solar radiation. This energy deficit is balanced by a radiation energy surplus at the equator and poleward heat transport by the ocean and the atmosphere. The radiation energy deficit is smaller in the antarctic region than in the arctic region. The base model setup (Fig. 1[A.Rev. #1 and T.C.]a) and observations (Fig. [A.Rev. #1 and T.C.]1b~~2~~) show a [T. Cronin]~~rather~~ pronounced arctic-antarctic asymmetry in the magnitude of the outgoing terrestrial radiation flux, which is in line with the higher average surface temperature (and lower average surface elevation) in the Arctic and also with a larger meridional heat flux from lower latitudes toward the Arctic.

[Anonym. Rev. #1]When~~If~~ Antarctica was assumed to be flat, on the other hand, the asymmetry in the simulated radiation budget decreased markedly (Fig. 1a). In the flat AA run, Antarctica was [T. Cronin]~~rather~~ similar to the Arctic in terms of the zonal mean radiation budget, which implies that the overall poleward heat transport was also more symmetric in the flat AA run. Atmospheric and oceanic meridional heat transport will be further analyzed in Section 3.3.

The slight increase in absorbed shortwave radiation over the antarctic continent in the flat AA run (Fig. 1a) is consistent with increased atmospheric absorption and also includes a minor contribution from an increase in snow albedo as the melting temperature is occasionally approached in the flat AA base run. The latter contribution is non-zero in spite of the fact that the entire antarctic continent remains covered by snow year around (not shown). This is because the snow albedo in the CESM decreases with temperature whenever the melting temperature is approached.

3.2 Surface temperature response to doubling CO_2

Doubling CO_2 in the base model setup led to the well known pattern of a strong polar amplification in the arctic and a less strong polar amplification in antarctic region (Fig. 2, based on the RAD re-runs) that is also found in certain transient climate change experiments. In the flat AA run, on the other hand, the polar amplification was increased in the antarctic region while it decreased over time in the arctic region (the temporal evolution in the original coupled runs will be discussed in Sect. 3.7).

This [Anonym. Rev. #1] deincrease of [Anonym. Rev. #1] asymmetry is also reflected in Table 3 (based on the original coupled runs), in which the polar warming due to doubling CO_2 was analyzed for three consecutive 25-year time slices starting in year 51 and ending in year 126. In the base run, the arctic region warmed on average by 1.40 ± 0.29 K (mean [T. Cronin] of three time slices± one standard deviation) more than the antarctic region. In the flat AA run, on the other hand, the difference between the aArctic and the antarctic warming was reduced to 0.59 ± 0.32 K. [T. Cronin] Thus, onOn average, about 56 ± 30% [T. Cronin] of the difference in warming between the arctic and the antarctic region (i.e. 0.81 ± 0.46 K of 1.40 ± 0.29 K) was explained [Anonym. Rev. #1] by the antarctic surface height for the three time slices. However, as evidenced by the large standard deviation, this ratio was not constant in time.

In the first time slice, only 24% of the difference were explained by antarctic surface height, while 64% were explained in the second and 80% in the third time slice. [Anonym. Rev. #1] WhenIf only antarctic temperature change [Anonym. Rev. #1] waswere taken into account [T. Cronin] (i.e. the arctic temperature increase was taken from the base setup while the antarctic temperature increase was taken from the flat AA setup), 73%, 26%, and 42% were explained by antarctic surface height. The differences are explained by a pronounced arctic warming toward the beginning of the flat AA 2xCO2 run compared to the flat AA control run and a weaker subsequent arctic warming (i.e. a cooling relative to the initial warming). This result is based on the original coupled runs and differs from the corresponding result of the RAD re-runs since the temporal evolution of the surface temperature differs [Anonym. Rev. #1] although the finding that polar amplification asymmetry decreases markedly in the flat AA model setup holds in the RAD re-runs as well. Because the original coupled runs reflect the standard configuration of the model, and also because the RAD re-runs are only available for the years 76 to 125, the original coupled runs were chosen for this analysis.

Before discussing the underlying temporal evolution of the zonal mean temperature in the original coupled runs in detail in Sect. 3.7, the reasons for the [Anonym. Rev. #1] deincreased polar amplification [Anonym. Rev. #1] asymmetry in the flat AA model setup (Fig. 2) will be analyzed in some detail [A.Rev. #1 and T.C.] based on the RAD re-runs which generally yield sufficiently similar results to the original runs for this analysis to be useful.

3.3 Atmosphere and ocean heat transport

In this section, the zonal mean AHT (Fig. 3) and OHT (Fig. 4) for the years 80-109 are compared between the base and the flat AA model setup and their changes in the corresponding CO_2 doubling runs are analyzed based on the RAD re-runs. As expected, based on Fig. 1a, AHT and OHT were more symmetric in the flat AA model setup than in the base setup (although they can not be expected to become completely symmetric because the overall land mass distribution differs between the northern and the southern hemisphere). In the control runs, the poleward AHT increased in the flat AA model setup compared to the base setup mainly in the southern hemisphere. Poleward OHT [A.Rev. #1 and T.C.] across the polar circles increased in the southern hemisphere and also slightly increased in the northern hemisphere. In the original coupled runs, on the other hand, poleward OHT [A.Rev. #1 and T.C.] across the polar circle in the northern hemisphere [A.Rev. #1 and T.C.] slightly decreased during this period [A.Rev. #1 and T.C.] (Fig. 5)~~(not shown)~~. Other findings in this section were not affected by this difference.

Doubling CO_2 led to an increased poleward AHT in the base and the flat AA model setup. The increase of the southward AHT across the polar circle in the 2xCO2 runs was larger in the flat AA model setup than in the base model setup, but poleward of 60°S ΔAHT changed sign. At the same time, the increase in southward OHT was maximum around this latitude. This indicates that AHT and OHT are closely linked and that they should not be considered in isolation. Both[Anonym. Rev. #1]~~,~~ AHT and OHT contributed to [Anonym. Rev. #1] de~~in~~creasing the [Anonym. Rev. #1] asymmetry in the flat AA run compared to the base run, and changes of OHT are not confined to the southern hemisphere especially in the tropics. In summary, for the CO_2 doubling experiments, AHT and OHT both contributed to an increased southward heat transport in the flat AA model setup, with OHT changes being more important in the Southern Ocean and AHT "taking over" above the continent.

3.4 Local radiative feedbacks

In addition to AHT and OHT, local radiative feedbacks and increased CO_2 forcing over Antarctica contributed to the [Anonym. Rev. #1] de~~in~~crease polar amplification [Anonym. Rev. #1] asymmetry in the flat AA run. Fig. 6 shows the CO_2 radiative forcing as well as various radiative feedbacks for the base and the flat AA model setup for years 80–109 from the PRP computations. The residual (RES) represents the difference between the radiative perturbation from runs in which all variables including the CO_2 concentration are replaced simultaneously and the sum of the individual contributions from the feedbacks including the PL feedback and the CO_2 forcing. For an identical 3-hour sampling interval, replacing all variables yielded the same radiative perturbation as the corresponding 2xCO2 coupled RAD re-run. [T. Cronin] The SUM and the RES terms in Fig. 6 are expected to balance the contributions from changes in AHT convergence, OHT convergence, and heat storage. The corresponding individual contributions were diagnosed separately as explained in Section 2 and they were found to be of the same order of magnitude as the SUM term which is much smaller than the individual contributions of the major feedbacks except CL (not shown). Unfortunately, however, as explained in Section 2, the diagnosed contributions do not add up to the SUM+RES term as expected.

The difference between Fig. 6 (a) and (b) is shown in Fig. 7. Maps of the feedbacks in the base model run are provided in Fig. 8. Fig. 9 shows maps of the differences between the feedbacks in the flat AA and the base model setup.

Shorter red than blue bars in Fig. 7 indicate that the difference of the local radiative feedbacks between the arctic and the antarctic region has decreased in the flat AA run. The polar asymmetry for FSU (that is the sum of all feedbacks except PL) has roughly halved. The main contribution was the LR feedback, which will be further analyzed in Sect. 3.5. In addition, the water vapor feedback increased in the antarctic region as expected for a deeper atmospheric column. The surface albedo feedback changed only slightly and the overall contribution of the cloud feedback was small in broad agreement with results from other coupled models (Pithan and Mauritsen, 2014).

The most pronounced surface albedo feedback in the Southern Ocean was found north of the Antarctic Circle (Fig. 8). The more positive feedback in this region in the flat AA run (Fig. 9) contributed to the overall [Anonym. Rev. #1] de~~in~~creased polar amplification [Anonym. Rev. #1] asymmetry. The antarctic region as defined here was not [T. Cronin] directly affected by the sea ice changes north of the Antarctic Circle (since it was defined as the region south of the Antarctic Circle), but rather indirectly via meridional heat transports. This indicates that the values in the bar charts should not be overinterpreted. Furthermore, the small tropical LR feedback in Fig. 8 is noteworthy which together with the large positive high latitude LR feedback led to a positive global LR feedback during years 80–109 of this particular run. The (model dependent) net cloud feedback over the Pacific warm pool was dominated by a negative short wave feedback rather than the predominantly positive long wave feedback.

In the next section, the large contribution from the LR feedback to the [Anonym. Rev. #1] de~~in~~crease in polar amplification [Anonym. Rev. #1] asymmet is analyzed in some detail. Then the results are combined with the results from the previous sections.

3.5 Contribution of surface temperature change to lapse rate feedback

The LR feedback was defined as the difference LR=TA-PL, where PL depends only on the change in surface temperature (which is applied at each height level throughout the atmospheric column) while for TA changes in surface as well as the atmospheric temperatures were taken into account. In the tropics, the atmospheric lapse rate is coupled to the surface temperature via deep convection and via the dependence of the slope of the moist adiabat on surface temperature. In the polar regions, where subsidence takes place and deep convection is absent, atmospheric temperatures are less strongly coupled to surface temperatures, and the LR feedback is less well understood.

Fig. 10 shows that the actual mid- and upper tropospheric temperature change in response to doubling CO_2 in the antarctic region was [T. Cronin] ~~rather~~ similar in the base and the flat AA model setup, even though assuming a flat Antarctica affected atmospheric dynamics in various ways. This indicates that the large difference in the LR feedback between the flat AA and the base model setup might not only depend on changes in the mid and upper tropospheric temperature profile. Instead, they could have been influenced by different surface temperatures in the base and the flat AA control run. [T. Cronin] The apparent mismatch between the dots and crosses and the profiles at the lowest atmospheric levels in Fig. 10 (b) and (d) is explained by the condition that all pressure levels where more than 20% of the grid points are above ground are shown in the profiles. Consequently, only a limited number of grid points entered the average temperature for the lowest atmospheric levels while the average surface temperature was computed as an average over all grid points.

In order to find out whether the difference of the LR feedback between the flat AA and the base run can be attributed to differences in atmospheric temperatures or in surface temperatures, a number of PRP sensitivity computations were conducted in which variables from flat AA model runs were substituted into results of runs from the base setup (see Sect. 2 and Table 2 for details). [T. Cronin]The results from these runs are shown in Fig. 11.

In the first sensitivity experiment (LRPLsens) surface air and atmospheric temperature were taken from the flat AA setup to perform the PRP computations. The LR feedback in this sensitivity computation is similar to the LR feedback in the flat AA standard PRP computation. This indicates that the depth of the atmospheric column was not the main reason for the difference of the LR feedback between the flat AA and the base model setup.

In the second sensitivity computation (LRSens), only the atmospheric temperatures were taken from the flat AA setup, and in the third computation (PLSens) only the surface temperatures were taken from the flat AA setup. When only atmospheric temperatures were replaced, the LR feedback was similarly strong as the one in the base setup. Applying only the surface temperatures from the flat AA model setup in the base model setup on the other hand explained the [T. Cronin]stronger antarctic~~weaker~~ LR feedback in the flat AA model setup, even though the actual atmospheric lapse rate above the lowest atmospheric model layer did not change in the PRP computations.

In other words, the difference of LR=TA-PL between the flat AA and the base run appeared to be dominated by a change of PL and not by a change of TA and it is therefore difficult to interpret the changes in the LR feedback in terms of atmospheric lapse rate changes

Consequently, the LR and the PL feedback will in the next section be considered together. The rationale for this is that [A.Rev. #1 and T.C.]in the present study setup the sum LR+PL [A.Rev. #1 and T.C.]in the antarctic region is mainly sensitive to changes in surface temperature and not to changes in the atmospheric lapse rate above the surface layer. Note that by definition, LR+PL corresponds to total temperature feedback TA, i.e. the perturbation that is obtained by substituting the surface as well as the atmospheric temperatures. [A.Rev. #1 and T.C.]The definition of the TA feedback is identical to the definition of the long-wave feedback in a study by Winton et al. (2006) and to the definition of the temperature feedback in a study by Block and Mauritsen (2013).

[A.Rev. #1 and T.C.]The usual decomposition of the total temperature feedback into PL and LR feedbacks is nevertheless useful for understanding polar climate change. As explained above, the PL feedback is defined as the hypothetical feedback that would be expected if the atmosphere would warm at the same rate as the surface. However, the polar atmosphere generally warms less than the surface due to a lack of vertical mixing (e.g. Manabe and Wetherald, 1975). The tropical atmosphere, on the other hand, warms more than the surface. Therefore, in order to radiate away a given amount of energy a larger surface warming is required in the polar regions compared to the tropics (Pithan and Mauritsen, 2014). The lack of atmospheric warming in the polar atmosphere relative to the surface is reflected in the large positive polar lapse rate feedback.

3.6 Local radiative forcing, feedbacks, and heat transport

In Sect. 3.3 it was argued that the partitioning between the atmospheric and oceanic heat transport toward Antarctica strongly depends on the exact latitude that is used to define the antarctic region. Furthermore, in Section 3.4 it was argued that the surface albedo feedback outside the antarctic region as defined by the grid points poleward of the Antarctic Circle almost certainly acts to [Anonym. Rev. #1]de~~in~~crease the polar amplification [Anonym. Rev. #1]asymmetry in contrast to the surface albedo feedback inside the region. Furthermore, in Section 2 it was explained that closing the energy budgets turned out to be more problematic than anticipated, especially for the Arctic. In spite of these caveats, a comparison between local forcings, feedbacks, changes of heat transport convergence and heat storagebudget terms is attempted here.

Fig. 12 shows essentially the difference between the blue and the red bars in Fig. 7 where PL and LR have been combined into a single temperature feedback based on the arguments in Sect. 3.5 and FSUP is defined as the sum of all feedbacks including the Planck feedback. In addition, the heat transport convergence differences and the heat storage terms are shown. On the whole it appears as if the changes in local feedbacks have increased the asymmetry, although this finding depends on whether or not one chooses to follow the arguments in the previous section and to include the Planck feedback here. Apart from the LR feedback (see Sect. 3.4) which here was combined with the Planck feedback into a single temperature feedback, only the CO_2 forcing and the WV feedback acted to decrease the polar amplification asymmetry.

On the other hand, atmospheric changes in heat transport and also changes in heat content (heat storage terms) appear to have contributed to the Anonym. Rev. #1 deincreased Anonym. Rev. #1 asymmetry found in the previous sections. Part of the reason for the change in heat content being fairly important is that the ocean heat content south of the Antarctic Circle decreases in the flat AA base run and increases in the flat AA 2xCO2 run.

This result should, however, not be over-interpreted since for example the albedo feedback most likely would contribute to the overall Anonym. Rev. #1 deincrease in Anonym. Rev. #1 asymmetry if contributions from outside the region were also taken into account. Furthermore, in Sect. 3.3, it was argued that ocean heat transport also contributed to an overall deincrease in asymmetry since it transports heat to the Southern Ocean where the atmospheric heat transport 'takes over'. A.Rev. #1 and T.C. Finally, in Sect. 3.3 it was shown that small OHT changes in response to doubling CO_2 across the Arctic Circle that contribute to the OHT difference in Fig. 12 depend on the whether the original runs or the RAD re-runs are analyzed.

In a more qualitative sense, Fig. 12 suggests that contributions from changes of heat transport convergence and from heat storage (which would be zero in equilibrium) were of roughly the same magnitude as contributions from local feedbacks, indicating that local feedbacks and changes in heat transport convergence both played a role.

3.7 Evolution of surface temperature in the coupled runs

Fig. 13 shows the temporal evolution of the zonal mean surface temperature in the control runs and the 2xCO2 runs for the original coupled runs. As expected, A.Rev. #1 and T.C. the largest surface temperature response to assuming Antarctica to be flat occurred during the first decades of the flat AA control run (Fig. 13c). These decades were not taken onto account in the preceding analysis. After this, the surface temperatures remained fairly stable in the flat AA control run, although the deep ocean was still adjusting. Taking the difference between the flat AA 2xCO2 run and the flat AA control run (as was done in the preceding sections) is expected to remove most of the latter effect.

A.Rev. #1 and T.C. Fig. 13b and d show thatAs expected, antarctic surface temperatures increased faster in the flat AA 2xCO2 run than in the base 2xCO2 run A.Rev. #1 and T.C. as expected based on the previous sections. The arctic temperatures varied strongly due to internal variability, which helps to explain the differences between the original coupled run and the coupled re-runs with half[T. Cronin]-hourly radiation calls which have [A.Rev. #1 and T.C.]been pointed out~~only briefly been mentioned~~ in the discussion of the ocean heat transport in Sect. 3.3.

The weaker arctic warming [A.Rev. #1 and T.C.]in the middle of the 2xCO2 base~~during the last third of the flat AA 2xCO2~~ run [A.Rev. #1 and T.C.](Fig. 13b) is an indication of a slowing of the ocean's meridional overturning circulation (MOC). Such a slowdown has often been found in CO_2 perturbation experiments, and it tended to be stronger in low[T. Cronin]-resolution low[T. Cronin]-complexity models compared to state-of-the art high[T. Cronin]-resolution models. Since the CESM was run at a low resolution in this study, this finding should also not be overinterpreted. [A.Rev. #1 and T.C.]In the 2xCO2 flat AA run, the MOC started to slow down earlier than in the 2xCO2 base run (Fig. 13d), which might indicate [A.Rev. #1 and T.C.]~~It is nevertheless interesting since it indicates~~ that assuming a flat Antarctica did not only influence the Antarctic region but also the arctic region. For a more reliable estimate of this effect coupled runs at a higher resolution and an ensemble of model runs with slightly perturbed initial conditions would be required.

[A.Rev. #1 and T.C.]Fig. 14a shows the evolution of the arctic and antarctic surface temperature for the base and the flat AA model setup and Fig. 14b shows ratios of the arctic to the antarctic amplification which are computed as:

$$f = \frac{A_{Ar}}{A_{AA}} = \frac{\hat{T}_{Ar,2xCO2} - \hat{T}_{Ar,Control}}{\hat{T}_{AA,2xCO2} - \hat{T}_{AA,Control}}$$

[A.Rev. #1 and T.C.]where $\hat{T}$ is a regional average 25-year running mean temperature.

[A.Rev. #1 and T.C.]It should be noted that antarctic warming relative to the respective control run (Fig. 14a) was stronger in the flat AA than in the base model setup almost throughout the entire 600 year period. However, even though the temperature in the flat AA control run stabilized after a moderate initial warming and even though the temperature evolution from the control run was subtracted in this analysis, it can not be completely ruled out that this moderate initial warming could have also played a role in the later development in the 2xCO2 flat AA run. Therefore, in retrospect, starting the flat AA 2xCO2 from a separate long flat AA spinup run and prescribing a more realistic gradual increase of the CO_2 concentration which would allow to also inspect the first decades of the CO2 perturbation experiments would have been better.

[A.Rev. #1 and T.C.]After 250 years, f was lower than unity in the base and the flat AA model setup which indicates that the antarctic temperature increase was stronger than the arctic temperature increase in both model setups. This finding is related to a slowdown of the north Atlantic MOC in both of the 2xCO2 runs which could in part be a transient feature as the MOC recovery times are known to be extremely long. Again, in order to gain confidence in this result, additional ensemble model runs at higher resolution and ideally also a comparison with results from a multi-model ensemble would be necessary. Since the aim of the various model sensitivity runs has been to investigate the sensitivity of the polar amplification asymmetry to antarctic surface height (and not to provide a future projection of antarctic climate change under global warming), the runs were performed without an ice sheet model. In order to arrive at a more credible projection of antarctic climate change, state-of-the art high resolution models that include state-of-the art ice sheet dynamics models should be used.

4 Conclusions

Idealized CO_2 doubling experiments in a low[T. Cronin]-resolution coupled climate model were performed in order to investigate the effects of antarctic surface height on the polar amplification asymmetry. It was found that antarctic surface height indeed played an important role in~~for~~ the slower antarctic warming as expected based on the early climate model study by Manabe and Stouffer (1980). Furthermore, it was found that assuming Antarctica to be flat strongly reduced the hemispheric asymmetry of the zonal mean top of the atmosphere radiation budget, which already by itself indicates that meridional heat transport was also more symmetric in the flat AA model setup.

The polar amplification in the 2xCO2 runs also became [Anonym. Rev. #1]notably~~significantly~~ more symmetric when Antarctica was assumed to be flat. In addition to meridional heat transport, also the stronger CO_2 radiative forcing and the stronger water vapor feedback over Antarctica in the flat AA runs contributed to the [Anonym. Rev. #1]de~~in~~crease in [Anonym. Rev. #1]asymmetry. All of these changes were expected in the deeper atmospheric column that resulted from assuming Antarctica to be flat. For ocean heat transport and the albedo feedback it was argued that also changes north of the Antarctic Circle had to be taken into account when assessing their contribution to the [Anonym. Rev. #1]de~~in~~creased polar amplification [Anonym. Rev. #1]asymmetry in the flat AA runs. Both [Anonym. Rev. #1]de~~in~~creased rather than [Anonym. Rev. #1]in~~de~~creased the polar amplification [Anonym. Rev. #1]asymmetry in the flat AA 2xCO2 run.

Among the local radiative feedbacks, the biggest contributor to the [Anonym. Rev. #1]de~~in~~creased polar amplification [Anonym. Rev. #1]asymmetry was the lapse rate feedback, in agreement with Lunt et al. (2012). However, based on results from additional experiments, it was argued that in this particular model setup, the change of the lapse rate feedback was mainly linked to the change in surface temperature and much less dependent on changes in the atmosphere above the surface. Therefore, it was argued that one might combine the lapse rate and the Planck feedback into a single temperature feedback. The disadvantage of this approach is that it blurs the distinction between the Planck and the lapse rate feedback. [A.Rev. #1 and T.C.]Although the rationale for decomposing the total temperature feedback into the Planck and the lapse rate feedback is less clear in the polar regions than in the tropics, such a decomposition is nevertheless useful for understanding polar climate change (see e.g. Pithan and Mauritsen, 2014; Payne et al., 2015). A more detailed discussion of this issue was given at the end of Sect. 3.5.~~On the other hand, unlike for the tropics in the polar regions there appears to be no clear rationale for separating the total temperature feedback into the Planck and the lapse rate feedback.~~

Other important factors such as stratospheric ozone depletion (Masson-Delmotte et al., 2013) that were found to contribute to the polar amplification asymmetry in previous studies were not investigated in this study.

Given the important role of increased atmospheric heat transport in the flat AA runs in the present study, one could argue that a decrease in land height due to antarctic melting would be favorable for increased atmospheric heat transport from mid latitudes. Consequently, once the antarctic surface height is lowered due to melting, it would be more difficult to restore the [Anonym. Rev. #1]antarctic ice sheet due to increased atmospheric heat transport.

Finally, it was found that assuming a flat Antarctica may~~does~~ not only influence the antarctic but also the arctic region. However, in order to arrive at more reliable results regarding this point, one would have to perform an ensemble of higher resolution model runs because it has long been understood that the MOC can be overly sensitive to perturbations in low T. Cronin-resolution coupled models. T. Cronin Potential future studies based on coupled climate model runs that aim to study the influence of surface elevation on the polar amplification asymmetry which is found in present-day observations and also in future climate projections (which often span only one or one and a half centuries) would benefit from a separate long flat AA spinup run and from prescribing a more realistic gradual increase of the CO_2 concentration.

5 Code availability

The CESM model code is available from http://www2.cesm.ucar.edu.

6 Data availability

The CERES satellite data product can be obtained from http://ceres.larc.nasa.gov/order_data.php. Model output used in this study can be provided by the author upon request.

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References

Alexeev, V. A., Langen, P. L., and Bates, J. R.: Polar amplification of surface warming on an aquaplanet in “ghost forcing” experiments without sea ice feedbacks, Clim. Dynam., 24, 655–666, doi:10.1007/s00382-005-0018-3, 2005.

Block, K. and Mauritsen, T.: [A.Rev. #1 and T.C.] Forcing and feedback in the MPI-ESM-LR coupled model under abruptly quadrupled CO_2, J. Adv. Model. Earth Syst., 5, 676–691, doi:10.1002/jame.20041, 2013.

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W. J., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A. J., and Wehner, M.: Long-term climate change: Projections, commitments and irreversibility, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by T. F. Stocker and D. Qin and G.-K. Plattner and M. Tignor and S. K. Allen and J. Boschung and A. Nauels and Y. Xia and V. Bex and P. M. Midgley, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

Colman, R. A. and McAvaney, B. J.: A study of general circulation model climate feedbacks determined from perturbed sea surface temperature experiments, J. Geophys. Res. Atmos., 102, 19 383–19 402, doi:10.1029/97JD00206, 1997.

Conley, A. J., Lamarque, J.-F., Vitt, F., Collins, W. D., and Kiehl, J.: PORT, a CESM tool for the diagnosis of radiative forcing, Geosci. Model Dev., 6, 469–476, doi:10.5194/gmd-6-469-2013, 2013.

Cronin, T. W. and Jansen, M. F.: [Anonym. Rev. #1] Analytic radiative-advective equilibrium as a model for high-latitudeclimate, Geophys. Res. Lett., 43, 449–457, doi:10.1002/2015GL067172, 2016.

DeConto, R. M. and Pollard, D.: Contribution of Antarctica to past and future sea-level rise, Nature, 531, 591–597, doi:10.1038/nature17145, 2016.

Fretwell, P., Pritchard, H. D., Vaughan, D. G., Bamber, J. L., Barrand, N. E., Bell, R., Bianchi, C., Bingham, R. G., Blankenship, D. D., Casassa, G., Catania, G., Callens, D., Conway, H., Cook, A. J., Corr, H. F. J., Damaske, D., Damm, V., Ferraccioli, F., Forsberg, R., Fujita, S., Gim, Y., Gogineni, P., Griggs, J. A., A.Hindmarsh, R. C., Holmlund, P., Holt, J. W., Jacobel, R. W., Jokat, A. J. W., Jordan, T., King, E. C., Kohler, J., Krabill, W., Riger-Kusk, M., Langley, K. A., Leitchenkov, G., Leuschen, C., Luyendyk, B. P., Matsuoka, K., Mouginot, J., Nitsche, F. O., Nogi, Y., Nost, O. A., Popov, S. V., Rignot, E., Rippin, D. M., Rivera, A., Roberts, J., Ross, N., Siegert, M. J., Smith, A. M., Steinhage, D., Studinger, M., Sun, B., Tinto, B. K., Welch, B. C., Wilson, D., Young, D. A., Xiangbin, C., and Zirizzotti, A.: Bedmap2: improved ice bed, surface and thickness datasets for Antarctica, Cyrosphere, 7, 375–393, doi:10.5194/tc-7-375-2013, 2013.

Gent, P. R., Danabasoglu, G., Donner, L. J., Holland, M. M., Hunke, E. C., Jayne, S. R., Lawrence, D. M., Neale, R. R., Rasch, P. J., Vertenstein, M., Worley, P. H., Yang, Z.-L., and Zhang, M.: The Community Climate System Model Version 4, J. Climate, 24, 4973–4991, doi:10.1175/2011JCLI4083.1, 2011.

Graversen, R. G. and Wang, M.: Polar amplification in a coupled climate model with locked albedo, Clim. Dynam., 33, 629–643, doi:10.1007/s00382-009-0535-6, 2009.

Graversen, R. G., Mauritsen, T., Tjernström, M., Källen, E., and Svensson, G.: Vertical structure of recent Arctic warming, Nature, 451, 53–56, doi:10.1038/nature06502, 2008.

Hall, A.: The role of surface albedo feedback in climate, J. Climate, 17, 1550–1568, 2004.

Holland, M. M. and Bitz, C. M.: Polar amplification of climate change in coupled models, Clim. Dynam., 21, 221–232, doi:10.1007/s00382-003-0332-6, 2003.

Hughes, T.: The West Antarctic ice sheet: Instability, disintegration, and initiation of ice ages, Reviews of Geophysics, 13, 502–526, doi:10.1029/RG013i004p00502, 1975.

Hunke, E. C. and Lipscomb, W. H.: The Los Alamos sea ice model, documentation and software, version 4.0, Tech. Rep. LA-CC-06-012, Los Alamos National Laboratory, 2008.

Hurrell, J. W., Holland, M. M., Gent, P. R., Ghan, S., Kay, J. E., Kushner, P. J., Lamarque, J.-F., Large, W. G., Lawrence, D., Lindsay, K., Lipscomb, W. H., Long, M. C., Mahowald, N., Marsh, D. R., Neale, R. B., Rasch, P., Vavrus, S., Vertenstein, M., Bader, D., Collins, W. D., Hack, J. J., Kiehl, J., and Marshall, S.: The Community Earth System Model A Framework for collaborative research, Bull. Amer. Meteorol. Soc., 94, 1339–1360, doi:10.1175/BAMS-D-12-00121.1, 2013.

Jeffries, M. O., Richter-Menge, J., and Overland, J. E.: Executive Summary, in: Arctic Report Card 2015, edited by Jeffries, M. O., Richter-Menge, J., and Overland, J. E., http://www.arctic.noaa.gov/reportcard, 2015.

Lawrence, D. M., Oleson, K. W., Flanner, M. G., Thornton, P. E., Swenson, S. C., Lawrence, P. J., Zeng, X., Yang, Z.-L., Levis, S., Sakaguchi, K., Bonan, G. B., and Slater, A. G.: Parameterization improvements and functional and structural advances in version 4 of the Community Land Model, J. Adv. Model. Earth Syst., 3, doi:10.1029/2011MS000045, 2011.

Lunt, D. J., Dunkley Jones, T., Heinemann, M., Huber, M., LeGrande, A., Winguth, A., Loptson, C., Marotzke, J., Roberts, R. C., Tindall, J., Valdes, P., and Winguth, C.: A model-data comparison for a multi-model ensemble of early Eocene atmosphere-ocean simulations: EoMIP, Clim. Past, 8, 1717–1736, doi:10.5194/cp-8-1717-2012, 2012.

Manabe, S. and Stouffer, R. J.: Sensitivity of a global climate model to an increase of CO_2 concentration in the atmopsphere, J. Geophys. Res., 85, 5529–5554, doi:10.1029/JC085iC10p05529, 1980.

Manabe, S. and Wetherald, R. T.: The effects of doubling the CO_2 concentration on climate of a general circulation model, J. Atmos. Sci., 32, 3–15, 1975.

Marshall, J., Armour, K. C., Scott, J. R., Kostov, Y., Hausmann, U., Ferreira, D., Shepherd, T. G., and Bitz, C. M.: The ocean's role in polar climate change: asymmetric Arctic and Antarctic responses to greenhouse gas and ozone forcing, Phil. Trans. R. Soc. A, 372, doi:10.1098/rsta.2013.0040, 2014.

Masson-Delmotte, V., Schulz, M., Abe-Ouchi, A., Beer, J., Ganopolski, A., Rouco, J. F. G., Jansen, E., Lambeck, K., Luterbacher, J., Naish, T., Osborn, T., Otto-Bliesner, B., Quinn, T., Ramesh, R., Rojas, M., Shao, X., and Timmermann, A.: Information from paleoclimate archives, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by T. F. Stocker and D. Qin and G.-K. Plattner and M. Tignor and S. K. Allen and J. Boschung and A. Nauels and Y. Xia and V. Bex and P. M. Midgley, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

Miller, G. H., Alley, R. B., Brigham-Grette, J., Fitzpatrick, J. J., Polyak, L., Serreze, M. C., and White, J. W. C.: Arctic amplification: can the past constrain the future?, Quat. Sci. Rev., 29, 1779–1790, doi:10.1016/j.quascirev.2010.02.008, 2010.

Payne, A. E., Jansen, M. F., and Cronin, T. W.: [Anonym. Rev. #1] Conceptual model analysis of the influence of temperature feedbacks on polar amplification, Geophys. Res. Lett., 42, 9561–9570, doi:10.1002/2015GL065889, 2015.

Pithan, F. and Mauritsen, T.: Arctic amplification dominated by temperature feedbacks in contemporary climate models, Nat. Geosci., 7, 181–184, doi:10.1038/NGEO2071, 2014.

Serreze, M. C. and Barry, R. G.: Processes and impacts of Arctic amplification: A research synthesis, Glob. Planet. Change, 77, 85–96, doi:10.1016/j.gloplacha.2011.03.004, 2011.

Serreze, M. C. and Francis, J. A.: The arctic amplification debate, Climatic Change, 76, 241–264, doi:10.1007/s10584-005-9017-y, 2006.

Smith, R., Jones, P., Briegleb, B., Bryan, F., Danabasoglu, G., Dennis, J., Dukowicz, J., Eden, C., Fox-Kemper, B., Gent, P., Hecht, M., Jayne, S., Jochum, M., Large, W., Lindsay, K., Maltrud, M., Norton, N., Peacock, S., Vertenstein, M., and Yeager, S.: The Parallel Ocean Program (POP) reference manual, Tech. Rep. LAUR-10-01853, Los Alamos National Laboratory, 2010.

Wetherald, R. T. and Manabe, S.: Cloud feedback processes in a general-circulation model, J. Atmos. Sci., 45, 1397–1415, 1988.

Wielicki, B. A., Barkstrom, B. R., Harrison, E. F., Lee, R. B., Smith, G. L., and Cooper, J. E.: Clouds and the Earth's Radiant Energy System (CERES): An earth observing system experiment, Bull. Amer. Meteorol. Soc., 77, 853–868, doi:10.1175/1520-0477(1996)077<0853:CATERE>2.0.CO;2, 1996.

Winton, M.: Amplified Arctic climate change: What does surface albedo feedback have to do with it?, Geophys. Res. Lett., 33, doi:10.1029/2005GL025244, 2006.

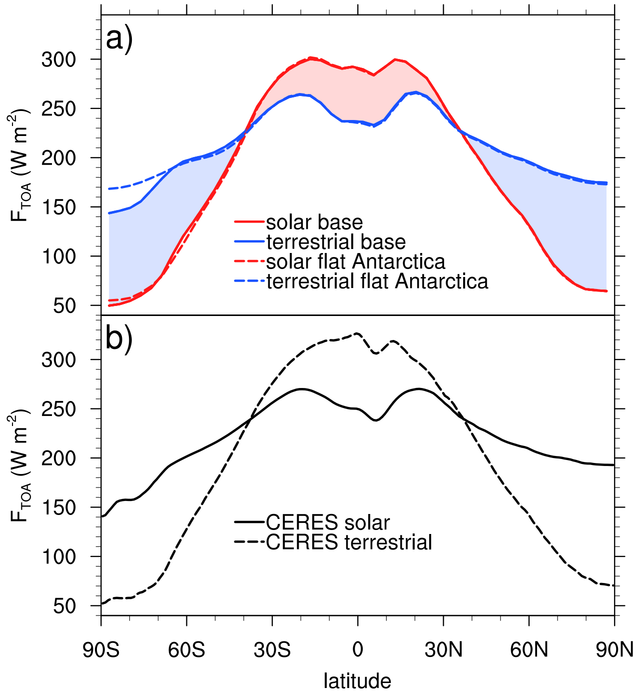

Figure 1. [A.Rev. #1 and T.C.](a) Zonal mean radiation budget at the top of the atmosphere (TOA) for years 80 to 109 of the base and flat AA control run: net downward solar (= absorbed shortwave, red lines) and upward terrestrial (= outgoing longwave, blue lines) radiation flux. The shaded areas are based on the base control run. Red shading indicates a net radiation surplus (i.e. on the net, more solar radiation is being absorbed than terrestrial radiation emitted) and blue shading a net radiation deficit. Since the focus is on the polar regions, the x-axis has not been scaled by the cosine of the latitude. [A.Rev. #1 and T.C.](b) Zonal mean radiation budget at the top of the atmosphere (TOA) for years 2001 to 2014 based on the CERES SYN1deg Edition 3A satellite data product. **Please note: figures 1 and 2 have been combined.**

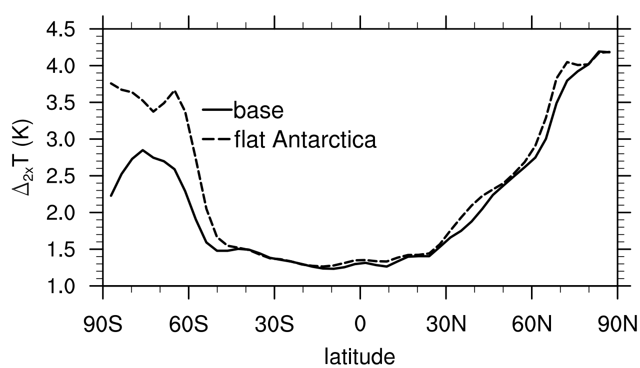

Figure 2. Surface air temperature increase for a CO_2 doubling in the base and the flat AA model setup for years 80-109 (from the RAD re-runs). **Please note: modified y-axis label.**

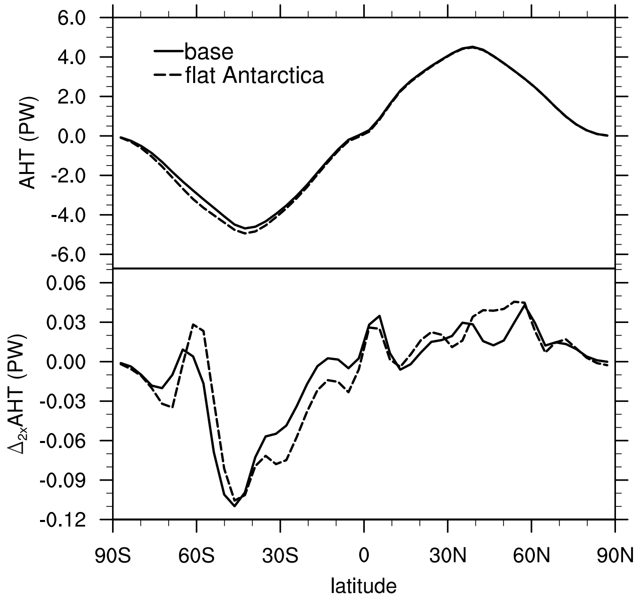

Figure 3. (a) Northward atmospheric heat transport (AHT) in petawatt in the base and the flat AA model setup for years 80-109. (b) Differences (2xCO2 minus Control) for doubling CO_2 [A.Rev. #1 and T.C.] (from the RAD re-runs).**Please note: modified y-axis label in lower panel.**

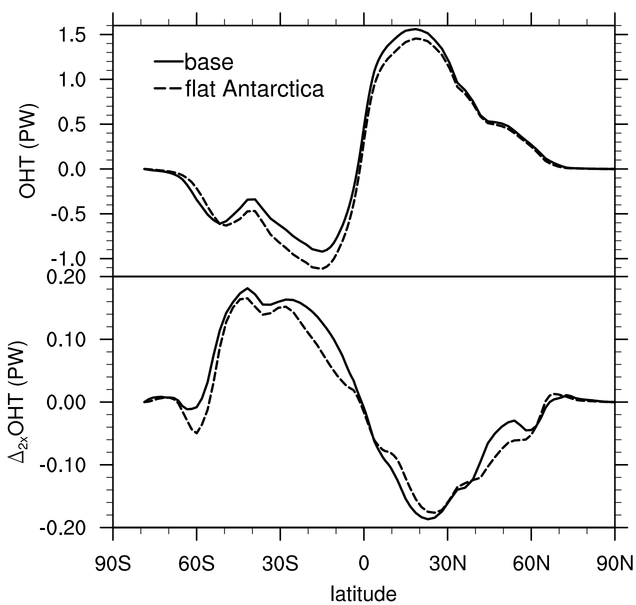

Figure 4. Same as Fig. 3 but for oceanic heat transport (OHT).**Please note: modified y-axis label in lower panel.**

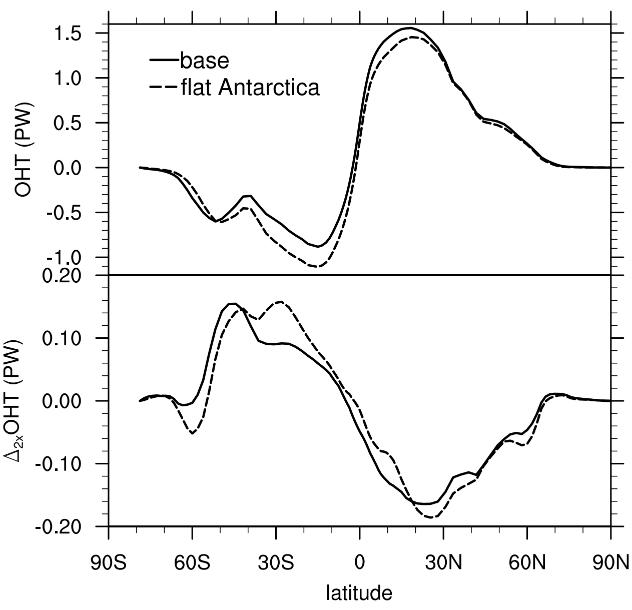

Figure 5. [A.Rev. #1 and T.C.] Same as Fig. 4 but from the original runs instead of the RAD re-runs. **Please note: newly added figure.**

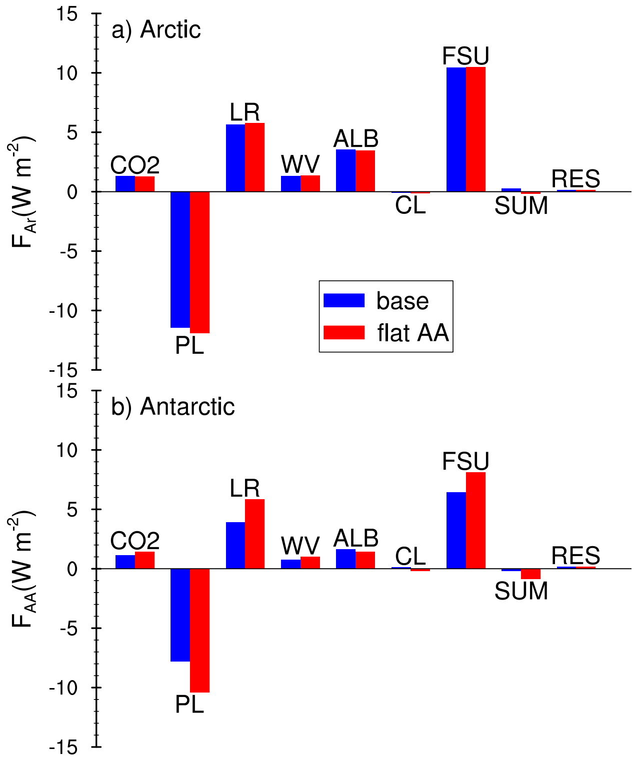

Figure 6. CO_2 radiative forcing (CO2) as well as Planck (PL), lapse rate (LR), water vapor (WV), albedo (ALB), and cloud (CL) radiative feedback based on two-sided PRP calculations for years 80–109. FSU=LR+WV+ALB+CL is the sum of the feedbacks except PL. The residual (RES) is the difference between the radiative perturbation from replacing all variables simultaneously and the sum (SUM=CO2+LR+WV+ALB+CL+PL) of the individual contributions including CO2 and PL. **Please note: modified y-axis labels.**

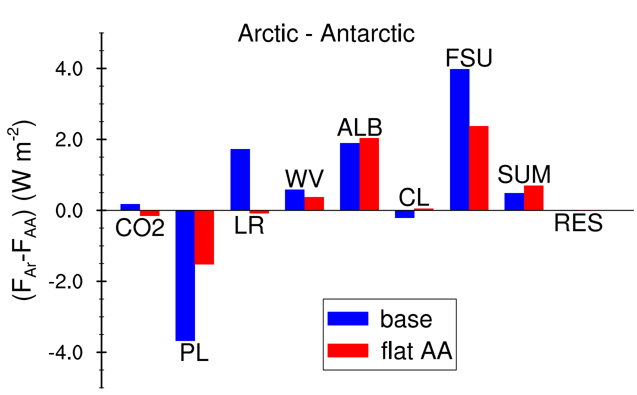

Figure 7. Differences between Fig. 6 (a) and (b). **Please note: modified y-axis label.**

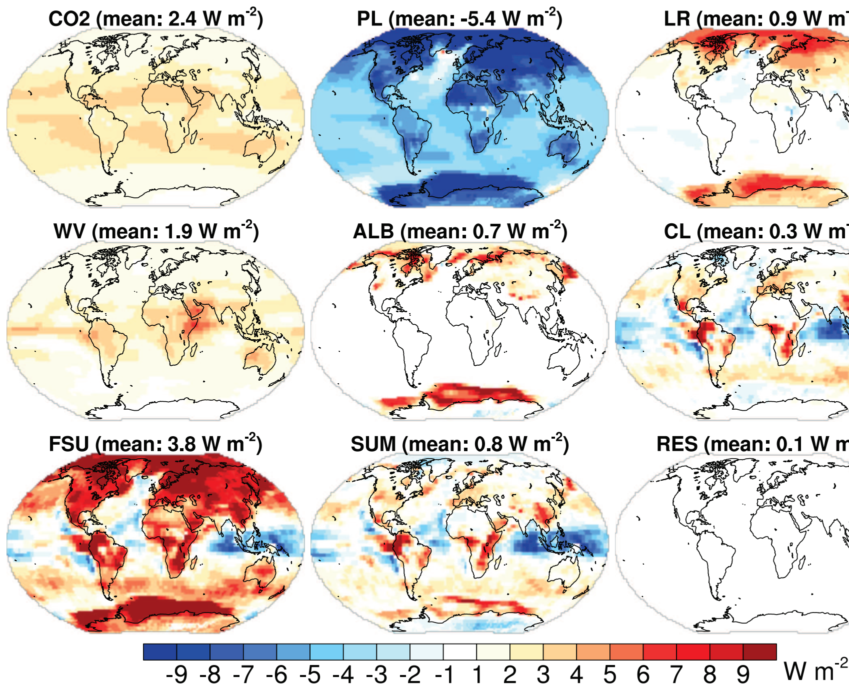

Figure 8. Radiative forcing and feedback maps for the base model setup for the years 80–109. Labels as in Fig. 6.

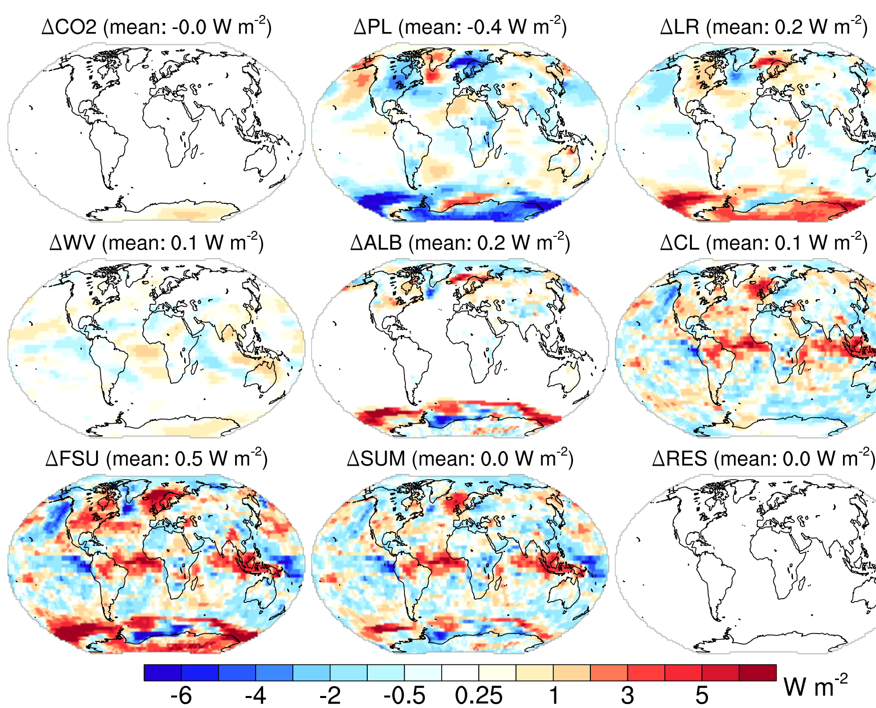

Figure 9. Differences between the flat AA and base the setup (comparable to Fig. 8).

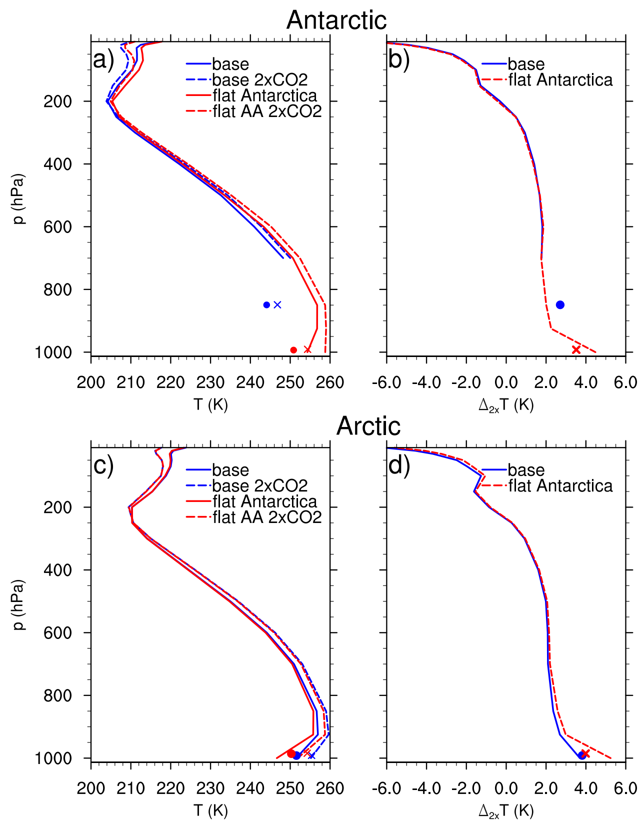

Figure 10. Average air temperature profiles for the antarctic and the arctic region from the coupled runs and differences (2xCO2 minus Control) for the base and the flat AA model setup for years 80–109. Dots and crosses denote average surface air temperature at the region average surface pressure. Dots correspond to solid and crosses to dashed lines. Only pressure levels where more than 20% of the grid points are above the ground are shown in the profiles. **Please note: modified x-axis label in (b) and (d).**

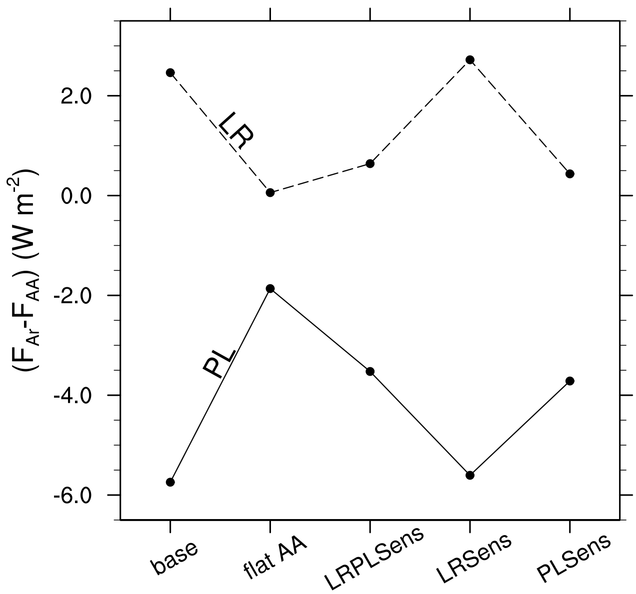

Figure 11. [Anonym. Rev. #1] Arctic minus Antarctic difference of the lLapse rate (LR) and Planck (PL) feedback in the base and the flat AA model setup and for the sensitivity calculations described in Table 2. [T. Cronin] All computations are based on PRP calculations using 73-hourly instantaneous model output and the original base and flat AA runs are analyzed. **Please note: modified y-axis label**.

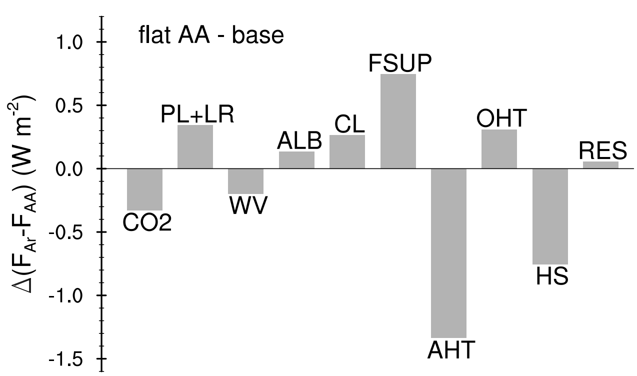

Figure 12. Difference flat AA minus base setup of [T. Cronin] $(F_{AR} - F_{AA})\Delta F$, where [T. Cronin] $(F_{AR} - F_{AA})\Delta F$ is the difference between the arctic and the antarctic region shown in Fig. 7. For the forcing and the feedbacks, this corresponds to the difference between the red and the blue bars in Fig. 7. FSUP=PL+LR+WV+ALB+CL is the sum of all feedbacks including the Planck feedback. It is compared to contributions from atmospheric and oceanic heat transport (AHT, OHT) and heat storage (HS). The residual (RES) is defined as the difference between HS and the sum of forcing, feedbacks and heat transport convergence (CO2+FSUP+AHT+OHT). **Please note: modified y-axis label.**

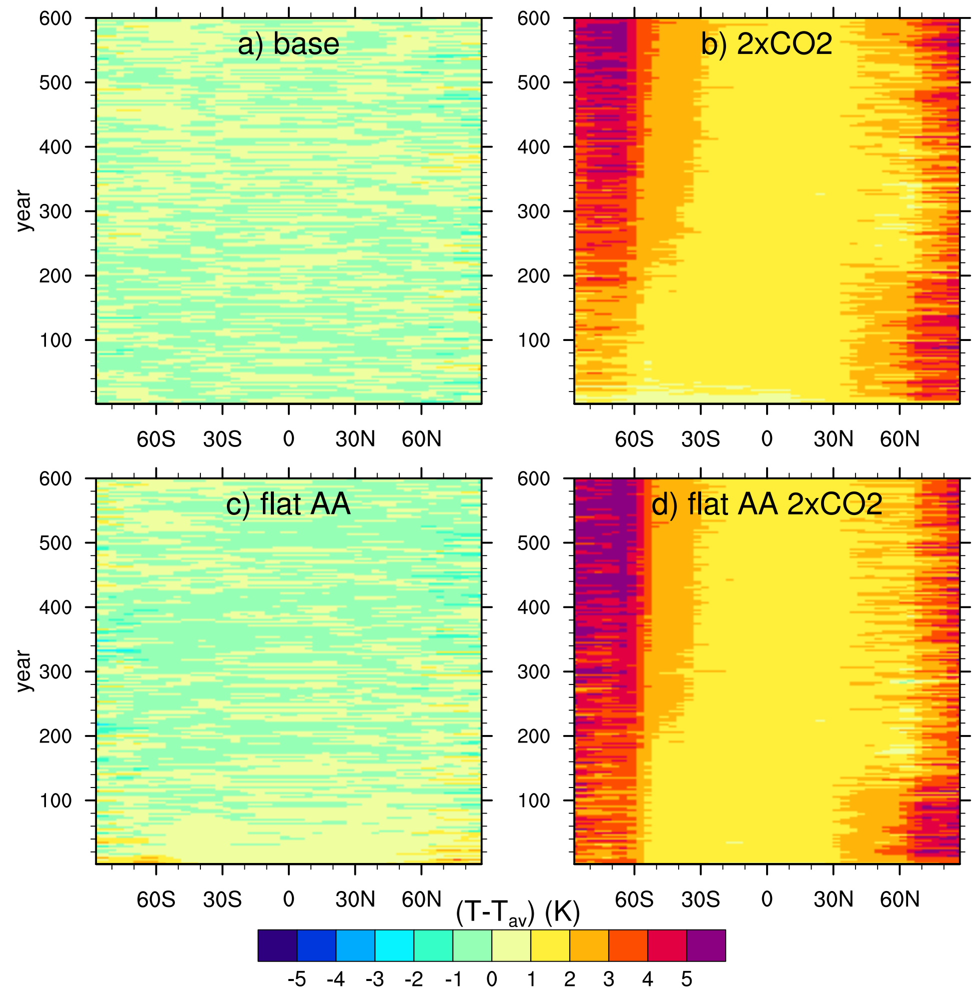

Figure 13. Difference between the zonal mean surface air temperature and the time averaged zonal mean surface air temperature from the corresponding control run (T_{av})~~anomaly~~ in the control and the 2xCO2 run for the base and the flat AA model setup. **Please note: extended runs by 400 years and modified color bar label.**

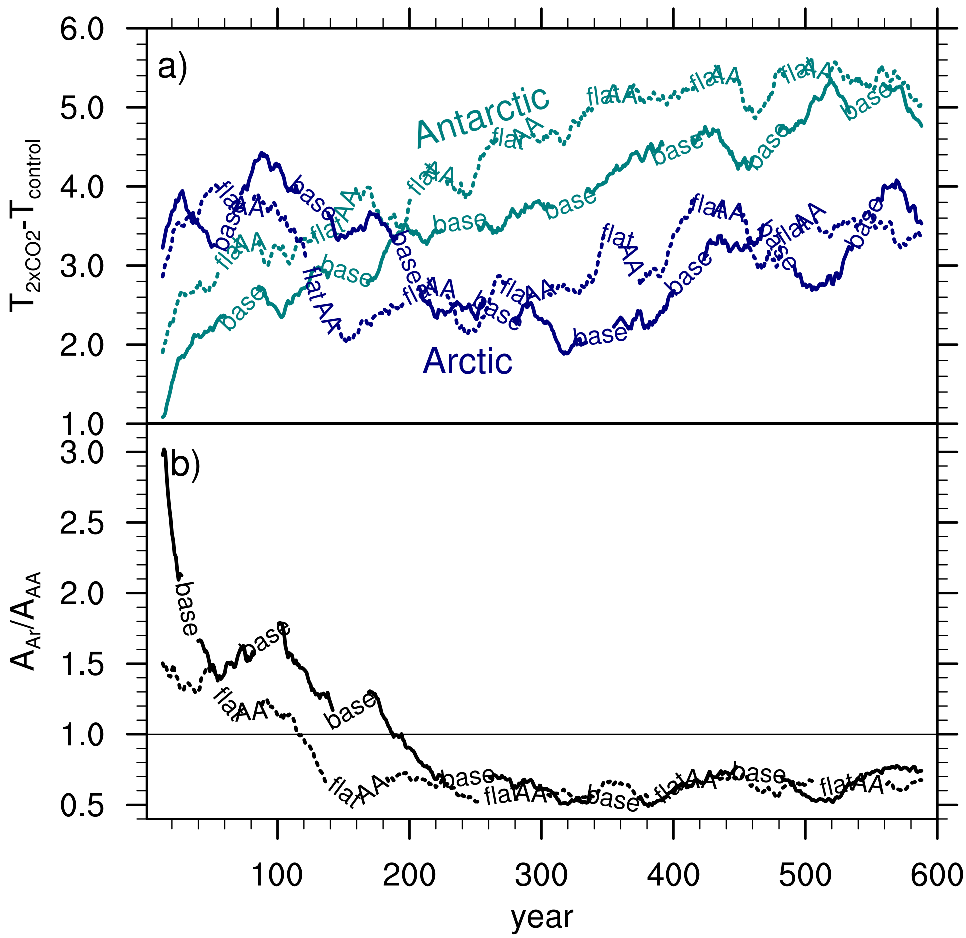

Figure 14. A.Rev. #1 and T.C. (a) 25-year running mean of the temperature difference between the 2xCO2 and the control runs for the arctic and the antarctic region in the base and the flat AA model setup and (b) ratio of arctic to antarctic amplification based on 25 year running mean time series. **Please note: newly added figure**

Table 1. Coupled Runs

run	description
base Control	Control run for constant year 1850 conditions
base 2xCO2	Same as base Control, but doubled CO_2 concentration
flat Antarctica Control	Control run for flat Antarctica (flat AA)
flat Antarctica 2xCO2	flat AA CO_2 doubling run

Table 2. Additional PRP Sensitivity Computations

label	variable(s) from flat AA model setup in base model setup
LRPLSens	surface air (T_s) and atmospheric (T_a) temperature
LRsens	atmospheric temperature T_a
PLSens	T_s and control T_a with added ΔT_s as in PL

Table 3. Mean arctic and antarctic warming (2xCO2 minus Control) $\pm$ one standard deviation for three consecutive 25-year time [T. Cronin] slices starting at year 51 for the base and the flat AA model setup.

	Arctic Warming (K)	Antarctic Warming (K)	Difference
base	3.95 $\pm$ 0.48	2.55 $\pm$ 0.22	1.40 $\pm$ 0.29
flat AA	3.76 $\pm$ 0.31	3.17 $\pm$ 0.01	0.59 $\pm$ 0.32