

**Response to Referee#1 on: “An ensemble of AMIP simulations with prescribed land surface temperatures” by Ackerley et al.**

**General Comments:**

*This paper by Ackerley et al. describes a suite of fixed land temperature experiments with a single AGCM and provides a thorough validation of the experiment setup. The fixed land temperature experiments fill an important gap in the current model hierarchy, particularly in terms of understanding the traditional AMIP-style simulations. The paper shows that the land surface temperature can be prescribed in a way that is over all consistent with the free-land setup. These experiments, which are made publically available, therefore are of great scientific value. My only concern with this generally well-written paper is the lack of scientific analysis. While the main purpose of this paper is to provide a description and validation of experiment design, there are a few points that concerns the soundness of the experiments and should be better addressed. Particularly, the positive precipitation bias in the Amazon stands out as perhaps the biggest caveat of the fixed land temperature experiments. If these experiments were to be used to study Amazon rainfall, such caveat needs to be better understood. And I suppose this paper should serve that purpose. The authors may expand on the hypothesis provided in a single sentence in L14-15 and elaborate on the mechanism provided in Cox et al. 1999.*

**Response:** The authors would like to thank the reviewer for undertaking their review of our work and for the positive and helpful comments that have been made. We do fully understand the reviewer’s point about scientific analysis; however, we feel that providing a solid (and relatively simple) evaluation of the simulations we have undertaken is very important for others who wish to use these data. Providing in-depth scientific analysis of the runs would likely result in an extremely lengthy paper and make it difficult to simply present the biases associated with these experiments. This is why we made Geoscientific Model Development our publication choice, as it is the perfect platform for such a paper. It is hoped that others will provide more scientific insight (there are two papers the author is aware of that are in review and showcase some of the scientific value of these runs) by downloading the data themselves. The responses to the main points are given below.

The authors also fully agree with the need to provide more insight to the Amazon precipitation in the prescribed land simulations, but unfortunately we did not save the canopy water diagnostics as monthly means throughout the run and cannot re-run all the experiments (the lead author no longer works at the institute). Nevertheless, we did save the canopy water in the restart files (instantaneous values every 3 months, which gives 116 values to average over each run) and we have plotted the difference between  $A_{pL}$  and  $A$  in Figure R1.1 below. There is higher canopy water storage in the  $A_{pL}$  run relative to the  $A$  run, which matches the region of higher latent heat flux (Figure S3(a) in the supplementary material) and precipitation (Figure 1(h)) and supports our hypothesis in the main text. Given that this is an average over relatively few instantaneous values, the changes may not be highly statistically significant; however, the result supports the physical interpretation. We will add the figure to the supplementary material as further evidence of the stated process while also stating the associated caveats with the following text (the caption will be the same as that shown in Figure R1.1 below):

“The change in canopy water loading ( $\text{kg m}^{-2}$ ) taken from 116 instantaneous seasonal values (first day of each season over 29 years) from both the  $A_{pL}$  and  $A$  simulations (Fig. S4). The 116

values are taken from the model restart files as climatological averages were not retained during the simulation. The positive change in canopy water loading corresponds with both the higher precipitation (Fig. 1(h) in the main text) and latent heat fluxes (Fig. S3(a)) that are seen in Apl relative to A, which agrees with the physical mechanism proposed in Section 3.2.1 of the main text.”

**Specific comments:**

1. *It might be worth mentioning the aquaplanet simulations that also have prescribed global surface temperature and have been used to indirectly study the impact of land surface temperature changes. For example, the CMIP6 standard aquaplanet simulations (e.g., He and Soden 2017) and the aquaplanet simulations with land-like temperatures (e.g., Tobias and Bjorn 2014). The lack of land in these aquaplanet simulations is an obvious shortcoming and the fixed land temperature experiments are a perfect solution. Tobias, B., and S. Bjorn, 2014: Climate and climate sensitivity to changing CO<sub>2</sub> on an idealized land planet. *J. Adv. Model. Earth Syst.*, 6, 1205–1223, doi:10.1002/2014MS000369. He, J., and B. J. Soden, 2017: Are-examination of the projected subtropical precipitation decline. *Nat. Clim. Change*, 7, 53–57, doi:10.1038/nclimate3157.*

**Response:** We have reviewed both of these pieces of work and agree with the reviewer that they are very useful additions to the cited literature in this paper. The He and Soden (2017) paper uses the opposite approach to our work in that an aquaplanet 4xCO<sub>2</sub> simulation is compared with the standard AMIP 4xCO<sub>2</sub> simulation. The impact of the land is inferred by subtracting one from the other (aqua vs AMIP with land) whereas our simulations suppress the land response (A4xpl) and compare it to the full (A4xpl4x) or land-only (Apl4x) simulations. Becker and Stevens (2014) on the other hand look at the response of various feedback processes in an idealised version of the ECHAM6 model. There are clear parallels between their idealised work and the simulations we have produced with prescribed land. Indeed, the cloud feedback processes highlighted by Becker and Stevens (2014) (e.g. the response of stratocumulus-type cloud to different land and CO<sub>2</sub> configurations) could be looked at in our simulations. We have therefore included references to both pieces of work in the 3<sup>rd</sup> paragraph of the Introduction.

2. *Page 4, Line 10. Are the land surface types prescribed or allowed to change?*

**Response:** The land surface types do not change in the version of the model we have used (i.e. it is not an interactive scheme with respect to surface fractional type definition). They therefore do not change in any of the experiments given in the paper.

3. *Page 7, Line 3. How is the plant physiological effect switched off? Can it be explained in a couple of sentences?*

**Response:** The calculation of photosynthesis in the vegetation scheme relies on the CO<sub>2</sub> concentration specified at the start of the run, as does the radiation scheme. In the ‘rad’ experiments, this is bypassed within the vegetation scheme by manually setting the CO<sub>2</sub>

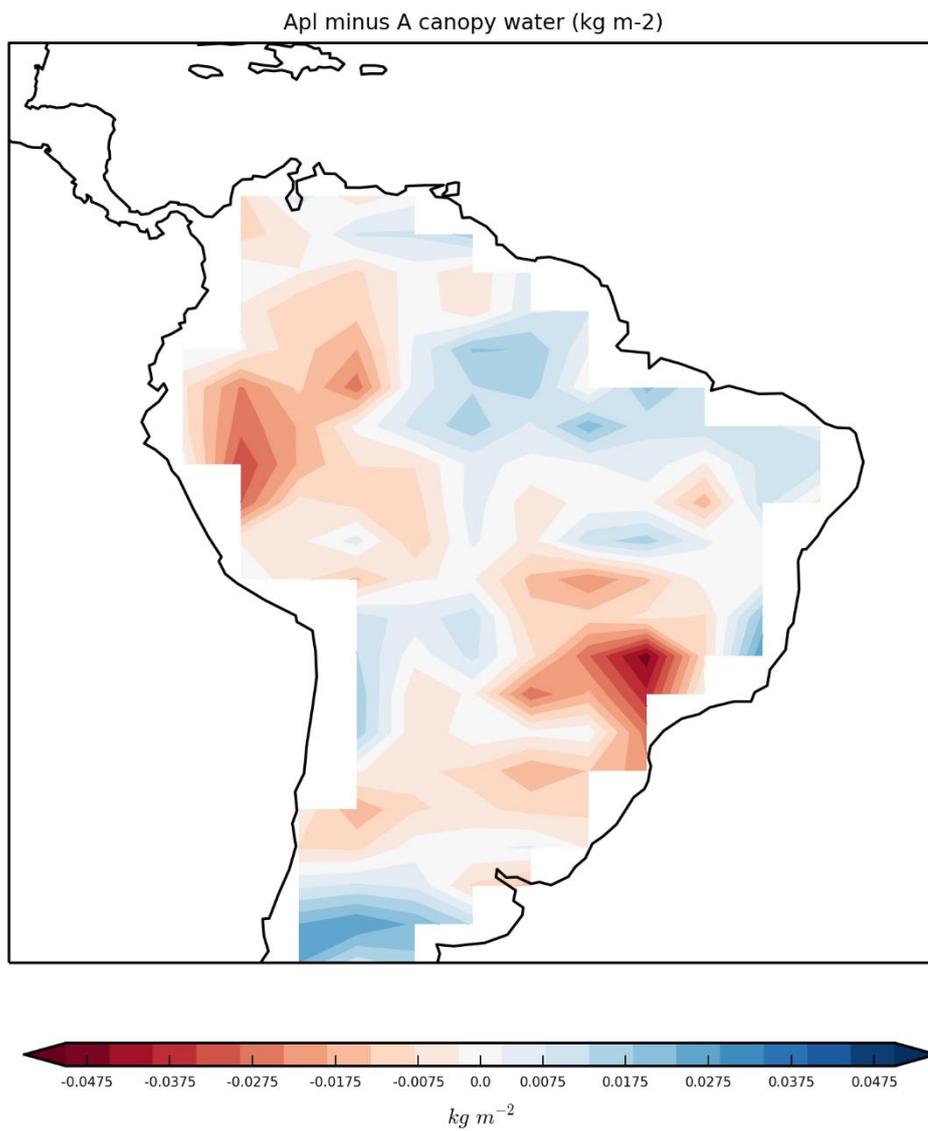
concentration to 346 ppmv in the code (whereas the atmosphere still 'sees' the specified value e.g. 1384 ppmv when quadrupled). This is how the physiological effect is 'switched off' i.e. it is a hard-wired bypassing of the value read in at the start of the run, which would normally be applied to both the vegetation and radiation schemes. We have therefore added:

"...and denoted as Arad4x from here on). This is done by setting the CO<sub>2</sub> concentration used in the photosynthesis calculation in the vegetation scheme to 346 ppmv but allowing the radiation scheme to 'see' the quadrupled value (i.e. 1384 ppmv)."

4. *Have the authors considered prescribing soil temperature and moisture separately (i.e., fix one and allow the other to change freely)?*

**Response:** The authors have considered such experiments; however, the aim of these experiments was to produce a set of AMIP prescribed land experiments that reproduced the free land experiments as closely as possible. Therefore, both the soil temperatures and moisture needed to be prescribed together to maintain consistency. This allowed us to initially identify any systematic errors that may have been present in the prescribed land runs. The soil temperature and moisture fields were then prescribed together in the individual forcing experiments to again remain consistent with the prescribed land experiments. This would then allow us to have confidence in whether the climatic changes seen in the simulations were 'land driven' (i.e. temperature and soil moisture) or not. Furthermore, by prescribing both fields together we are able to maintain the strong coupling between soil moisture and land temperature, segregating the two processes could be considered unphysical. Also, given the ~30 year length of the model simulations, there may be a long spin-up period required for the soil moisture field if it is allowed to vary freely with prescribed land temperatures, which could reduce the statistical significance of any observed changes in climate. The necessary testing for such an experiment was therefore beyond the scope and resources of the ensemble we have produced. Nevertheless, we would certainly advocate running such experiments in the future or encourage others to do so with the code that has been made available.

**Figure**



**Figure R1.1:** The difference in the canopy water loading ( $kg\ m^{-2}$ ) in the A<sub>PL</sub> simulation relative to A.

**Response to Referee#2 on: “An ensemble of AMIP simulations with prescribed land surface temperatures” by Ackerley et al.**

**General comments:**

*This paper describes an ensemble of experiments with the ACCESS AGCM in ‘AMIP’ style (with variants), but with the novel feature of fixing land surface temperatures. The method is described, then a large range of experiments where land surface temperatures are prescribed under various combinations of increased SSTs, fixed/variable stomatal resistance, changed CO<sub>2</sub>, changed solar constant. The analysis shows that the patterns of temperature, rainfall and MSLP are well preserved, and that the temperature fixing works effectively. Analysis is restricted to showing the effectiveness of the method throughout the very wide range of experiments.*

*This paper is a good fit for GMD, and is an effective and useful description of the methodology and effectiveness of this novel approach, and a generally clear description of the range of model results available for analysis.*

**Response:** The authors would like to thank the reviewer for undertaking the review and for their positive and helpful comments. We have answered each of the points raised below and hope they are to the reviewer’s satisfaction.

**Specific comments:**

*I have only a few, mostly minor comments, essentially on clarifying the presentation:*

**Response:** Please see our responses below.

- 1. It is unclear what is done with snow cover, and surface temperatures over snow. What about inconsistencies such as snow cover present, but surface temperature >0C? What if snow falls on an above zero point or is there already and T>0?*

**Response:** The snow cover is allowed to change interactively in response to the prescribed surface temperature. Therefore (as would be the case in the ‘free land’ simulations), snow falling on land with temperatures above freezing would be melted based on the mass deposited and the melting rate at a given temperature. On surface points where snow is lying and the prescribed surface temperature rises above freezing point, the same process would occur (i.e. snow melt would occur based on the snow mass and surface temperature). There is always the possibility that some inconsistency may exist, which is unavoidable when running the model in such an idealised way. One option could have been to prescribe the snow field in these experiments too. Nevertheless, given the very small differences in the climatological fields presented (even at high latitudes where the snow issue would be largest) it is highly unlikely that there are any major inconsistencies that have a strong impact on the mean climate.

- 2. Discuss early what is done over sea ice (it is alluded to, but only later in the discussion).*

**Response:** We state that, “prescribed, observational SSTs and sea ice concentrations from 1979 to 2008 (30 years long)...” are used (Section 2.2.1). We do not prescribe the temperature of the sea ice and realise that this is not mentioned in the text. We have therefore adjusted the end of section 2.2.2 as follows to be clearer:

“Finally, land surface temperatures are not prescribed over both the permanent ice sheets (Antarctica and Greenland, to avoid the development of negative temperature biases that are discussed in Ackerley and Dommenges, 2016) and within/on sea ice. The impact of not specifying the land temperatures over the ice sheets or sea ice temperature is likely to be negligible (see Section 3).”

3. *Why is soil moisture also set? This is not explained. Would it be possible to set but not soil moisture? What would be the ramifications of that?*

**Response:** This point is also raised by the other reviewer (and also discussed there) and is an important point that should be addressed here too. Both the soil moisture and land temperature are set together to maintain as much consistency between the prescribed land and the ‘free land’ simulations. Segregating the two processes could be considered unphysical as the soil moisture and temperature fields are closely coupled. Another issue is associated with changing more than one variable at once. For example, in the  $A_{4xPL}$  simulation, would precipitation changes be due to changing the land temperature or a change in soil moisture in response to the new temperature field? By prescribing both together we are able to say that the responses we see are due to the constrained land conditions as a whole, while accepting that we cannot separate this into the moisture-driven and temperature-driven effects. It is also worth noting that de-coupling the soil moisture and temperature fields (by allowing soil moisture to vary while prescribing temperature) would require a spin up period to allow the soil moisture to come into equilibrium with the temperature field (e.g. through evaporation). The atmosphere (e.g. precipitation) would then need time to reach an equilibrium with the new surface moisture field associated with the prescribed temperature field and then the soil moisture would need to adjust to the new precipitation field (and so on). This may therefore need multiple years of spin up, which would diminish the strength of the statistical relationships presented. Such an issue is not present in perturbed SST experiments as the ocean thermal properties are relatively uniform (relative to the land) but over the land, in order to maintain land surface temperatures and soil moisture consistency, it is therefore clear that both fields need to be prescribed.

While there are issues (see above) with allowing the soil moisture to change with prescribed temperatures, the authors do think that the work could be extended to undertake such experiments but it was beyond the scope of the current study. We state in Section 2.2.2 that, “The surface temperature, soil moisture and soil temperatures are all prescribed every 3 hours for the whole period 1980–2008 to minimise the differences between free and prescribed land simulations.” Given the discussion above, the authors feel this is enough justification for the experiments that we have presented.

4. P 3 lines 17-21: long complex sentence – break up

**Response:** Sentence changed to: “All of the forcing agents outlined above have different impacts on land temperatures and both the global and regional climate. Therefore it would be useful to quantify the separate contributions of the land, the atmosphere (e.g. increased long-wave absorption), plant physiology and SSTs in the global and regional climate response.”

5. P3, 25-27: Unclear sentence

**Response:** Lines 25-27 changed to: “The main aim of this study is to describe and validate a set of AMIP simulations against those with prescribed land conditions. This study also presents an evaluation of experiments that employ different combinations of land conditions with the different SST, CO<sub>2</sub> and insolation specifications.”

6. P4, l21: ‘An initial estimate...’. Unclear – is this for freely varying T? Also start new para here.

**Response:** New paragraph started there and the sentence now begins with, “In the free land experiments...”

7. P7, l3: clarify why this is a ‘radiative response’ only: surface albedo of plants only is allowed to change? Also what about surface roughness?

**Response:** We have added the following to the end of point (4) in section 2.2.1: “...and denoted as Arad4x from here on). This is done by setting the CO<sub>2</sub> concentration used in the photosynthesis calculation in the vegetation scheme to 346 ppmv but allowing the radiation scheme to ‘see’ the quadrupled value (i.e. 1384 ppmv).”

Plant albedo and roughness length do not change. The only variable that changes is the CO<sub>2</sub> concentration ‘seen’ by the radiation scheme while the vegetation scheme ‘sees’ the unperturbed value. This is in-line with the cited literature and that of CFMIP (Doutriaux-Boucher et al., 2009; Boucher et al., 2009; Andrews et al., 2011; Webb et al., 2017).

8. P7, L25: don’t you mean on top of the ice sheets?

**Response:** Indeed. Changed to, “The impact of not specifying the temperatures over the ice sheets...”.

9. *Sometimes a hyphen means minus, and sometimes it means hyphen, and sometimes the mathematical minus is used. This all gets a bit confusing. Examples are P9, L19, 'A-ERA-Interim means 'A minus ERA-interim'. Fig 2 first line of caption, minus and dashed both mean minus. My suggestion (i) drop the hyphen e.g. in ERAinterim. (ii) when '-' means minus actually use the mathematical symbol (iii) the first time used, e.g. P9L19 spell it out "(i.e. A minus ERAinterim)".*

**Response:** We can see the confusion caused by this. We have fixed it by doing the following:

- ERA-Interim is referred to as ERAI in the text now (except in the first instance).
- We have spelled out 'minus' instead of using the symbol to make things clearer.
- We have used '-' in Table 3 due to columns overrunning beyond the edge of the page (this can be resolved if the manuscript reaches the typesetting stage).
- We have not changed the figure notation (e.g. (a)–(d)) nor range notation (e.g. 1–3 K) as this is the journal's style.

10. *P9, L20. Please comment further on the temperature anomalies over the oceans, considering SSTs are fixed.*

**Response:** There are several causes of the difference. One reason may be that ERA-Interim provides 2 m air temperatures whereas ACCESS outputs 1.5 m air temperature. The ACCESS air temperatures would therefore be systematically higher than those of ERA-Interim. Next, while the near surface air temperature will be constrained by the SST, the reanalysis data is adjusted with data assimilation whereas the ACCESS AMIP run is not. The difference may therefore be due to a systematic error in the lower atmosphere in the ACCESS run that is interpolated to the near surface whereas the ERA-Interim data are corrected towards observations (this point is made in section 4 of Kumar et al., 2013). The SST datasets are also different between ERA-Interim and those used by the ACCESS AMIP run (see Table 1 in Dee et al, 2011, and [https://pcmdi.llnl.gov/mips/amip/amip2/#source\\_data](https://pcmdi.llnl.gov/mips/amip/amip2/#source_data)) and the differences may be due to that. Overall, the figure is not given to highlight the differences between the ACCESS AMIP simulation and ERA-Interim, it is there to show that the differences in TAS between the prescribed and free land simulations are negligible when compared with the 'model biases' relative to observations. Please note however, we have changed the sentence in the paper to read 'Fig. 1(a)' as the original only said 'Fig. 1.'

11. *P10, first para: worth noting that the biggest differences are over sea ice, where surf temp is not prescribed.*

**Response:** We have added the following to that paragraph: "...and the largest changes are at high-latitudes where sea ice is located (sea ice temperatures are not prescribed)."

12. P10, L13: *don't you mean that this is checking the climate change response is consistent for a given boundary change (e.g. SST)? After all you are comparing the differences.*

**Response:** Agreed. We have changed the sentence to: "In order to validate whether the climate responses in the prescribed land simulations are consistent with their free land counterparts for a given boundary forcing..."

13. P11, L18: *bias -> dry bias*

**Response:** Changed as suggested.

14. Table 4: *why bother with italics AND asterisks?*

**Response:** It makes the numbers stand out better (but still less conspicuous than the significant values) whereas just one or the other can make it difficult to distinguish at a glance. We prefer to do this rather than use bold type for the significant changes. The journal may decide to change it if we reach the typesetting stage and we would rather keep it if possible.

15. Section 3.4/Fig 3: *why stop at 300hPa? It would be of interest to go higher, e.g. to 100hPa.*

**Response:** We have re-plotted Figure 3 to 100 hPa (as suggested by the reviewer) and it makes no difference to our statements/conclusions in the paper. We have included the new version that goes to 100 hPa in the revised version of the document. It is also included at the bottom of this response for reference.

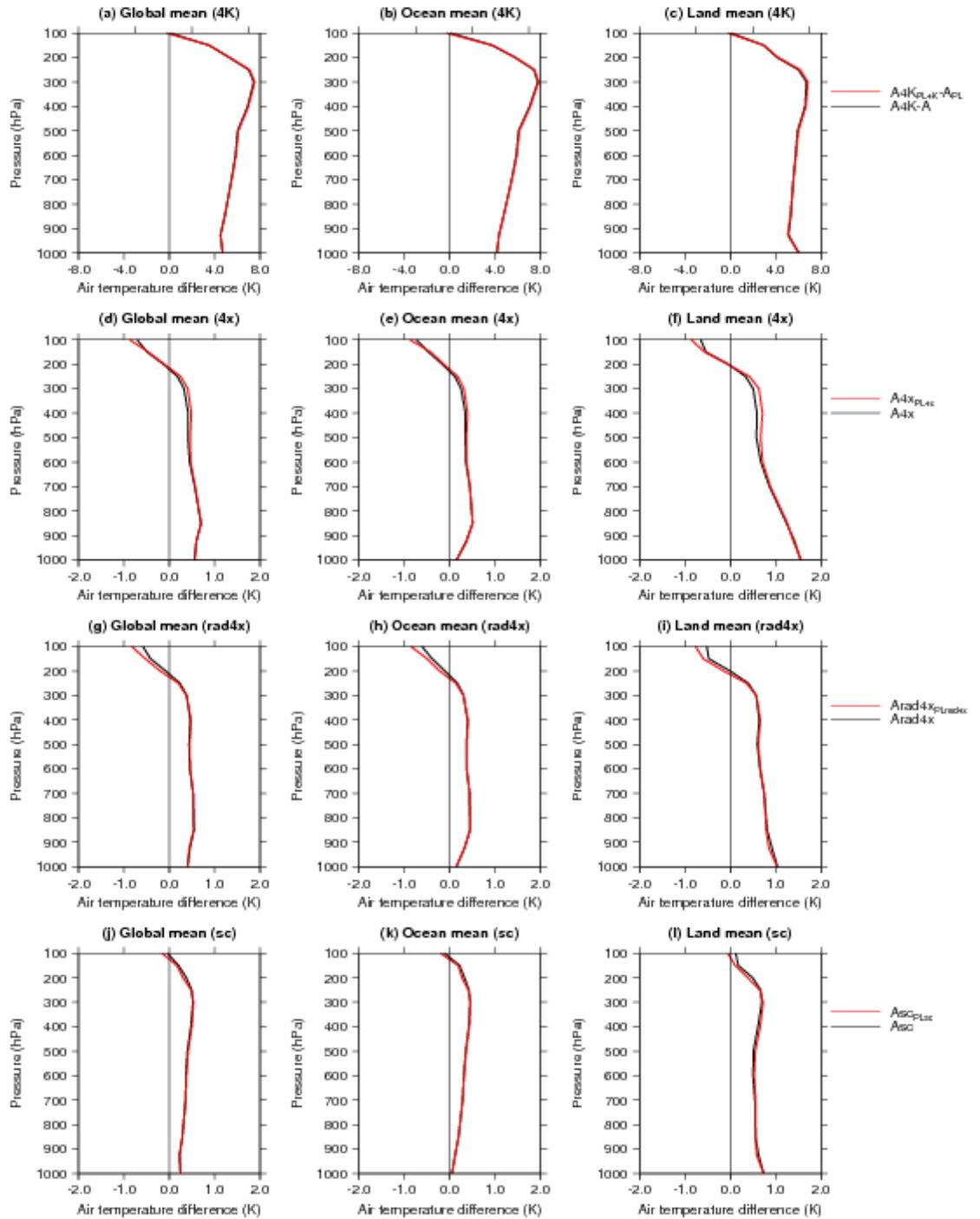
16. P15, last line: *spell out what a land/sea contrast of 0.25 means: Delta T ocean/Delta T land? See also line 9 on p16.*

**Response:** We have included a footnote at the first mention of the land/sea contrast that reads: "The global mean change in TAS over land divided by the global mean change in TAS over the ocean as done by Sutton et al. (2007)."

17. *Fig 4. Can you put a heading over each column to help summarise for the reader? E.g. LHS could say "Land fixed, but changes to SST, CO2, stomates, SC", RHS could say "Land changes, isolated from prescribed land experiments" or similar. This would help the reader get their head around the complexity of these combinations.*

**Response:** We have included an annotation above each column with the left side saying, "AMIP land, perturbed boundary conditions" and the right side saying, "Land from perturbed boundary conditions, AMIP atmosphere/SST/solar constant".

FIGURE



**New version of Figure 3:** Differences (relative to A or AP L — see key for each row) in global mean (column 1), ocean-only mean (column 2) and land-only mean (column 3) air temperature (K) for (a)–(c) the A4K experiments, (d)–(f) the A4x experiments, (g)–(i) Arad4x experiments and (j)–(l) the Asc experiments, respectively.

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# An ensemble of AMIP simulations with prescribed land surface temperatures

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**Abstract.** General circulation models (GCMs) are routinely run under Atmospheric Modelling Intercomparison Project (AMIP) conditions with prescribed sea surface temperatures (SSTs) and sea ice concentrations (SICs) from observations. These AMIP simulations are often used to evaluate the role of the land and/or atmosphere in causing the development of systematic errors in such GCMs. Extensions to the original AMIP experiment have also been developed to evaluate the response of the global climate to increased SSTs (prescribed) and carbon-dioxide (CO<sub>2</sub>) as part of the Cloud Feedback Model Intercomparison Project (CFMIP). None of these international modelling initiatives has undertaken a set of experiments where the land conditions are also prescribed, which is the focus of the work presented in this paper. Experiments are performed initially with freely-varying land conditions (surface temperature and, soil temperature and moisture) under five different configurations (AMIP, AMIP with uniform 4 K added to SSTs, AMIP SST with quadrupled CO<sub>2</sub>, AMIP SST and quadrupled CO<sub>2</sub> without the plant stomata response, and increasing the solar constant by 3.3%). Then, the land surface temperatures from the free-land experiments are used to perform a set of “AMIP-prescribed land” (PL) simulations, which are evaluated against their free-land counterparts. The PL simulations agree well with the free-land experiments, which indicates that the land surface is prescribed in a way that is consistent with the original free-land configuration. Further experiments are also performed with different combinations of SSTs, CO<sub>2</sub> concentrations, solar constant and land conditions. For example, SST and land conditions are used from the AMIP simulation with quadrupled CO<sub>2</sub> in order to simulate the atmospheric response to increased CO<sub>2</sub> concentrations without the surface temperature changing. The results of all these experiments have been made publicly available for further analysis. The main aims of this paper are to provide a description of the method used and an initial validation of these AMIP-prescribed land experiments.

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## 1 Introduction

In order to evaluate the atmosphere and land modules of general circulation models (GCMs), simulations can be run under “Atmospheric Model Intercomparison Project” (AMIP) specifications (Gates, 1992; Gates et al., 1999). Typically, both sea surface temperatures (SSTs) and sea ice concentrations (SICs) are prescribed from observations over some reference period (e.g. 1979–2014 in the Coupled Model Intercomparison Project Phase 6—CMIP6—experiment, see Eyring et al., 2016) with the atmosphere and land allowed to respond freely to the SST and SIC field. Such AMIP simulations help to understand the role of the atmosphere and/or land in the development of model errors. Further to the standard AMIP experiments, quadrupled CO<sub>2</sub> (amip4xCO<sub>2</sub>) and spatially uniform 4K SST increase (amip4K) experiments were incorporated as part of CMIP5 (see Taylor et al., 2012) by the Cloud Feedback Model Intercomparison Project (CFMIP, Bony et al., 2011). The amip4xCO<sub>2</sub> experiment was designed to identify the “rapid cloud response” to increased CO<sub>2</sub> and the amip4K experiment was intended to investigate the impact of the dynamical response of the atmosphere (to the higher SST) on cloud feedbacks (Bony et al., 2011). The CFMIP experiments have also been used to examine the regional precipitation response to both CO<sub>2</sub> forcing and higher SSTs (e.g. Bony et al., 2013; Chadwick et al., 2014; He and Soden, 2015). The amip4xCO<sub>2</sub> and amip4K experiments are also included in CMIP6 (see Webb et al., 2017). While the AMIP experiments described above are designed to investigate the response of the land and the atmosphere to the imposed SST and CO<sub>2</sub> conditions, there is scope to further isolate the response of the atmosphere by prescribing the land conditions too. Such a method of prescribing the land has not been attempted (to our knowledge) as part of the CFMIP/CMIP initiative; however, there are several key issues from the CFMIP and CMIP6 experiments that could at least be partially addressed by running a set of AMIP simulations with prescribed land conditions, for example:

- (1) How does the Earth system respond to forcing and what is the role of the land in that response? (Adapted from Eyring et al., 2016)
- (2) How can the understanding of circulation and regional scale precipitation (particularly over the land) be improved? (Adapted from Webb et al., 2017)

Prescribing global surface temperatures (including the land) in order to, for example, suppress the surface response to a radiative forcing is not a new idea. Such an approach has previously been used to understand the strength of coupling between the land and atmosphere in GCMs (Koster et al., 2002). In another example, Shine et al. (2003) prescribed land temperatures in order to estimate the climate sensitivity parameter of an intermediate complexity GCM in a variety of greenhouse gas and aerosol forcing experiments. Furthermore, a better estimate of the radiative forcing from e.g. quadrupling CO<sub>2</sub> may be attained from GCMs by fixing land surface temperatures as the changes in land temperature can change the atmosphere (e.g. circulation, clouds and precipitation) in a manner that can affect the simulated global radiation balance (Andrews et al., 2012a, 2015). Unfortunately, the method of prescribing land temperatures (as well as SSTs) has not been developed widely for use in

multinational modelling efforts (such as CMIP) and has only been used in one-off idealised modelling experiments such as those described by Dommenges (2009) and Ackerley and Dommenges (2016).

Work by Bayr and Dommenges (2013) used the prescribed land temperature experiments from Dommenges (2009) and data from the CMIP3 experiment to show that higher land temperatures (and specifically increasing the land-sea thermal contrast) is an important driver of circulation change under global warming. However, there are many different mechanisms/forcing agents that can cause the land surface temperatures to increase (or decrease), which may also have an impact on the global circulation. For example, land surface temperatures increase by more than 4 K in amip4k-type experiments (e.g. Joshi et al., 2008), which indicates that land temperatures can change substantially in response to changes in SSTs. Land temperatures also increase directly in response to increased CO<sub>2</sub> concentrations, which cause increased downwelling long-wave radiation and cloud adjustments (~~Dong et al., 2009; Cao et al., 2012~~) (Dong et al., 2009; Cao et al., 2012; Tobias and Bjorn, 2014). This increase in land temperatures forms part of the direct CO<sub>2</sub> effect, which drives both global (Allen and Ingram, 2002) and regional (~~Bony et al., 2013; Chadwick et al., 2014; Merlis, 2015~~) (Bony et al., 2013; Chadwick et al., 2014; Merlis, 2015; He and Soden, 2017) precipitation responses; however it is currently unclear how much of this effect is due to increases in atmosphere or land temperatures. To complicate matters further over the land, the degree of land surface warming and precipitation change are also sensitive to the physiological response of plant stomata, which close as CO<sub>2</sub> concentrations increase and thereby reduce evapotranspiration and precipitation locally (Doutriaux-Boucher et al., 2009; Boucher et al., 2009; Andrews et al., 2011). Finally, land surface temperatures (and therefore circulation and precipitation) also respond to changes in insolation (e.g. the “abrupt Solar-fixed SST” experiments in Chadwick et al., 2014; Andrews et al., 2012b). ~~Given that all of the different~~ All of the forcing agents outlined above have ~~very~~ different impacts on land temperatures and ~~the global circulation (and precipitation), both~~ the global and regional climate. Therefore it would be useful to quantify the separate contributions of the land (~~temperature and soil moisture~~), the atmosphere (e.g. increased long-wave absorption), plant physiology and SSTs ~~to the circulation change separately (and any other aspects of regional and global climate change)~~ in the global and regional climate response. Prescribed land experiments could achieve this and the modelling framework developed by Ackerley and Dommenges (2016) for the Australian Community Climate and Earth System Simulator (ACCESS) provides an opportunity to do so. There is also scope to provide a platform to share the results with the wider scientific community through the Australian National Computing Infrastructure (NCI) and the ARC Centre of Excellence for Climate System Science (ARCCSS).

The main aim of this study is to describe and validate a set of AMIP simulations ~~run with freely varying land conditions~~ against those with prescribed land conditions ~~and observational datasets~~. This study also presents an evaluation of ~~further~~ experiments that employ different combinations of land conditions with the different SST, CO<sub>2</sub> and insolation specifications. Finally (and most importantly), the study provides information on where these data can be accessed for others to use.

The model used, experimental outline and reference datasets are given in Section 2, including a description of how the land datasets were generated. In Section 3, the AMIP simulations with prescribed land are then validated against the original AMIP (freely varying land) simulations from which the land conditions were taken. The results of the AMIP simulations with different combinations of land conditions, SSTs, CO<sub>2</sub> concentrations and the solar constant are described in Section 4.1. The results of uniformly increasing the land surface temperatures alone by 4 K and, raising both the land surface and sea surface

temperatures by 4 K are discussed in Section 4.2. The summary, concluding remarks and future work (e.g. further development opportunities) are given in Section 5.

## 2 Model, experiments and reference datasets

### 2.1 Model

#### 5 2.1.1 General background

The GCM used in this study is the Australian Community Climate and Earth System Simulator (primarily ACCESS1.0) in an atmosphere-only configuration, which is identical to that used in Ackerley and Dommenges (2016). The version of ACCESS1.0 used here has a horizontal grid spacing of 3.75° (longitude) x 2.5° (latitude) and 38 vertical levels. Parameterized processes include precipitation, cloud, convection, radiative transfer, boundary layer processes and aerosols. The representation of the  
10 land surface and soil processes is of primary relevance to this study, which is simulated by the Met Office Surface Exchange Scheme (MOSES, Cox et al., 1999; Essery et al., 2001). Sub-grid scale surface heterogeneity is represented by splitting the grid box into smaller 'tiles' of which there are nine different types specified. Tiles may be vegetated (e.g. grasses) or non-vegetated (e.g. bare soil) and the tiles within a grid box can comprise any fractional combination of the surface types. Surface variables (such as temperature, long-wave and short-wave radiation, and latent and sensible heat fluxes) are calculated for each  
15 tile individually and then summed to give a representative grid box mean value, which is passed back into the main model. Also of relevance is the representation of soil properties (i.e. soil moisture and temperature), which is simulated over four vertical layers (0.1, 0.25, 0.65 and 2 m deep). The model code is available by following the instructions in the *Code and data availability* Section.

#### 2.1.2 Prescribing land temperatures

20 The land surface temperatures are prescribed using the same method described in Ackerley and Dommenges (2016)—the reader is directed there for more in-depth discussion. Nevertheless, the calculation of the surface temperature in the free land simulations (i.e. land surface temperature and, soil moisture and temperature are allowed to vary freely) and the code changes made to prescribe it are discussed here. ~~An~~

In the free land experiments, an initial estimate of the land surface temperature is calculated from the existing surface  
25 conditions using:

$$T_* = T_s + \frac{1}{A_*} \left[ R_s - H - \lambda E + \frac{C_c}{\Delta t} (T_*^{prev} - T_s) \right] \quad (1)$$

where the temperature of the first soil layer from the previous time step is denoted as  $T_s$  (K),  $A_*$  is the coefficient for converting fluxes into temperature in this instance ( $\text{W m}^{-2} \text{K}^{-1}$ ),  $R_s$  is the net radiation into the surface (both long-wave and short-wave,  $\text{W m}^{-2}$ ),  $H$  is the surface sensible heat flux ( $\text{W m}^{-2}$ ),  $\lambda E$  is the latent heat flux ( $\text{W m}^{-2}$ ),  $C_c$  is the areal heat  
30 capacity of the surface ( $\text{J m}^{-2} \text{K}^{-1}$ ),  $\Delta t$  is the length of the time step (s) and  $T_*^{prev}$  is the surface temperature from the time

step before the current time (K). The value of  $T_*$  from Eq. 1 is then adjusted implicitly within the model depending upon the moisture availability and changes of state such that:

$$\Delta T_{*EVAP} = -\frac{\Delta H + \Delta(\lambda E)}{A_*} \quad (2)$$

$$5 \quad T_* = T_{*Eq.1} + \Delta T_{*EVAP} \quad (3)$$

A land surface temperature increment due to evaporation (Eq. 2— $\Delta T_{*EVAP}$ , K) is calculated from the adjustments to the sensible heat flux ( $\Delta H$ ,  $W m^{-2}$ ) and the latent heat flux ( $\Delta(\lambda E)$ ,  $W m^{-2}$ ) that are made after diagnosing the moisture availability. The temperature increment is then simply added to the value of  $T_*$  calculated in Eq. 1 (i.e.  $T_{*Eq.1}$ , K) via Eq. 3. If there is no snow present then  $T_*$  is unchanged for the rest of the time step at that land point. If however, snow is present on the land surface then the temperature is adjusted further to account for any snow melt ( $\Delta T_{*MLT}$ , K) and is again simply added to the value calculated in Eq. 3 by the following:

$$T_* = T_{*Eq.3} + \Delta T_{*MLT} \quad (4)$$

More details on these equations (i.e. Eqs. 1–4) can be found in the relevant papers that describe the MOSES module (i.e. Essery et al., 2001; Cox et al., 1999).

15 When the surface temperatures are prescribed, Eq. 1 is simply changed to be:

$$T_* = T_{PRES} \quad (5)$$

Where  $T_{PRES}$  is the input, prescribed temperature (K) field (discussed in Section 2.2.2, below). Furthermore, the increments calculated in Eqs. 2–4 are set to zero so that the surface temperature cannot change implicitly within the time step. The surface radiation budget therefore only depends upon  $T_{PRES}$ .

20 It is also worth noting here that the existing ACCESS model code has the option for prescribing deep soil temperatures and soil moisture content. When the soil temperatures and moisture are prescribed (as stated in the experiments below), that option is switched on in the code and soil moisture and deep soil temperatures are set from an input field as outlined in the experiments below.

## 2.2 AMIP simulations

25 All experiments undertaken in this study are summarised in Table 1 for ease of reference. More details on these simulations are given in Sections 2.2.1, 2.2.3, 2.2.4 and 2.2.5, below.

### 2.2.1 "Free land" simulations

The following simulations are undertaken with freely varying land conditions ("land conditions" refers to surface temperature, soil temperature and soil moisture from here on), i.e. Eqs. 1–4 are used by the model.

**Table 1.** A summary of the experimental specifications. In the sea surface temperature (SST) column, A refers to SSTs from the AMIP run and A4K to those of the AMIP+4K (A4K) run. 'FREE' refers to freely varying land temperatures and soil moisture. Plant physiology is set to 'ON' when vegetation responds to CO<sub>2</sub> changes and 'OFF' when it uses the default value (346 ppmv) i.e. only atmospheric radiation responds to higher CO<sub>2</sub>. Experiments are ordered following the descriptions in Sections 2.2.1, 2.2.3, 2.2.4 and 2.2.5.

| Run I.D. [run length: years]                             | SST                | Land Conditions | CO <sub>2</sub> [ppmv] | Plant Physiology | Solar Constant [W m <sup>-2</sup> ] |
|--|--------------------|-----------------|------------------------|------------------|-------------------------------------|
| Free land simulations                                    |                    |                 |                        |                  |                                     |
| (Section 2.2.1).   |                    |                 |                        |                  |                                     |
| A [30]   | A                  | FREE            | 346                    | ON               | 1365                                |
| A4K [30]   | A4K (i.e. AMIP+4K) | FREE            | 346                    | ON               | 1365                                |
| A4x [30]   | A                  | FREE            | 1384                   | ON               | 1365                                |
| Arad4x [30]  | A                  | FREE            | 1384                   | OFF              | 1365                                |
| Asc [30]   | A                  | FREE            | 346                    | ON               | 1410.7                              |
| Prescribed land simulations                              |                    |                 |                        |                  |                                     |
| (Section 2.2.3).   |                    |                 |                        |                  |                                     |
| A <sub>PL</sub> [29]                                     | A                  | A               | 346                    | ON               | 1365                                |
| A4K <sub>PL4K</sub> [29]                                 | A4K                | A4K             | 346                    | ON               | 1365                                |
| A4x <sub>PL4x</sub> [29]                                 | A                  | A4x             | 1384                   | ON               | 1365                                |
| Arad4x <sub>PLrad4x</sub> [29]                           | A                  | Arad4x          | 1384                   | OFF              | 1365                                |
| Asc <sub>PLsc</sub> [29]                                 | A                  | Asc             | 346                    | ON               | 1410.7                              |
| Single forcing experiments                               |                    |                 |                        |                  |                                     |
| (Section 2.2.4).   |                    |                 |                        |                  |                                     |
| A4K <sub>PL</sub> [29]                                   | A4K                | A               | 346                    | ON               | 1365                                |
| A <sub>PL4K</sub> [29]                                   | A                  | A4K             | 346                    | ON               | 1365                                |
| A4x <sub>PL</sub> [29]                                   | A                  | A               | 1384                   | ON               | 1365                                |
| A <sub>PL4x</sub> [29]                                   | A                  | A4x             | 346                    | ON               | 1365                                |
| Arad4x <sub>PL</sub> [29]                                | A                  | A               | 1384                   | OFF              | 1365                                |
| A <sub>PLrad4x</sub> [29]                                | A                  | Arad4x          | 346                    | OFF              | 1365                                |
| Asc <sub>PL</sub> [29]                                   | A                  | A               | 346                    | ON               | 1410.7                              |
| A <sub>PLsc</sub> [29]                                   | A                  | Asc             | 346                    | ON               | 1365                                |
| Uniform surface temperature experiments (Section 2.2.5). |                    |                 |                        |                  |                                     |
| A4K <sub>PLU4K</sub> [29]                                | A4K                | A+4K            | 346                    | ON               | 1365                                |
| A <sub>PLU4K</sub> [29]                                  | A                  | A+4K            | 346                    | ON               | 1365                                |

- (1) AMIP run: An AMIP run using prescribed, observational SSTs and sea ice concentrations from 1979 to 2008 (30 years long). CO<sub>2</sub> concentrations are set to 346 ppmv and, sulphur dioxide, soot and biomass burning aerosol emissions are representative of those for the year 2000 C.E. Land conditions are allowed to vary freely. The experiment is denoted as **A** from here on.
- 5 (2) AMIP4K run: The same as A but a uniform 4 K added to the SST field (denoted as **A4K** from here on).
- (3) AMIP4xCO<sub>2</sub> run: The same as A but CO<sub>2</sub> is quadrupled to 1384 ppmv (denoted as **A4x** from here on).
- (4) AMIP4xCO<sub>2</sub> no plant physiological response i.e. radiative (rad) only: The same as A4x but the plant physiological response to CO<sub>2</sub> is switched off (as described in Andrews et al., 2011; Boucher et al., 2009; Doutriaux-Boucher et al., 2009, and denoted as **Arad4x** from here on). [This is done by setting the CO<sub>2</sub> concentration used in the photosynthesis calculation in the vegetation scheme to 346 ppmv but allowing the radiation scheme to ‘see’ the quadrupled value \(i.e. 1384 ppmv\).](#)
- 10 [This is done by setting the CO<sub>2</sub> concentration used in the photosynthesis calculation in the vegetation scheme to 346 ppmv but allowing the radiation scheme to ‘see’ the quadrupled value \(i.e. 1384 ppmv\).](#)
- (5) AMIP +3.3% solar constant: The same as A except the solar constant is increased by ~3.3% to 1410.7 W m<sup>-2</sup> as done by Andrews et al. (2012b), which gives a similar sized radiative forcing to the 4xCO<sub>2</sub> experiments (denoted as **Asc** from here on).
- 15 All AMIP simulations were initialised with conditions from 1<sup>st</sup> October 1978 and run until the end of December 2008.

### 2.2.2 Specifications for generating the prescribed land conditions

In order to generate the necessary fields to prescribe the land conditions, instantaneous values of the surface temperature on each tile and, soil temperature and moisture (on each soil level) are output every three hours from experiments (1)–(5) above. In the “prescribed land” simulations, the land conditions are read in by the model every 3 hours and updated (by interpolation) every hour (two time steps). Furthermore, land conditions from the first 15 months of the AMIP free land simulations are not used (i.e. the prescribed land simulations are run from January 1980 to December 2008, inclusive) to ensure that no impacts from the land scheme “spinning up” are included in the prescribed runs. The surface temperature, soil moisture and soil temperatures are all prescribed every 3 hours for the whole period 1980–2008 to minimise the differences between free and prescribed land simulations. The interpolated, 3-hourly data are used instead of time step (30 minute) data due to limitations of reading in such large datasets in the current ACCESS1.0 framework. The prescribed land conditions experiments will therefore not be identical to the free land simulations. Nevertheless, earlier work by Ackerley and Dommenges (2016) note that a simulation with temperatures updated each time step is “almost climatologically indistinguishable” from another using 3-hourly data. Therefore, corresponding free and prescribed land simulations should be climatologically alike, which is evaluated in Section 3. Finally, land surface temperatures are not prescribed over [both the permanent ice sheets \(Antarctica and Greenland\) to avoid the development of negative temperature biases that are discussed in Ackerley and Dommenges \(2016\)](#) (Antarctica and Greenland, to avoid the development of negative temperature biases that are discussed in Ackerley and Dommenges, 2016) [and within/on sea ice](#). The impact of not specifying the ~~land temperatures under~~ [temperatures over](#) the ice sheets [or sea ice](#)

20  
25  
30

[temperature](#) is likely to be negligible ~~and is discussed in Section 3~~ (see [Section 3](#)). The input data fields are available by following the instructions in the *Code and data availability* Section.

### 2.2.3 AMIP prescribed land simulations

All simulations that have prescribed land conditions are denoted with a "PL". The AMIP prescribed land simulations use Eq. 5 instead of Eq. 1, both  $\Delta T_{*EVAP}$  and  $\Delta T_{*MLT}$  set to zero and, the following boundary conditions are used:

- (6) AMIP prescribed land run: The same as A except land conditions are also prescribed from A. Experiment is denoted as **A<sub>PL</sub>** from now.
- (7) AMIP4K prescribed land run: As A4K except land conditions are prescribed using the output from A4K. Experiment denoted as **A4K<sub>PL4K</sub>** from now.
- 10 (8) AMIP4xCO<sub>2</sub> prescribed land run: As A4x except land conditions are prescribed using the output from A4x. Experiment is denoted as **A4x<sub>PL4x</sub>** from now.
- (9) AMIP4xCO<sub>2</sub> no plant physiological response prescribed land run: As Arad4x except land conditions are prescribed using the output from Arad4x. Experiment is denoted as **Arad4x<sub>PLrad4x</sub>** from now.
- 15 (10) AMIP +3.3% solar constant prescribed land run: As Asc except land conditions are prescribed using the output from Asc. Experiment is denoted as **Asc<sub>PLsc</sub>** from now.

### 2.2.4 Combinations of AMIP land and ocean conditions (“combined” experiments)

In these experiments, different combinations of land, SST, atmospheric CO<sub>2</sub> and solar irradiance boundary conditions are used. These experiments were designed to single out the impact of the land response to a forcing on the atmosphere or the impact of that forcing agent without the land responding. Again (as in Section 2.2.3), Eq. 5 instead of Eq. 1 and, both  $\Delta T_{*EVAP}$  and  $\Delta T_{*MLT}$  are set to zero for these simulations. The boundary conditions used in these experiments are:

- (11) SST field from A4K and land conditions from A. From now, denoted as **A4K<sub>PL</sub>**.
- (12) SST field from A and land conditions from A4K. From now, denoted as **A<sub>PL4K</sub>**.
- (13) SST and land conditions from A with CO<sub>2</sub> concentrations the same as in A4x. From now, denoted as **A4x<sub>PL</sub>**.
- (14) SST and CO<sub>2</sub> concentrations the same as A and land conditions from A4x. From now, denoted as **A<sub>PL4x</sub>**.
- 25 (15) SST and CO<sub>2</sub> concentrations (no plant response) from Arad4x and land conditions from A. From now, denoted as **Arad4x<sub>PL</sub>**.
- (16) SST and CO<sub>2</sub> concentrations the same as A and land conditions from Arad4x. From now, denoted as **A<sub>PLrad4x</sub>**.

(17) SST and land conditions from A and solar constant as in Asc. From now, denoted as  $\mathbf{A}_{scPL}$ .

(18) SST and land conditions from Asc and solar constant as in A. From now, denoted as  $\mathbf{A}_{PLsc}$ .

### 2.2.5 Uniform surface temperature perturbation (“uniform” experiments)

An extra two experiments are undertaken to identify the impact of applying a uniform increase in temperature over the land only (analogous to the AMIP4K SST experiment but for the land) and a uniform global increase in surface temperature (i.e. global warming with minimal land-sea contrast). As in Sections 2.2.3 and 2.2.4, Eq. 5 is used instead of Eq. 1 and, both  $\Delta T_{*EVAP}$  and  $\Delta T_{*MLT}$  set to zero for these simulations. The boundary conditions used in these experiments are:

(19) Uniform increase in land surface temperatures from A by 4 K and SST field from A4K. From now, denoted as  $\mathbf{A4K}_{PLU4K}$ .

(20) Uniform increase in land surface temperatures from A by 4K and SST field from A. From now, denoted as  $\mathbf{A}_{PLU4K}$ .

10 In both experiments (19) and (20), soil temperatures and moisture are prescribed from the A experiment.

### 2.3 Reference datasets

ERA-Interim ([ERA-I](#)) data are taken from 1980–2008 (Dee et al., 2011) for both the surface air temperature (TAS) and pressure at mean sea level (PSL) for comparison with the A and  $A_{PL}$  simulations. ~~ERA-Interim~~[ERA-I](#) reanalysis data have been used to evaluate TAS globally for the 5<sup>th</sup> Coupled Model Intercomparison Project (Flato et al., 2013). ~~ERA-Interim~~[ERA-I](#) data provide 15 a globally complete (unlike surface observations which are heterogeneously spread), observationally constrained (as is PSL) dataset for comparison with the simulations in this study. Furthermore, there is good agreement between reanalysis-derived TAS and gridded data from station-based estimates (Simmons et al., 2010), which suggests the ~~ERA-Interim~~[ERA-I](#) derived TAS is a reliable dataset.

For precipitation, the Climate Prediction Centre Merged Analysis of Precipitation (CPC CMAP Xie and Arkin, 1997; 20 Arkin et al., 2018) data, for the years 1980–2008 inclusive, are used. The CMAP data are derived from a combination of satellite-based instruments. It is important to note that, while there are biases in any reference dataset and others could be used (e.g. GPCP or CMORPH for rainfall, see Adler et al., 2003; Joyce et al., 2004, respectively), the focus of the paper is not to explore the model biases themselves. The reference datasets are simply used to show that there is no negative impact on the simulated climate (relative to the free land simulations) when the land conditions are prescribed.

## 25 3 Verification of the AMIP prescribed land runs

### 3.1 Surface air temperature: TAS

The difference (~~A-ERA-Interim~~[A minus ERA-I](#)) in grid-point mean (averaged over all simulated years) TAS is plotted in Fig. 1(a). Positive anomalies ( $\sim 0.5$  K) are visible over many ocean basins but the largest differences are over the land ( $> 1$  K magnitude over North Africa, Antarctica and the Himalaya). Nevertheless, the temperature biases in Fig. 1(a) are consistent

with those presented in Flato et al. (2013) from the CMIP5 multi-model mean (their Fig. 9.2(b)) and the global mean RMSD of 1.68 K (Table 2) is also comparable to the mean absolute grid-point errors of 1–3 K also given in Flato et al. (2013) (their Fig. 9.2(c)). The largest model errors primarily occur in the regions that have the largest uncertainties in the ~~ERA-Interim~~ ERA-Interim-ERA-Interim ~~ERA-Interim-ERA-Interim~~ ERA-Interim-ERA-Interim TAS dataset (e.g. North Africa, Antarctica and the Himalaya— Flato et al., 2013, their Fig. 9.2(d)). Finally, the pattern correlation between A and ~~ERA-Interim-ERA-Interim~~ ERA-Interim-ERA-Interim fields is approximately 1 (Table 2), which indicates that relatively low and high surface temperatures are simulated in the correct geographical locations. Overall therefore, the TAS field in the ACCESS1.0 AMIP simulation (and the biases) are consistent with those of other models.

The difference in TAS for  $A_{PL}$  relative to A is plotted in Fig. 1(b). It is immediately obvious that the differences in TAS<sup>1</sup> between  $A_{PL}$  and A are much smaller than those between A and ~~ERA-Interim-ERA-Interim~~ ERA-Interim-ERA-Interim (Fig. 1(a)). There are also very few places where the differences are statistically significant in Fig. 1(b) and the largest changes are at high-latitudes where sea ice is located (sea ice temperatures are not prescribed). Furthermore, the RMSD is much larger between A and ~~ERA-Interim-ERA-Interim~~ ERA-Interim-ERA-Interim than between  $A_{PL}$  and A (1.69 K and 0.13 K, respectively in Table 2). Overall, in terms of TAS, the A and  $A_{PL}$  simulations are climatologically very similar such that the inter-model differences are much smaller than the model-reanalysis differences.

Each of the "prescribed land" (PL) simulations ( $A4K_{PL4K}$ ,  $A4x_{PL4x}$ ,  $Arad4x_{PLrad4x}$  and  $Asc_{sc}$ , described in Section 2.2.3) are compared with their corresponding free land simulations ( $A4K$ ,  $A4x$ ,  $Arad4x$  and  $Asc$ , respectively, Section 2.2.1) in order to validate them. The differences in TAS are non-significant over the vast majority of the globe for the prescribed versus free land simulations (Figs. 1(c)–(f)). Moreover, the RMSD between each experiment pair is 0.11 K with pattern correlations of unity or close to unity (see Table 2). Therefore, the values of TAS in the  $A4K_{PL4K}$ ,  $A4x_{PL4x}$ ,  $Arad4x_{PLrad4x}$  and  $Asc_{PLsc}$  runs are almost climatologically indistinguishable from those of  $A4K$ ,  $A4x$ ,  $Arad4x$  and  $Asc$ , respectively (as intended).

In order to ~~further~~ validate whether the ~~PL simulations adequately reproduce the climate of climate responses in the prescribed land simulations are consistent with~~ their free land counterparts ~~under different boundary conditions for a given boundary forcing~~ (i.e. SST+4K, 4xCO<sub>2</sub> and +3.3% insolation), the differences in TAS between corresponding free and prescribed land pairs (e.g. [ $A4K_{PL4K}$  ~~-A~~ minus  $A_{PL}$ ] ~~-minus~~ [~~A4K-A~~  $A4K$  minus A]) are plotted in Figs. 2(a)–(d). Furthermore, the RMSD and pattern correlations for the differences in TAS between those corresponding prescribed and free land pairs are given in Table 3. Pattern correlations are proximately 1 for all experiment pairs (Table 3). Furthermore, the RMSD values are <0.1 K, which is a similar magnitude to the differences plotted in Fig. 1(c)–(f) and smaller than the differences in TAS associated with each change in boundary condition (see Figs. S1(a)–(d) and S2(a)–(d), Supplementary Material). Therefore, the changes in TAS for  $A4K_{PL4K}$ ,  $A4x_{PL4x}$ ,  $Arad4x_{PLrad4x}$  and  $Asc_{PLsc}$  relative to  $A_{PL}$  are almost identical to those of  $A4K$ ,  $A4x$ ,  $Arad4x$  and  $Asc$  relative to A (compare Figs. S1(a)–(d) and S2(a)–(d), Supplementary Material). Overall, the responses of TAS to the perturbed SST, CO<sub>2</sub> and insolation in the prescribed land simulations are very similar to those in the free land simulations.

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<sup>1</sup>Note: the calculation of TAS is performed by interpolating between the surface temperature and that of the lowest model level in ACCESS1.0, therefore changes in the temperature at level 1 may also change TAS even if surface temperatures are unchanged.

**Table 2.** The area-weighted root-mean-squared-differences (RMSD) and pattern correlations (PC) for surface air temperature (TAS), precipitation (PR) and mean sea level pressure (PSL) for the A and  $A_{PL}$  simulations relative to the "observational" (OBS) reference datasets (rows 2 and 3). Rows 4–8: the RMSDs and PCs for each "prescribed land" simulation relative to its counterpart "free land" simulation (experiment names defined in Section 2).

| Difference between                      | RMSD TAS (K) | PC TAS | RMSD PR (mm day <sup>-1</sup> ) | PC PR | RMSD PSL (hPa) | PC PSL |
|---|--------------|--------|---------------------------------|-------|----------------|--------|
| A <u>minus</u> OBS                      | 1.68         | ≈1     | 1.25                            | 0.92  | 2.40           | ≈1     |
| $A_{PL}$ <u>minus</u> OBS               | 1.69         | ≈1     | 1.26                            | 0.92  | 2.48           | ≈1     |
| $A_{PL}$ <u>minus</u> A                 | 0.13         | 1.00   | 0.28                            | ≈1    | 0.45           | 1.00   |
| A4K $_{PL4K}$ <u>minus</u> A4K          | 0.11         | ≈1     | 0.27                            | ≈1    | 0.31           | ≈1     |
| A4x $_{PL4x}$ <u>minus</u> A4x          | 0.11         | 1.00   | 0.30                            | 0.99  | 0.44           | 1.00   |
| Arad4x $_{PLrad4x}$ <u>minus</u> Arad4x | 0.11         | ≈1     | 0.27                            | ≈1    | 0.31           | ≈1     |
| Asc $_{PLsc}$ <u>minus</u> Asc          | 0.11         | 1.00   | 0.28                            | ≈1    | 0.47           | 1.00   |

"≈1" implies that the correlation coefficient is not unity, but rounds to unity when only two decimal places are considered.

## 3.2 Precipitation: PR

### 3.2.1 Prescribed vs free land experiment pairs

Differences between the A simulation and CMAP precipitation fields are plotted in Fig. 1(g). Precipitation is too high over the western Indian Ocean, the northern Tropical Pacific and within the mid-latitudes of both hemispheres. Conversely, precipitation is too low over the south-western Maritime Continent, central Africa, Amazonia and over the Antarctic. The precipitation biases over the western Indian Ocean and Amazonia are also visible in the CMIP5 multi-model mean (see Fig. 9.4(b) in Flato et al., 2013). The rainfall biases in the remaining regions (listed above) are consistent with those presented in Walters et al. (2011) for HadGEM2-A (the model from which ACCESS1.0 is derived, see Bi et al., 2013). The RMSD is 1.25 mm day<sup>-1</sup> (Table 2) for A relative to CMAP, which is consistent with the values presented for HadGEM2-A by Walters et al. (2011) (2.02 mm day<sup>-1</sup> for JJA and 1.54 mm day<sup>-1</sup> for DJF, relative to GPCP data). Overall, the precipitation biases in the A simulation are consistent with those in other GCMs.

The differences in precipitation between  $A_{PL}$  and A are plotted in Fig. 1(h) and (as with TAS) it is clear that almost none of the differences in precipitation are significant. Furthermore, the RMSD between  $A_{PL}$  and CMAP is almost identical to that of A relative to CMAP and, the RMSD for  $A_{PL}$  relative to A is smaller by almost a factor of five (see Table 2) than relative to CMAP. The pattern correlations between  $A_{PL}$  and A are also approximately equal to one, which shows that regions with relatively high and low precipitation (climatologically) are almost identical in the two respective simulations. Therefore, the differences in PR between  $A_{PL}$  and A are small in terms of the climatological mean.

As with TAS, the differences in PR between other prescribed land simulations (A4K $_{PL4K}$ , A4x $_{PL4x}$ , Arad4x $_{PLrad4x}$  and Asc $_{sc}$ ) and their respective free land runs (4K $_{PL4K}$ , A4x $_{PL4x}$ , Arad4x $_{PLrad4x}$  and Asc $_{sc}$ ) are plotted in Figs. 1(i)–(l). Very

few of the differences in PR are statistically significant; however, there is an increase in precipitation over Amazonia in all of the prescribed land runs relative to their free land counterparts. A similar region of higher precipitation over Amazonia between prescribed and free land simulations is also seen in Ackerley and Dommenges (2016). Given that there is no change in surface temperature or soil moisture (both prescribed) it may be that rainwater is accumulating in the vegetation canopy and being re-evaporated (see Cox et al., 1999). Indeed, there is an increase in the latent heat flux over the region with higher precipitation in all of the prescribed land simulations relative to the free land simulations (see Fig. S3 ~~and Fig. S4~~ which shows the change in canopy water loading for  $A_{PL}$  relative to A—in the Supplementary Material). This is a systematic bias in the prescribed land simulations relative to their free land counterparts; however, the precipitation is approximately 1–2 mm day<sup>-1</sup> higher in the prescribed land runs, which almost exactly offsets the  $\sim 2$  mm day<sup>-1</sup> dry bias for the A simulation relative to CMAP (Fig. 1(g)). Therefore, the prescribed land simulation is closer to the observed estimate than the free land simulation. A more detailed investigation into Amazonian rainfall is beyond the scope of this current general overview and evaluation paper, but such a study may be useful to understand the dry bias over the Amazon in the free land simulations.

As with TAS, the RMSD and pattern correlations for the differences in PR between corresponding prescribed and free land pairs (e.g. [ $A4K_{PLAK}$  ~~A~~ minus  $A_{PL}$ ] ~~minus~~ [~~A4K~~ A4K minus A]) are given in Table 3. The pattern correlations lie between 0.8 and 0.95 (Table 3) for the change in PR between the perturbed PL simulations ( $A4K_{PLAK}$ ,  $A4x_{PLAx}$ ,  $Arad4x_{PLrad4x}$  and  $Asc_{PLsc}$ ) and their free land counterparts ( $A4K$ ,  $A4x$ ,  $Arad4x$  and  $Asc$ ), relative to their respective control simulations ( $A_{PL}$  and  $A$ ). Furthermore, the RMSD values lie in the range 0.22 ~~–0.38~~ –0.38 mm day<sup>-1</sup>, which is a similar magnitude to the differences plotted in Fig. 1(c)–(f) and Figs. 2(e)–(h). Therefore, the differences between corresponding prescribed and free land simulations (e.g.  $A4K_{PLAK}$  and  $A4K$ ) are much smaller than the PR differences caused by the boundary condition changes (see Figs. S1(e)–(h) and S2(e)–(h), Supplementary Material). The lower pattern correlation values and higher RMSDs for PR relative to TAS are likely to be due to TAS being more highly constrained by the prescribed surface temperatures than PR (i.e. TAS is diagnostically calculated from the surface temperature and the temperature of the lowest model level).

For further verification, the changes in global, ocean and land mean precipitation are presented in Table 4. The differences in precipitation between the free land and PL experiment pairs are all the same sign (i.e. corresponding positive or negative) and lie within  $\pm 0.08$  mm day<sup>-1</sup> (i.e. small). The largest difference occurs over land in  $A4K_{PLAK}$  experiment where the increase in precipitation (relative to  $A_{PL}$ ) is statistically significant whereas, for  $A4K$  relative to  $A$ , it is not. The higher precipitation over the Amazon (Fig. 2(e)) is likely to be contributing to the higher land-mean precipitation in  $A4K_{PLAK}$  relative to  $A4K$ . Conversely, the dry bias over the Amazon in the free land simulations may equally be a factor for the muted response of the mean precipitation over land in the  $A4K$  experiment relative to  $A4K_{PLAK}$ . Again, a more detailed investigation into Amazonian rainfall biases is beyond the scope of this study; however, given the sensitivity of this region to model configuration and climate change (see Good et al., 2013) the prescribed land simulation may be a useful tool to investigate Amazon precipitation further. Another point of note is that precipitation increases significantly in the runs without plant physiological responses to CO<sub>2</sub> but does not change in those without (Table 4). In the  $A4x$  and  $A4x_{PL}$  experiments, plant stomata respond to increasing CO<sub>2</sub> by narrowing and thereby reducing moisture availability for precipitation from transpiration. In  $Arad4x$  and  $Arad4x_{PLrad4x}$  however, the stomatal response is switched off and so evapotranspiration can increase in response to land surface warming,

**Table 3.** The area-weighted root-mean-squared-differences (RMSD) and pattern correlations (PC) for the response in the climate to the perturbed boundary conditions (SST+4K, 4xCO<sub>2</sub> and +3.3% solar constant (Section 2) for each "prescribed land" pair relative to the corresponding "free land" pair.

| Difference between   | RMSD TAS (K) | PC TAS | RMSD PR (mm day <sup>-1</sup> ) | PC PR | RMSD PSL (hPa) | PC PSL |
|--|--------------|--------|---------------------------------|-------|----------------|--------|
| (A4K <sub>PLAK</sub> - A <sub>PL</sub> ) - (A4K - A4K - A)             | 0.08         | ≈1     | 0.38                            | 0.92  | 0.45           | 0.96   |
| (A4x <sub>PL4x</sub> - A <sub>PL</sub> ) - (A4x - A4x - A)             | 0.09         | ≈1     | 0.27                            | 0.89  | 0.38           | 0.92   |
| (Arad4x <sub>PLrad4x</sub> - A <sub>PL</sub> ) - (Arad4x - Arad4x - A) | 0.08         | 0.99   | 0.22                            | 0.88  | 0.35           | 0.91   |
| (Asc <sub>PLsc</sub> - A <sub>PL</sub> ) - (Asc - Asc - A)             | 0.08         | 0.99   | 0.25                            | 0.83  | 0.33           | 0.91   |

"≈1" implies that the correlation coefficient is not unity, but rounds to unity when only two decimal places are considered.

as can precipitation. These results are consistent with those of Doutriaux-Boucher et al. (2009), Boucher et al. (2009) and Andrews et al. (2011).

### 3.3 Pressure at mean sea level: PSL

#### 3.3.1 Prescribed vs free land experiment pairs

- 5 The difference in PSL for A relative to ~~ERA-Interim~~ ERAI is plotted in Fig. 1(m) in order to provide a surface-based indication of changes in the atmospheric circulation (as also done in Collins et al., 2013). The RMSD for A relative to ~~ERA-Interim~~ ERAI is 2.4 hPa; however, the pattern correlation is almost unity (see Table 2) and indicates that regions with relatively high and low PSL correspond well. There are several biases in the PSL field, nonetheless. Positive PSL anomalies are visible in A relative to ~~ERA-Interim~~ ERAI over the Arctic (largest anomaly around 90°E), the north Pacific, northern Africa and the Mediterranean
- 10 and, between 30°S–60°S in each ocean basin (see Fig. 1(m)). There are negative anomalies over central and southern Africa, South America, North America and Antarctica. The PSL anomalies though, are consistent with those presented in Martin et al. (2006) (their Fig. 6), who used a higher-resolution (half the grid spacing of ACCESS1.0) version of HadGEM2 (from which ACCESS1.0 is developed—see Bi et al., 2013).

The RMSD (2.48 hPa) and pattern correlations (≈1) for the A<sub>PL</sub> simulation are almost identical to those of A relative to ~~ERA-Interim~~ ERAI. Furthermore, the RMSD between A<sub>PL</sub> and A is 0.45 hPa and the pattern correlation is unity (Table 2),

15 which indicates that the PSL field is reproduced well in the A<sub>PL</sub> simulation relative to A. The main difference in the PSL fields between A<sub>PL</sub> and A occurs over the Arctic (Fig. 1(n)), which is consistent with the lower temperatures there (see Fig. 1(b)). Nevertheless, over the vast majority of the globe, the differences in the simulated PSL field between A<sub>PL</sub> and A are not statistically significant.

- 20 The RMSDs for each of the other corresponding PL and free-land simulations (e.g. A4K<sub>PLAK</sub> versus A4K) lie between 0.3–0.5 hPa with pattern correlations of close to unity (see Table 2). The magnitudes and distribution of PSL in the PL simulations therefore compare well with their free land counterparts (as with A<sub>PL</sub> versus A). In terms of grid-point PSL values, the largest differences occur in the northern and southern polar regions (see Figs. 1(o)–(r)); however, the differences in PSL are not

**Table 4.** The difference in global, land points and sea points mean precipitation,  $\text{mm day}^{-1}$  [%] for each of the specified simulations in rows 1, 5, 9 and 13 (details of each simulation are given in Section 2). Numbers in italics and marked with an asterisk are not statistically significant using the Student's t-test ( $p > 0.05$ ).

|             |   |  |
|-------------|---|--|
| Region      | <del>A4K-A</del> <u>A4K minus A</u>       | A4K <sub>PLAK</sub> <del>A</del> <u>minus A<sub>PL</sub></u>       |
| Global mean | 0.38 [12.33]                              | 0.38 [12.32]   |
| Land mean   | <i>0.01 [0.33]*</i>                       | 0.09 [4.04]  |
| Sea mean    | 0.53 [15.16]                              | 0.50 [14.37]   |
| Region      | <del>A4x-A</del> <u>A4x minus A</u>       | A4x <sub>PL4x</sub> <del>A</del> <u>minus A<sub>PL</sub></u>       |
| Global mean | -0.19 [-6.11]                             | -0.18 [-5.94]  |
| Land mean   | <i>0.00 [-0.14]*</i>                      | <i>0.02 [0.86]*</i>  |
| Sea mean    | -0.27 [-7.52]                             | -0.27 [-7.63]  |
| Region      | <del>Arad4x-A</del> <u>Arad4x minus A</u> | Arad4x <sub>PLrad4x</sub> <del>A</del> <u>minus A<sub>PL</sub></u> |
| Global mean | -0.13 [-4.31]                             | -0.14 [-4.40]  |
| Land mean   | 0.10 [4.80]                               | 0.11 [4.97]  |
| Sea mean    | -0.23 [-6.47]                             | -0.24 [-6.72]  |
| Region      | <del>Ase-A</del> <u>Asc minus A</u>       | Asc <sub>PLsc</sub> <del>A</del> <u>minus A<sub>PL</sub></u>       |
| Global mean | -0.05 [-1.61]                             | -0.05 [-1.66]  |
| Land mean   | 0.15 [7.58]                               | 0.16 [7.51]  |
| Sea mean    | -0.13 [-3.78]                             | -0.14 [-3.93]  |

statistically significant over the vast majority of grid points. Overall, the small differences in the PSL fields between the PL and free land simulations suggest that the simulated, climatological global circulations are very similar.

Again (as with TAS and pr), the RMSD and pattern correlations for the differences in PSL between corresponding prescribed and free land pairs (e.g. [A4K<sub>PLAK</sub> ~~A~~ minus A<sub>PL</sub>] ~~minus~~ [~~A4K-A~~ A4K minus A]) are given in Table 3. The RMSD between the change in PSL associated with each boundary condition perturbation for the PL simulations relative to their free land counterparts lie between 0.33 and 0.45 hPa (Table 3). The largest RMSD for PSL changes (0.45 hPa) occurs in the SST+4K experiments (i.e. [A4K<sub>PLAK</sub> ~~A~~ minus A<sub>PL</sub>] relative to [~~A4K-A~~ A4K minus A]); however, the changes in PSL associated with increasing global SSTs are much larger (approximately  $\pm 3.5$  hPa, see Fig. S2(i), Supplementary Material) than the RMSD. The changes in PSL associated with quadrupling CO<sub>2</sub> are  $\pm 2.5$  hPa (Figs. S2(j) and (k)) are larger than the RMSD between the corresponding prescribed and free land simulations (0.38 hPa and 0.35 hPa, see Table 3). The smallest changes in PSL occur in the increased solar constant simulations (around  $\pm 1.5$  hPa, Fig. S2(l)) and likewise, the lowest RMSD between the PL and free land simulations (0.33 hPa, see Table 3). Finally, the pattern correlations between the PL and free land simulations are all  $> 0.9$  (column 7, Table 3), which shows that the spatial changes in PSL associated with each boundary condition change are

also very similar. The largest grid-point differences in PSL primarily occur in polar regions, where surface temperatures are not prescribed (Figs. 2(i)–(l)); however, the differences in PSL are not statistically significant over the majority of the globe.

### 3.4 Vertical profiles: Global, ocean-only and land-only means

As a final validation, the vertical changes in mean air temperature ( $t_a$ ) associated with the SST+4K, 4xCO<sub>2</sub>, 4xCO<sub>2</sub>rad and +3.3% insolation are plotted for the PL (red lines) and free land (black lines) in Fig. 3. Furthermore, the  $t_a$  profile differences are compared with results from other studies (where available) for further validation of these simulations.

The global, ocean and land mean changes in  $t_a$  for ~~A4K-A~~A4K minus A are almost identical to those of ~~A4K<sub>PLAK</sub>~~-A minus A<sub>PL</sub> (values lie within approximately  $\pm 0.1$  K, see Figs. 3(a)–(c)). Furthermore,  $t_a$  values are higher at all levels from 1000 hPa to ~~200–100~~ hPa, with the largest increase around 300 hPa. Overall, atmospheric dry stability increases as a result of increasing global SST by 4 K both globally and over the ocean with a slight decrease in dry stability over land between approximately 1000 to 500 hPa. The changes to the  $t_a$  profiles in both the PL (~~A4K<sub>PLAK</sub>~~-A minus A<sub>PL</sub>) and free simulations (~~A4K-A~~A4K minus A) agree with those described in Dong et al. (2009) and He and Soden (2015).

The differences in  $t_a$  between the prescribed (red lines) and free (black lines) land for the 4xCO<sub>2</sub> experiments (both with and without plant physiology) are plotted in Figs. 3(d)–(i). As with the SST+4K experiments, the differences between the prescribed and free land simulations are small ( $\sim \pm 0.1$  K) and primarily restricted to the land in the ~~A4x<sub>PLAx</sub>~~ and ~~A4x~~ experiments. The largest ~~changes~~increases in  $t_a$  from quadrupling atmospheric CO<sub>2</sub> occur around 850 hPa for the global and ocean mean regardless of whether the plant physiological response to CO<sub>2</sub> is included or not (Figs. 3(d), (e), (g) and (h)) in agreement with Dong et al. (2009), Kamae and Wanatabe (2013), Richardson et al. (2016) and Tian et al. (2017).

Finally, the  $t_a$  profiles for the 3.3% increase in insolation simulations (~~Asc~~ and ~~Asc<sub>PLsc</sub>~~ relative to ~~A~~ and ~~A<sub>PL</sub>~~, respectively) are plotted in Figs. 3(j)–(l). Again, the differences between the free and prescribed land simulations are small ( $\sim \pm 0.1$  K) and the vertical distribution of  $t_a$  changes are almost identical. Atmospheric dry stability increases globally and over the ocean, with the largest increases in  $t_a$  around 300 hPa (Figs. 3(j) and (k)), which compares well with the model results of Cao et al. (2012). Conversely, air temperatures increase uniformly by approximately 0.8 K from ~~950–500~~950–500 hPa in both the ~~Asc~~ and ~~Asc<sub>PLsc</sub>~~ simulations (Fig. 3(l)) over the land; however, dry static stability increases around 300 hPa (again in agreement with Cao et al., 2012).

Overall, the differences in  $t_a$  between the prescribed and free land simulations are small relative to the changes associated with each boundary condition change. Furthermore, the changes in  $t_a$  in both the prescribed and free land simulations are consistent with those in other studies.

## 4 Surface air temperature changes in the “combined” and “uniform” experiments

Only the changes in surface air temperature are discussed below for each of the “combined” and “uniform” temperature perturbation experiments (outlined in Sections 2.2.4 and 2.2.5, respectively) to verify that the temperature response is consistent

with the imposed boundary conditions. The changes in precipitation and circulation associated with these experiments are to be discussed in a future piece of work (Chadwick et al., in prep.).

#### 4.1 “Combined” experiments

Changes in TAS over the land can be seen in the experiments that use land conditions from the AMIP runs with changed boundary conditions i.e. A4K<sub>PL</sub>, A4x<sub>PL</sub>, Arad4x<sub>PL</sub> and Asc<sub>PL</sub> (Figs. 4(a)–(d)). As the calculation of TAS is performed by interpolating between the surface temperature and that of the lowest model level in ACCESS1.0, changes in the temperature at level 1 will change TAS even if surface temperatures are unchanged. This explains why TAS increases over the land in A4K<sub>PL</sub>, as the global atmosphere will warm from increased SST (Fig 4(a)). There are also positive TAS anomalies over high-latitudes in all the experiments plotted in Fig. 4 relative to A<sub>PL</sub>, which is unsurprising as the snow cover and surface temperatures are not prescribed there. The changes in TAS are also higher over the ocean than the land (land/sea contrast<sup>2</sup> is 0.25).

The changes in TAS for A4x<sub>PL</sub>, Arad4x<sub>PL</sub> and Asc<sub>PL</sub> are not statistically significant over the majority of the land surface and may be related to adjustments in the surface sensible and latent heat fluxes as the atmosphere responds to the increase in CO<sub>2</sub> concentrations or insolation (Figs. 4(b)–(d)). Conversely, the changes in TAS over the land are statistically significant and positive in all runs with perturbed land surface conditions (Figs. 4(e)–(h)). Overall, relative to A<sub>PL</sub>, the changes in TAS for the simulations described in Section 2.2.4 (plotted in Fig. 4) are consistent with the land surface and boundary condition perturbations imparted upon them.

#### 4.2 “Uniform” experiments

The spatial differences in TAS are plotted in Fig. 5(a) for the A4K<sub>PLU4K</sub> simulation relative to A<sub>PL</sub>. The changes in TAS over the land and the sea are very similar with a land-sea thermal contrast of 0.9. The main difference in TAS between the land and the ocean is over Antarctica and Greenland where the surface temperatures not prescribed and the temperature change is muted.

In the A<sub>PLU4K</sub> experiment (relative to A<sub>PL</sub>), TAS increases over all land points by 1.5–~~4.5~~ 4.5 K (statistically significant) except over Antarctica and Greenland where temperatures are not prescribed (Fig. 5(b)). Another interesting feature of this simulation is that the land-sea thermal contrast is very large (with a value of 40); however, the large contrast is unsurprising given the large temperature increase is only applied to the land.

### 5 Summary, conclusions and future work

This paper has outlined the results of a novel set of AMIP-type model simulations that use prescribed SSTs and land surface fields (surface temperature, soil temperature and soil moisture). The main results of this study are:

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<sup>2</sup>[The global mean change in TAS over land divided by the global mean change in TAS over the ocean as done by Sutton et al. \(2007\).](#)

- (1) The differences in climate between the simulations with freely varying land conditions and their prescribed land counterparts (e.g. A vs  $A_{PL}$ ) are much smaller than the underlying systematic errors relative to the observational datasets (i.e. A vs OBS). Therefore, prescribing the land conditions does not degrade the model-simulated climate.
- (2) The changes in global mean precipitation and vertical temperature profiles in the A4K, A4x, Arad4x and Asc experiments are almost identical to those of their corresponding prescribed land simulations—A4K $_{PL4K}$ , A4x $_{PL4x}$ , Arad4x $_{PLrad4x}$  and Asc $_{PLsc}$ .
- (3) The changes in TAS associated with holding the land fixed while changing a forcing agent (e.g. A4x $_{PL}$ ) or fixing the forcing agent and using the land response to that agent (e.g. A $_{PL4x}$ ) are consistent with imposed state and are therefore applied correctly.
- (4) The “U4K” experiments (results described in Section 4.2) provide a novel extension to the A4K experiment where the land-sea thermal contrast is suppressed; however, the TAS response is very similar to that of the A4K $_{PL4K}$  experiment.
- (5) Likewise, the A $_{PLU4K}$  simulation resembles the TAS response in the Asc $_{PLsc}$  experiment, except the magnitude of the climatic changes are larger in A $_{PLU4K}$ .

Overall, this study has presented a set of experiments that could be used to answer questions about the separate roles of the land, ocean and atmosphere under climate change. While this study evaluates those simulations, it does not provide an in-depth scientific analysis of all the model simulations undertaken. By providing those data for others to download, it is the intention of this paper to provide a background analysis for validation purposes and to provide information on how to acquire these data. These simulations may also help to answer some of the key questions arising from the CFMIP and CMIP initiatives (see Eyring et al., 2016; Webb et al., 2017, respectively) given in Section 1 and to provide a better understanding of the regional drivers of precipitation over the land.

*Code and data availability.* The model source code for ACCESS is not publicly available; however, more information can be found through the ACCESS-wiki at <https://accessdev.nci.org.au/trac/wiki/access>. Any registered ACCESS users who wish to gain access to the source code described in this paper can do so from the following:

**For A, A4K and A4x**

[https://access-svn.nci.org.au/svn/um/branches/dev/cxf565/r3909\\_my\\_vn7.3@4793](https://access-svn.nci.org.au/svn/um/branches/dev/cxf565/r3909_my_vn7.3@4793)

**For Arad4x**

[https://access-svn.nci.org.au/svn/um/branches/dev/dxa565/src\\_plant\\_co2/src@10276](https://access-svn.nci.org.au/svn/um/branches/dev/dxa565/src_plant_co2/src@10276)

**For Asc**

[https://access-svn.nci.org.au/svn/um/branches/dev/dxa565/src\\_solcnst/src@10274](https://access-svn.nci.org.au/svn/um/branches/dev/dxa565/src_solcnst/src@10274)

**For A $_{PL}$ , A4K $_{PL4K}$ , A4x $_{PL4x}$ , A4K $_{PL}$ , A $_{PL4K}$ , A4x $_{PL}$ , A $_{PL4x}$ , A $_{PLrad4x}$ , A $_{PLsc}$ , A4K $_{PLU4K}$  and A $_{PLU4K}$**

[https://access-svn.nci.org.au/svn/um/branches/dev/dxa565/src\\_presT\\_reg/src@9826](https://access-svn.nci.org.au/svn/um/branches/dev/dxa565/src_presT_reg/src@9826)

**For Arad4x $_{PLrad4x}$  and Arad4x $_{PL}$**

[https://access-svn.nci.org.au/svn/um/branches/dev/dxa565/src\\_presT\\_reg\\_np/src@10269](https://access-svn.nci.org.au/svn/um/branches/dev/dxa565/src_presT_reg_np/src@10269)

**For  $Asc_{PLsc}$  and  $Asc_{PL}$**

[https://access-svn.nci.org.au/svn/um/branches/dev/dxa565/src\\_presT\\_reg\\_sc/src@10272](https://access-svn.nci.org.au/svn/um/branches/dev/dxa565/src_presT_reg_sc/src@10272)

5 Data are publicly available from the National Computational Infrastructure (NCI) (see Ackerley, 2017). Input surface temperature, soil moisture and deep soil temperatures are also available from the NCI upon request (also refer to Ackerley, 2017). The relevant doi (and other metadata) for each of the individual experiments can be found in the supplementary file attached to this paper (*plamip\_expts\_doi\_list.xlsx*). Use of these data in any publications requires both a citation to this article and an appropriate acknowledgement to the data resource page (see Ackerley, 2017, for more details on acknowledging the dataset)

*Competing interests.* The authors declare that they have no conflict of interest.

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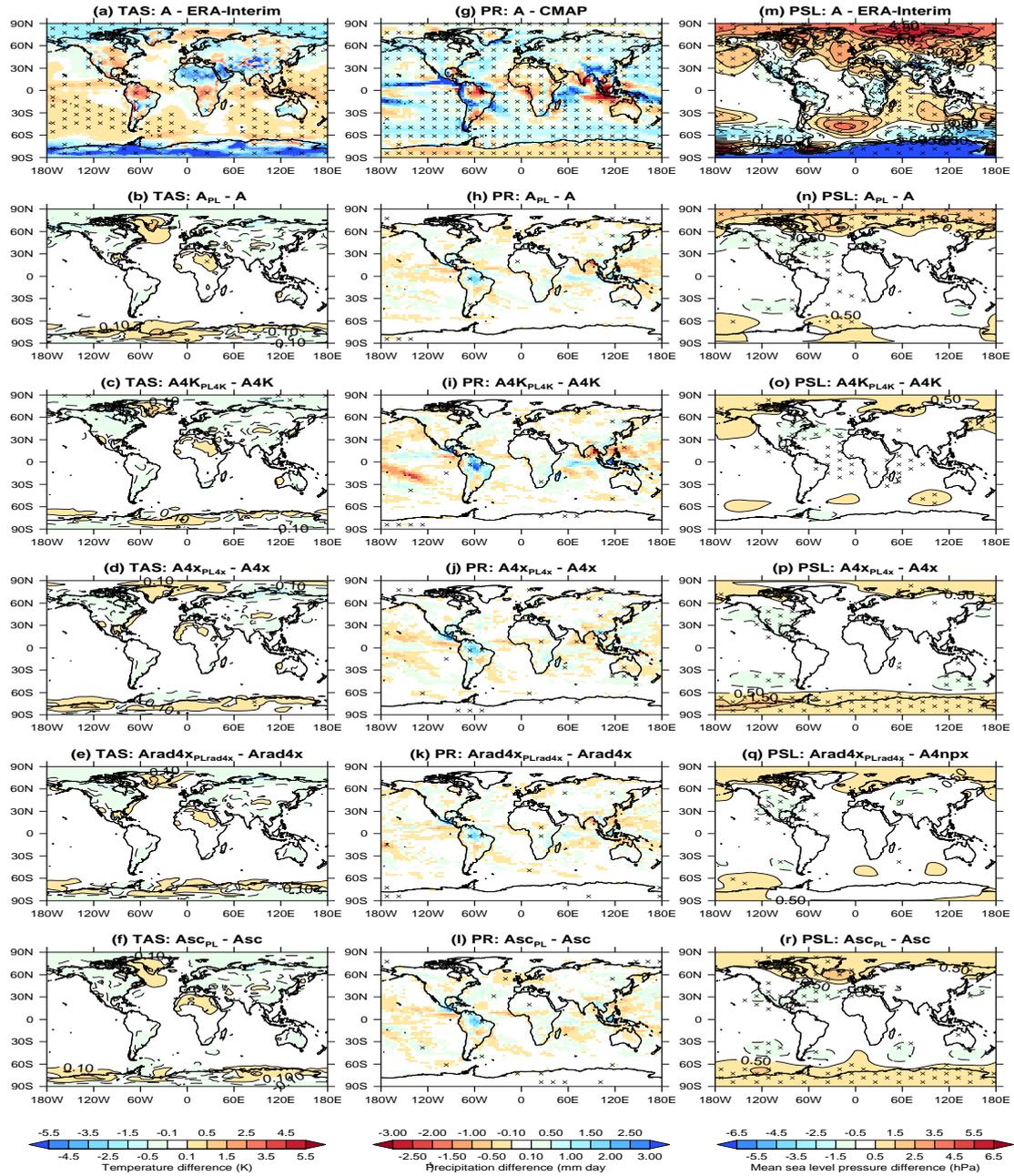
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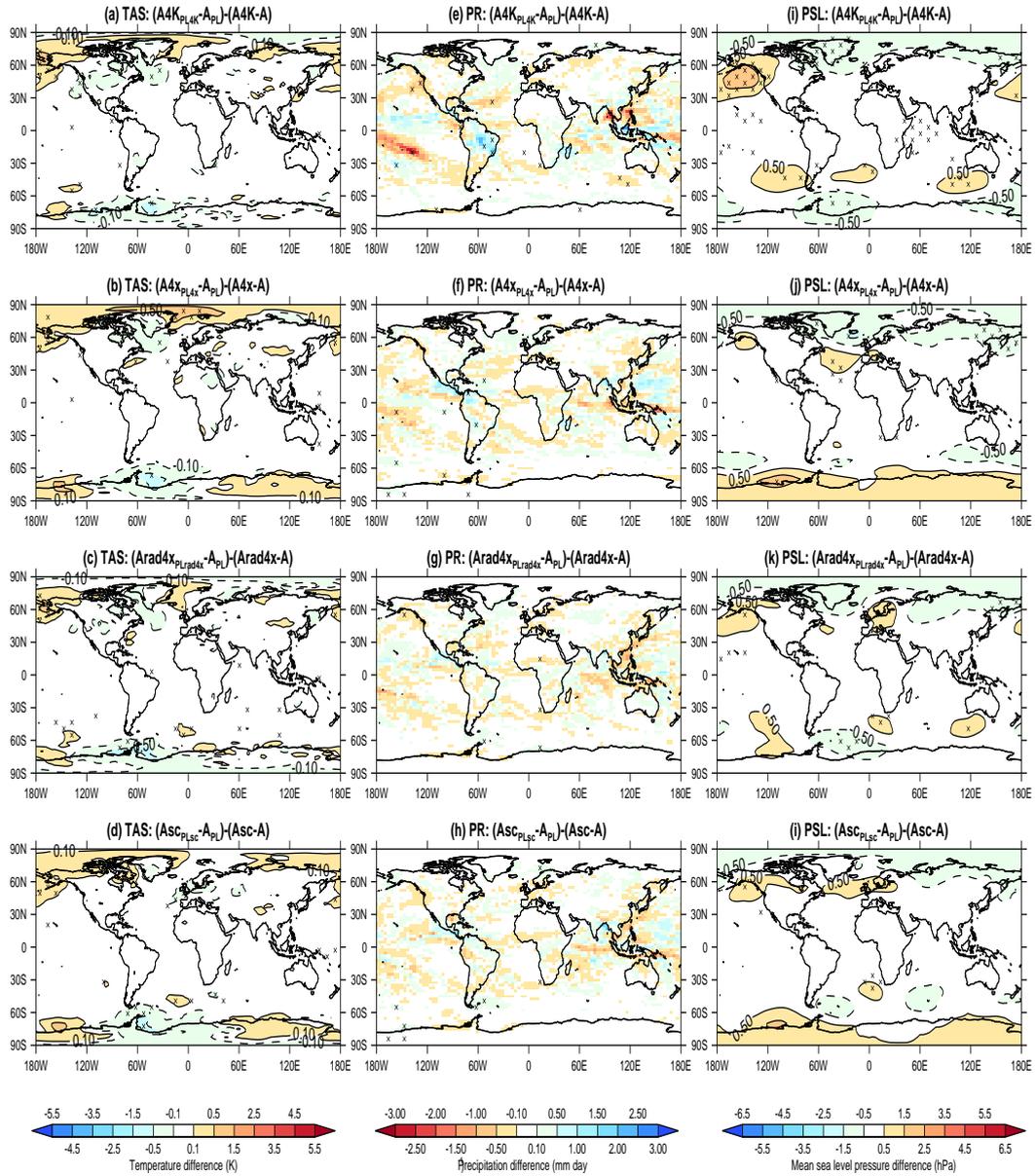
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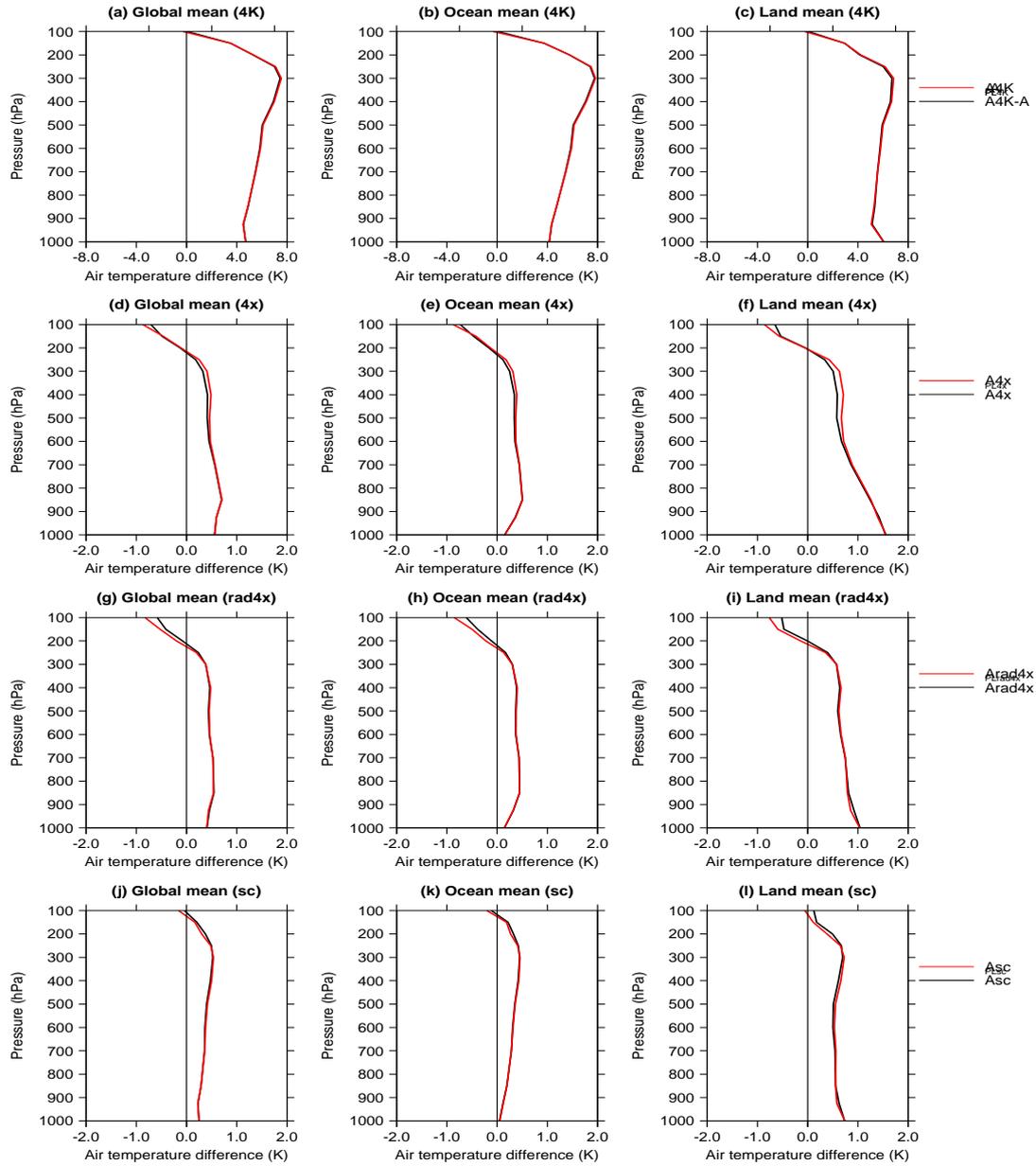
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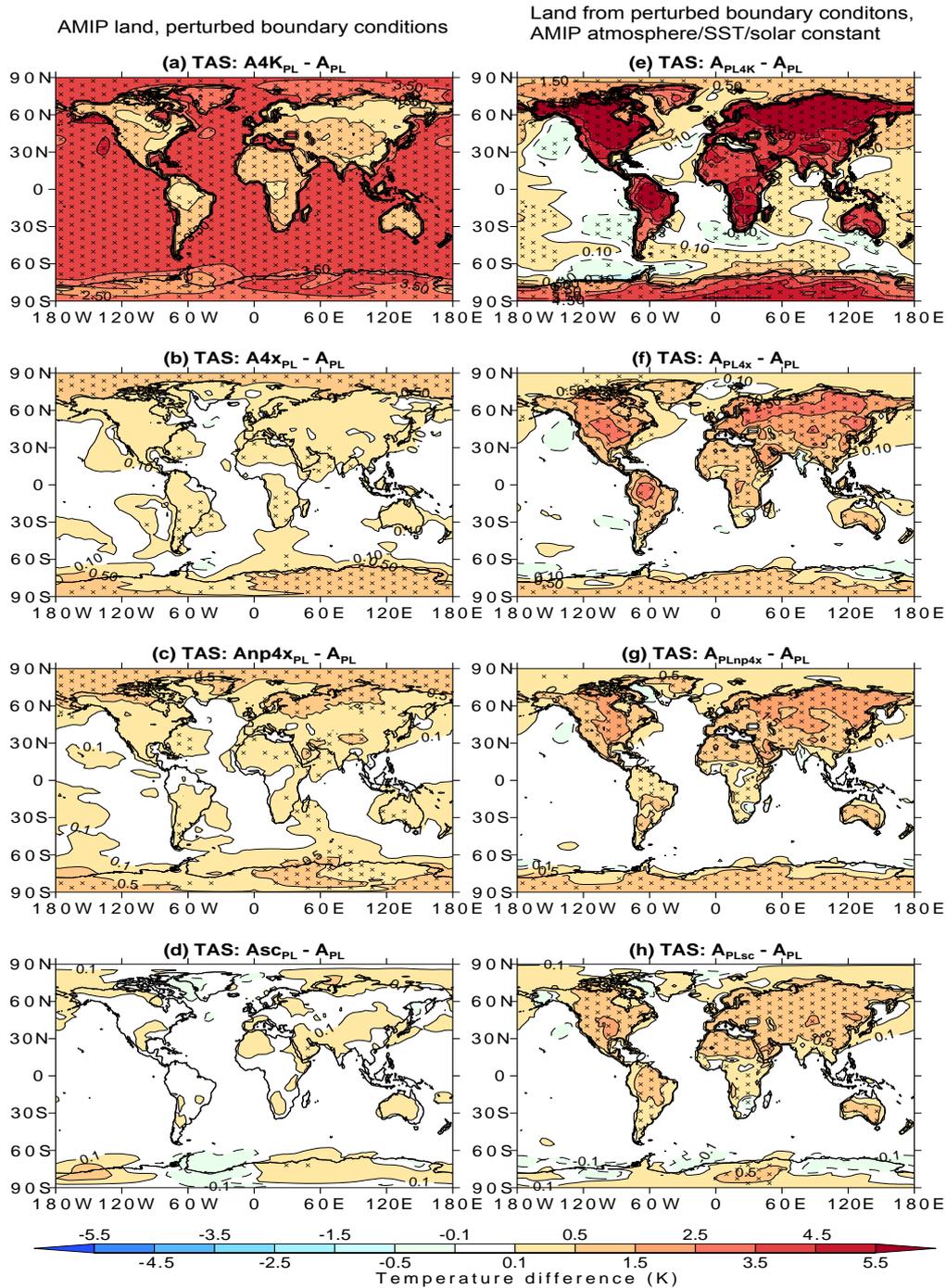
**Figure 1.** Differences in surface air temperature (TAS, K) for (a)  $A - ERA-Interim$  minus ERAI, (b)  $A_{PL} - A$  minus A, (c)  $A4K_{PL4K} - A4K$  minus A4K, (d)  $A4x_{PL4x} - A4x$  minus A4x, (e)  $Arad4x_{PLrad4x} - Arad4x$  minus Arad4x and (f)  $Asc_{PL} - Asc$  minus Asc. Equivalent differences between observations/simulations are given in (g)–(l) and (m)–(r) for precipitation (PR,  $mm\ day^{-1}$ , CMAP data used in (g)) and mean sea level pressure (PSL, hPa, ERA-Interim data used in (m)), respectively. The points labelled with an "x" indicate the differences are statistically significant using the Student's t-test ( $p \leq 0.05$ ).



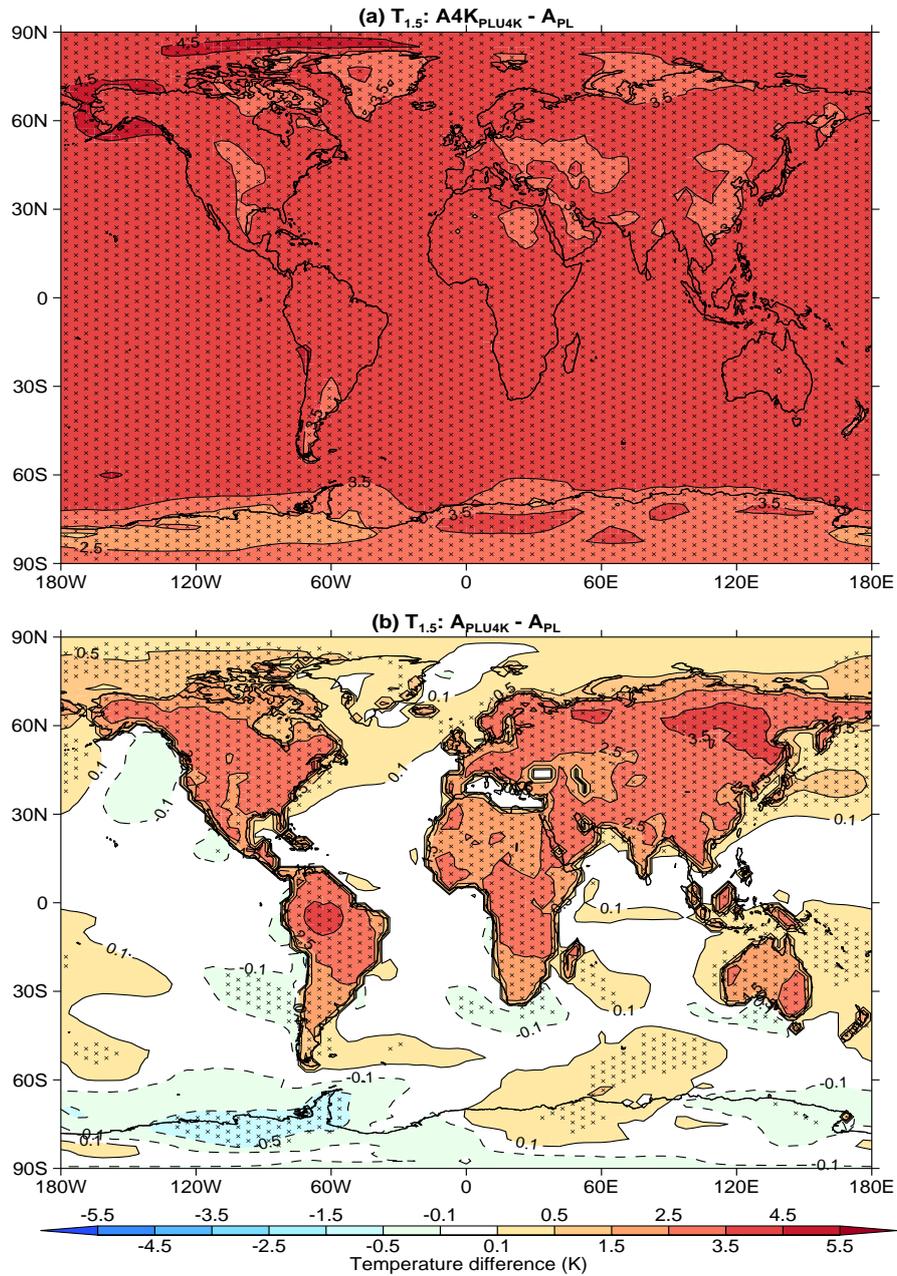
**Figure 2.** Differences in surface air temperature (TAS, K) for (a)  $[A4K_{PLAK} - A_{minus} A_{PL}] - [A4K - A4K_{minus} A]$  (b)  $[A4x_{PLAx} - A_{minus} A_{PL}] - [A4x - A4x_{minus} A]$ , (c)  $[Arad4x_{PLrad4x} - A_{minus} A_{PL}] - [Arad4x - Arad4x_{minus} A]$  and (d)  $[Asc_{PLsc} - A_{minus} A_{PL}] - [Asc - Asc_{minus} A]$ . Equivalent differences between simulations are given in (e)–(h) and (i)–(l) for precipitation (PR,  $\text{mm day}^{-1}$ ) and mean sea level pressure (PSL, hPa), respectively. The points labelled with an "x" indicate the differences are statistically significant using the Student's t-test ( $p \leq 0.05$ ).



**Figure 3.** Differences (relative to A or  $A_{PL}$ —see key for each row) in global mean (column 1), ocean-only mean (column 2) and land-only mean (column 3) air temperature (K) for (a)–(c) the A4K experiments, (d)–(f) the A4x experiments, (g)–(i) Arad4x experiments and (j)–(l) the Asc experiments, respectively.



**Figure 4.** Differences in surface air temperature (TAS, K) for (a)  $A_{4K_{PL}} - A_{PL}$ , (b)  $A_{4x_{PL}} - A_{PL}$ , (c)  $A_{rad4x_{PL}} - A_{PL}$ , (d)  $A_{sc_{PL}} - A_{PL}$ , (e)  $A_{PL4K} - A_{PL}$ , (f)  $A_{PL4x} - A_{PL}$ , (g)  $A_{PLrad4x} - A_{PL}$  and (h)  $A_{PLsc} - A_{PL}$ . The points labelled with an "x" indicate the differences are statistically significant using the Student's t-test ( $p \leq 0.05$ )



**Figure 5.** Differences in surface air temperature (TAS, K) for (a)  $A4K_{PLU4K} - A_{PL}$ , (b)  $A_{PLU4K} - A_{PL}$ . The points labelled with an "x" indicate the differences are statistically significant using the Student's t-test ( $p \leq 0.05$ )