Geosci. Model Dev. Discuss.,
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Geoscientific Model Development Discussions

GMDD

Interactive comment

Interactive comment on "Overview of climate change in the BESM-OA2.5 climate model" *by* Vinicius Buscioli Capistrano et al.

Vinicius Buscioli Capistrano et al.

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Reply to the Reviewer 1 (updated with corrected indication of changes)

First of all, we would like to thanks the extraordinary review. It is evident the importance of your suggestions, which is associated with the quality and relevance of all information for GDM reader. The original manuscript was planned to intercompare BESM climate model with CMIP5 ensemble, documenting the well-known physical responses to increased CO2. Therefore, many analysis (tables and figures) were proposed with this view, having side-by-side BESM and CMIP5. We agree with the main issue pointed out by both reviewers, that the GMD reader would not be interested if BESM has climate sensitivity within ensemble dispersion. Thinking in this way, we rewrite parts of the manuscript (following the reviewers' suggestions) where comparisons BESM vs. CMIP5 were mentioned, bringing more discussion about BESM response. Moreover, new figures focusing on BESM results was added, however the original figures and tables remained without change.

1. **The title is too vague. The paper is not about BESM-simulated climate change in general – that would imply showing results from historical or projection simulations. The paper is in fact about BESM simulated climate sensitivity and feedbacks.**
   Reply: According to the suggestion of the anonymous Reviewer 2, the article title was changed to "Assessing the performance of climate change simulation results from BESM-OA2.5 in comparison to a CMIP5 model ensemble".

2. **A re-organisation of Section 2 Model Description. At the moment, it has only one subsection, which is a mixture of model description and comparison to the previous version. This should be split cleanly into two subsections focused on each aspect. The model description should be more complete.**
   Reply: The Section 2 was split in two parts as requested. Moreover, the model configuration was more detailed. Please, see page 3 lines 11.

3. **The paper spends too long discussing CMIP5 models when it really should be discussing BESM. Three changes would fix the balance**

   (a) **First, Section 3.2 needs to be shortened because it is essentially a retelling of Andrews et al. (2012) and Vial et al. (2013). In the context of the paper the reader is only interested in the physical meaning of the**

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different variables estimated by the Gregory and kernel methods.
Reply: As far as we have two different methods, we decided explicit all calculations. It worth noting that the first technique is the same as Andrews et al. (2012), however the other does not share the same methods with Vial et al. (2013). The radiative kernel method applied here is similar to its origin paper (Soden et al., 2008), whereas Vial et al. (2013) separated the feedback and the rapid adjustment using different protocols run (see next question).

(b) **Second, the results presented in Sections 4.1 and 4.2 need to be compared to the original papers: are the results replicated? How many models have been added/removed compared to the original papers?**
Reply: As mentioned by the reviewer, the climate sensitivities of 26 CMIP5 coupled models (including BESM-OA2.5) were assessed using the Gregory et al. (2004) linear regression between net radiation in TOA and surface temperature changes, as well as it was performed by Andrews et al. (2012) for 15 CMIP5 coupled models. In the present work, we included the following models: ACCESS1-0, ACCESS1-3, bcc-csm1-1, BESM-OA2.5, BNU-ESM, CCSM4, FGOALS-g2, FGOALS-s2, GISS-E2-H, GISS-E2-R, e inmcm4. For the 15 same models, we found similar results with respect to Andrews et al. (2012). Such small difference may we can attribute grid interpolation as explained in line 4 of page 8. In order to partitioned the feedback agents we used the radiative kernel described in Soden and Held (2006) and Soden et al (2008) and Shell et al (2008). In turn, Vial et al. (2013) adapted this previous methodology to consider the tropospheric adjustment to CO2 (comparison between abrupt4xCO2 and sstClim4xCO2, instead of abrupt4xCO2 and piControl).

(c) **Third, a lot of the analysis in Section 4.3 is about CMIP5 models in general (page 10 especially), and that has been said already in other papers so could just be repeated briefly. Instead, the space could be**

used to deepen the analysis of the BESM simulations.
Reply: New information was added to include what was requested.

4. **The authors frequently compare BESM to the CMIP5 average, or say that it is within the CMIP5 range (which is often large), or note where BESM is an outlier. But such statements are only mildly useful. After all, it may not be a good thing to be close to the CMIP5 average. Instead, readers need evidence for a deep understanding of why BESM behaves like it does.**

   (a) **Why is there a radiative imbalance of 2 W m^{-2}? That is a large value. Does that cause a model drift? Does the model conserve energy?**
   Reply: The AGCM stand-alone run shows a net radiation at TOA of 0.25 W m^{-2} during 20 years of simulation (Fig. 1a). Such radiative imbalance is within the range simulated by different atmospheric models. However, in the coupled simulation, the net radiation imbalance at TOA is amplified up to -4 W m^{-2} (Fig. 1b). The reason for such imbalance is related to higher loss of energy at TOA both from the outgoing long-wave radiation (OLR) and outgoing short-wave radiation (OSR), compared with AGCM stand-alone simulation (Fig. 1c and 1d). In Fig. 1c and 1d, the solid lines represent the coupled model and the dashed lines represent the AGC. The higher loss of energy through the outgoing short-wave radiation is potentially duo to enhanced cloud formation in the coupled model run.

   (b) **Then, why is the 2xCO2 radiative forcing at the higher end of the range? Is it an issue for the radiative transfer code?**
   Reply: BESM-OA2.5 was integrated with UKMET radiative code for SW and LW in order to compare the imbalance of the first year, which is a proxy to the Instantaneous Radiative Forcing.

   (c) **... why is BESM an outlier in terms of cloud feedbacks? The reader is told that the answer lies in the high latitudes, but what are the mechanisms? Change in low-cloud cover? Change in phase from ice to**

liquid?

Reply: It is evident from figures presented in the manuscript, that BESM is an outlier for the cloud feedbacks. This is due to a strong shortwave component response over both the Arctic and the Southern Ocean near Antarctica. Considering the SW CRE/ðİŻěTas [described by Cess et al. (1989)] and the individual components of feedbacks cloud mask, we can note that those higher values cloud feedback are mainly consequences of the sum of SW CRE/ΔT_{as} and the cloud masking for albedo feedback [-(ðİIJĘa-ðİIJĘac)], as shown in Figure 2. For Arctic region, the major contributor for BESM be an outlier is the SW CRE, while for over the ocean near the Antarctic is the albedo feedback cloud mask. In this latter, since the radiative kernel for both all- and clear-sky are the same throughout the models, the difference among them is due to the albedo change [$\Delta a/\Delta T(K_a - K_a^{cs})$]. Over the both regions (Arctic and near Antarctic), an increase in cloud fraction above 850 hPa and a decrease below that level for BESM is observed, which means a low-level clouds upward shifting . Moreover, the increase in cloud cover above 850 hP is stronger than the reduction below (Figure 3a). As consequence, a negative SW CRE change is present in those regions, that is that response to the increase in sun shading (Figure 3b). However, the SW cooling is smaller than the heating provided by LW radiation, as presented in the net effect (Figure 3d). The net radiation heating change is more intense around 60oS, that can be related to the more intense surface albedo change. We could not investigate the change in phase from ice to liquid because we did not designed the experiments to have the liquid and ice water content in their outputs. We pretend develop a new analysis about it in a next work.

(d) **Finally, regarding the "warming hole" in the North Atlantic, does BESM simulate it for the reasons listed by Drijfhout et al. (2012)?**

Reply: A new work about the "warming hole" is in preparation by Nobre et al (2019), which will have more information about BESM transient responses to radiative forcing in that region.

5. Other comments:

   - **Page 2 line 3: The main result of the "trapping" of infrared radiation is an increase in ocean heating content, since this is the Earth system component with the largest heat capacity.**
     Reply: Done (p.2 l.6)
   - **Page 2 line 20: The wet-gets-wetter etc. is probably too simple and more subtle descriptions are now preferred, see for example Marvel and Bonfils, doi:10.1073/pnas.1314382110 (2013).**
     Reply: Done (p.2 l.26)
   - **Page 3, line 10: Is the model hydrostatic or not?**
     Reply: It is hydrostatic. This is information was add in the Model description section (p. 3 l. 17)
   - **Page 3, line 21: What microphysical processes? Clouds?**
     Reply: It is about the microphysical parameterization of precipitation.
   - **Page 3, line 24: The 2m subscript is confusing. Are the authors talking of diagnostic or prognostic variables here?**
     Reply: Those variables are diagnostic for the atmospheric model, however it is important in the ocean-atmosphere coupling (p. 4 l.15).
   - **Page 4, section 3.1: It would be useful to refer to the CMIP6 DECK here (Eyring etal. doi:10.5194/gmd-9-1937-2016, 2016) since piControl and abrupt4xCO2 are both mandatory simulations within the DECK. Referring to CMIP6 would make the paper more current.**
     Reply: Done (p. 5 l. 7).
   - **Page 4, lines 26–31: Need to move the statements on page 5 lines 27–28 and page 6, lines 15–16 here to list the advantages and limitations**

of both methods in one place.
Reply: As far as we decided maintain a separated description of those methods (as discussed previously), we also let the limitation and advantages in different sections.

- **Page 5, line 27: Would be useful to refer to Soden et al. doi:10.1126/science.aau1864 (2018) here.**
  Reply: Done (p.6, l. 16)
- **Page 7, lines 24-25: That statement needs to be clarified and referenced. Perhaps Zelinka et al doi:10.1175/JCLI-D-12-00555.1, 2013?**
  Reply: New information based on the Methods section was provided.
- **Caption of Figure 2: Please make figure captions standalone by defining all acronyms and variables.**
  Reply: Done.
- **Figure 4: It would be helpful to put a dashed line at lambda = 0 on each panel, tomake easier to see where the feedback parameters switch sign.**
  Reply: Done.

Complete Figure Captions

Figure 1 – Net of the radiation of TOA simulated by (a) stand-alone AGCM for 20 yearsand (b) BESM-OA2.5 Historical for the first 20 years (1850-1870). (c) and (d) areoutgoing long-wave radiation and outgoing short-wave radiation, respectively. In (c)and (d) the solid lines represent the coupled model and the dashed lines represent the AGCM. Units are in W m-2.

Figure 2. SW Cloud feedback and the albedo and SW humidity feedbacks cloud mask-ing for the CMIP5 multi-model ensemble-mean (solid line) and BESM-OA2.5 (solid linewith dots). Inter-model standard deviations for each latitude are in yellow.

In blue are the feedback limits based on the maximum and minimum values for each latitudeamong the models, not including BESM-OA2.5.

Figura 3. Vertical profiles of the zonal mean of the 4xCO2 - piControl mean difference-for the following variables: (a) Cloud fraction, Radiative heating-cooling rate (dT/dt) of(b) shortwave, (c) longwave and (d) sum of shortwave and longwave.

Interactive comment on Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-209, 2018.

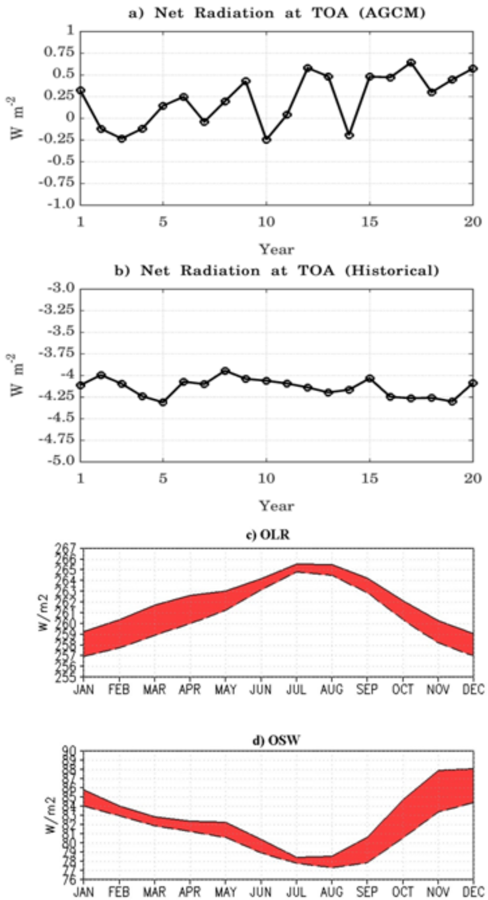

Fig. 1.

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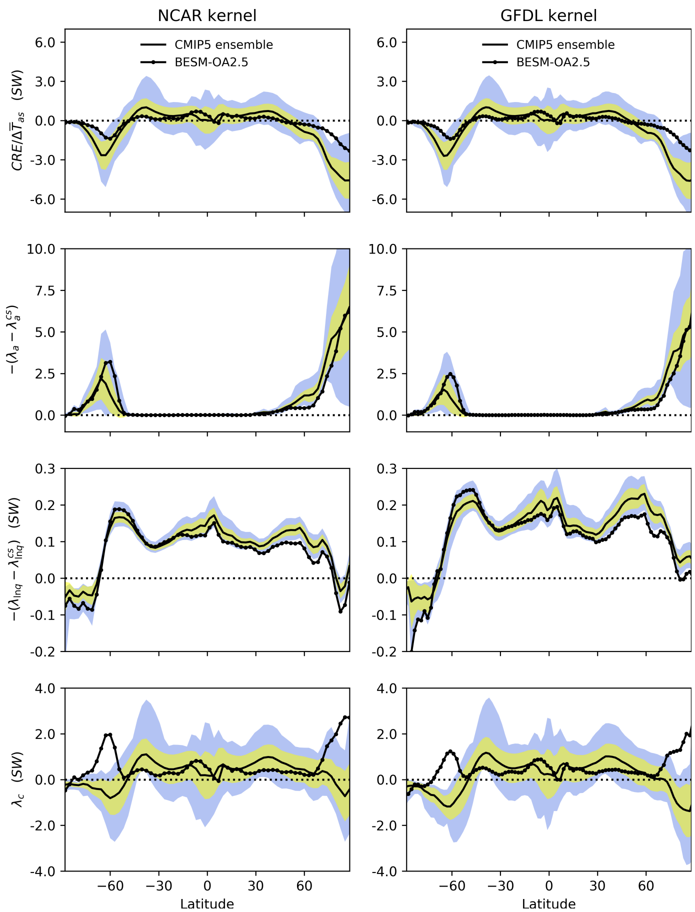

Fig. 2.

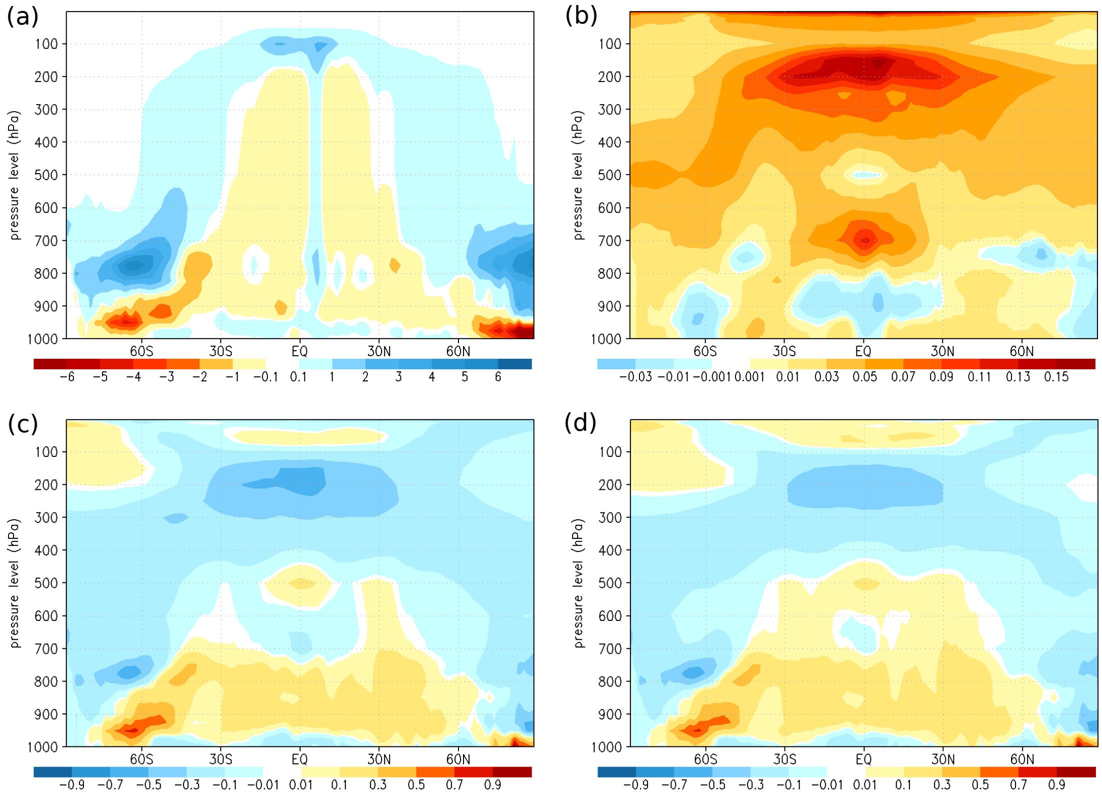

Fig. 3.

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Reply to the Reviewer 2 (updated with corrected indication of changes)

First of all, we would like to thanks the extraordinary review. It is evident the importance of your suggestions, which is associated with the quality and relevance of all information for GDM reader. The original manuscript was planned to intercompare BESM climate model with CMIP5 ensemble, documenting the well-known physical responses to increased CO2. Therefore, many analysis (tables and figures) were proposed with this view, having side-by-side BESM and CMIP5. We agree with the main issue pointed out by both reviewers, that the GMD reader would not be interested if BESM has cli-

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mate sensitivity within ensemble dispersion. Thinking in this way, we rewrite parts of the manuscript (following the reviewers' suggestions) where comparisons BESM vs. CMIP5 were mentioned, bringing more discussion about BESM response. Moreover, new figures focusing on BESM results was added, however the original figures and tables remained without change.

1. **... the paper is severely out of balance in that it dwells too much on discussing (and interpreting) CMIP5 model results, while entering too less into the potential origin of BESM-OA2.5 peculiarities. [...] the focus needs to be on the BESM results and their proper appraisal.**
   Reply: Please see the specific and technical remarks.

2. **In the current text I find the statements in the last paragraph (p. 12, l. 11ff.) rather strange. The main objective of BESM is not supposed to "show climate sensitivity and thermodynamical responses similar to . . . CMIP5" but rather "to study the climate system [with a model able] to reproduce changes that are physically understood". Besides, that the latter objective should be pursued by any climate model activity, what does this mean for the present paper and its priorities?**
   Reply: Please see the specific and technical remarks.

3. **The authors use (or rather combine) two ways of calculating radiative feedbacks, viz. the regression method from Gregory et al. (2004) and the individual feedback calculation method from radiative kernels. This is quite recommendable, on principle. However, the methods are not equivalent as the phrase "seemingly redundant" (p. 4; l. 27) is suggesting. . . The kernel methods includes [. . .] rapid adjustments directly induced from the CO2 forcing. More severe, the regression method implies that the radiative feedbacks are consistent with the actual radiative transfer module used in the**

climate model, while this is not true for the kernel method, if another than the radiative kernel from the actual climate model is used (as is the case here). The authors are apparently aware of this fact (p. 5, l. 25, p. 7, l. 16), but repeatedly fail to appreciate it when interpreting results.
Reply: The manuscript was changed to include this concerns. Please, see answers in the specific remarks section.

4. **In the same context the authors might also consider to refer to Forster et al. (2016) and Smith et al. (2018) here (beyond Vial et al., 2013), with respect to the options of calculating and interpreting effective radiative forcings, radiative adjustments and feedbacks, and climate sensitivity parameters. Are there abrupt4xCO2 simulations with fixed SST from BESM-OA2.5 that could be included in the discussion? Or are those intended to be analyzed in further BESM studies?**
Reply: We have not performed an abrupt4xCO2 with fixed SST. We know that it is important to find the rapid adjustment of the troposphere and surface. Therefore, we intended to analyze this issues in a next BESM version.

5. **Further, I have some concerns about deriving the ECS (which is for 2xCO2) from 4xCO2 simulations by using a factor 2 (p. 6, l. 22). Is this really a standard method? Then it's certainly at odds with available knowledge (e.g., Boer et al., 2003; Knutti and Rugenstein, 2015). However, the authors could argue that they used the same approximation, crude or not, for all evaluated models.**
Reply: We used the same method of Andrews et al (2002), that obtained the ECS (for 2xCO2) from comparison between piControl and Abrupt4xCO2.

6. **Even if the focus of the paper were redirected towards the BESM performance, I still suggest a modified title, for example: "Assessing the performance of climate change simulation results from BESM-OA2.5 in compari-**

son to a CMIP5 model ensemble".
Reply: Done

7. **Specific and Technical Remarks**

- **p. 1, l. 8 (Abstract): For the following two sentences I would rather expect a general assessment of BESM rather than pure repetition of specific parameter results. While it is obviously true (and worth mentioning) that BESM-OA2.5 is not an outlier off the CMIP ensemble, its appraisal ought to be more process directed.**
  Reply: The abstract was modified in order to attend what was requested.
- **p. 2, l. 1: "..., commonly referred to as", I think this is rather a simplification for less developed models, so "..., sometimes given as" may be preferable.**
  Reply: Done (p. 2 l. 5)
- **p. 2, l. 20: There is a formal contradiction here: "... is robust from ... models" does not fit with "... uncertainty is likely to arise from ... inter-model spread", please reformulate.**
  Reply: After changes in the paragraph, the sentence became out of context, then was removed.
- **p. 3, l. 3: "Differences ...", this sentence may be omitted as it is essentially repeated at p. 3, l. 3.**
  Reply: Done.
- **p. 3 l. 16: "... uses BAM ... with simpler and computationally cheaper parameterizations"; Does this mean that BESM-OA2.3 uses the original BAM? Why has this been changed and could there be consequences of**

the simplification for the response behavior of the model as addressed in the present paper?

Reply: As required by the other Referee, more information about physical parameterization was included in the manuscript. Moreover, it was mentioned that BAM is the atmospheric component of the climate model BESM-OA2.5. For the current study we used a different parameterization set from that of the evaluation paper of BAM (Figueroa et al. 2016), mainly because a computationally cheap set is desirable in a long simulation. However, changes in those sets result in different climate change response. For instance, a different radiative scheme probably will lead to a different radiative forcing (p. 3, l. 11).

- **p. 3, l. 20: From the preceding text, it is puzzling that the simplified model should have a better representation of the ToA radiative budget. I assume, however, that this is a result of more careful parameter tuning (but this is not mentioned). Like referee$\#1$, I also wonder whether this relatively large ToA radiative balance bias leads to a considerable present-day surface temperature bias. Does the coupled atmosphere-ocean model use a flux correction?**

  Reply: A simulation with the atmospheric component only (BAM) presents a imbalance of 0.25 W m^{-2}. The imbalance of -4 W $^{-2}$ is related to higher loss of energy at TOA both from the outgoing long-wave radiation and outgoing short-wave radiation, compared with AGCM stand-alone simulation. Despite of this constant imbalance, the surface temperature is in thermodynamic equilibrium in a piControl run. BESM adopted the coupling strategy of pass variables through the surface interface instead of flux. It means that ocean component receive atmospheric variables and calculate the fluxes from atmosphere to ocean, then return variables for atmospheric component in order to calculate fluxes from ocean to atmosphere. Moreover, we do not apply flux correction for our simulations.

- **p. 3, l. 22: "surface layer"; I assume you mean the "planetary boundary layer", don't you? Or does tis refer to pure diagnostics, as suggested by the following sentence.**
  Reply: The surface layer is the lowest layer of the planetary boundary layer.
- **p. 4, l. 4: "general mean present-day climate state"**
  Reply: Done.
- **p. 4, l. 7: "BESM-OA2.5 also is capable ..."; this sentence is rather vague, are you talking about ocean variability here? Or does this include the leading modes of long-term atmospheric variability like NAO, PNA etc. ?**
  Reply: It is about leading modes of long-term climate variability. The sentence "manly that related to Atlantic Ocean", that can contribute to this misunderstand, was removed.
- **p. 4, l. 11: "overturning"**
  Reply: Done.
- **p. 4, l. 12: "slightly"**
  Reply: Done.
- **p. 4, l. 14: You might wish to address the matter of storm track variability here, but only if this is supposed to be a field of BESM application in the future. And if it has been actually studied, of course.**
  Reply: The Storm Track variability of BESM has not been studied yet. This issue will be investigated in a future work.
- **p. 4, l. 30: "... the Gregory et al. (2004) method ..."; from various reasons it may be preferable to introduce (and refer to) the respective method as "... the regression method ...". Mainly, because using the terms "regression" and "radiative kernel" directly points to the methodical differences.**
  Reply: Done.

- **p. 5, l. 17: "... we extract the clear sky radiative flux components from the BESM and CMIP data bases in order to ..."**
  Reply: Done.
- **p. 5, l. 25: (see major remarks above) – as the assumption is not necessarily true a remark should be made on the consequence for interpretation in case that there are substantial differences between the radiation modules.**
  Reply: As suggested, new information about radiative kernel limitation has been written in the Methods section.
- **p. 6, l. 4 (and l. 11): No information is given on how stratospheric temperature (and water vapour) changes are accounted for when calculating the feedback parameters. I recommend at least making a statement, if those contributions are included in the Planck feedback, or if they are shifted to the residuum Re (which I guess is, what you actually did). See also Rieger et al. (2017, their Fig. 5).**
  Reply: Differently from Rieger et al. (2017), the stratospheric adjustment was not investigated here. All feedback calculation was obtained integrating from the surface up to the tropopause. Thereby, it is mentioned that the stratospheric changes are shifted to the residuum (p. 7, l. 5).
- **p. 6, l. 17: "... cloud feedback is approximated using ..."; I'm aware that this is a standard method, so the authors are not responsible for the quality of this approximation.**
  Reply: Done.
- **p. 6, l. 22: I expect that the respective 30 year periods are not fully stationary as the deep ocean components of the various models have not reached equilibrium. If your analysis allows, please give some information on the remaining trend in the evaluated periods. Or have the data been de-trended before using them as an input to the radiative**

kernels?

Reply: The time-scale to a coupled model reach a thermodynamic equilibrium is more than 1000 years. Therefore, it is true that the stationary phase is not reached in the analyzed period. We proceeded similar to Vial et al. (2013), that used a 10-year period centered around the 130th year after the CO2 quadrupling in abrup4xCO2. The models data were not submitted to de-trended in the feedback estimation through kernel method.

- **p. 7, l. 5: "... the spatial inner product ..."; the authors might like to introduce the term in this way, but I assume they compute what is elsewhere called the 'Pearson correlation coefficient', hence I recommend to use the latter term through the rest of the paper.**

  Reply: The "spatial inner product" is similar to the "Pearson correlation coefficient" applied to space instead of time as it is commonly used. Therefore, to distinguish between the application for space and time we used the term "spatial inner product".
- **p. 7, l. 9: "These linear regressions ..."; this sentence is hard to read and needs rewriting. With the current formulation, it is not possible to unravel for which purpose all-sky or clear-sky data haven been used.**

  Reply: The application of all-sky and clear-sky is explained in Method section: "... we decompose the feedback parameter into shortwave (SW) and longwave (LW) radiation components and we extract the clear sky radiative flux components from the BESM and CMIP data bases in order to estimate the cloud radiative forcing or cloud radiative effect CRE defined as the difference between the all-sky and clear-sky feedback parameters Andrews et al. (2012)" (p.6 l. 4).
- **p. 7, l. 11: The values given are at odds with what is written p. 5, l. 12, concerning G, λ, and ECS. Please, give an explanation (which is probably to be found in the fact that no actual equilibrium has actually been reached).**

Reply: New information was added in Methods section (p. 5 l. 26-30)

- **p. 7, l. 13: "... similar to those of Andrews et al. ..."; in fact, the reader certainly expects no less than this, as those authors used CMIP5 data as well. Where does the difference come from? Interpolation as mentioned on p. 4, l. 23?**
  Reply: Small differences are found in the analysis, which we attribute to the interpolation of the data. It was better explained in the manuscript (p.8 l. 3-8)
- **In the simulations with BESM, has there any form of "radiation double calling" been used to calculate radiative forcings or feedbacks? That could help to assess whether the radiation parameterization within BESM produces results (largely) consistent with the GFDL and NCAR kernels.**
  Reply: There is not a "radiation double calling" module in BESM. We agree that it is could be a important implementation to include in future versions.
- **p. 7, l. 28: "Both radiative kernels are used ..."**
  Reply: Done.
- **p. 8, l. 4: The following discussion (of Figure 4) is an example in a text flow that is largely out of scope with the paper's focus. Most of this is established knowledge from a multitude of previous papers. A clear change of perspective towards the specific features of BESM is advisable.**
  Reply: The figure description was change to include the new perspective requested (p. 8 l. 29)
- **p. 8, l. 6: "The faster increase ...", I assume you mean "stronger", don't you?**
  Reply: It was changed to "stronger" (p. 9 l. 35).
- **p. 8, l. 7: The two sentences discussing the possible cause-and-effect**

relation of water vapor and lapse-rate feedbacks is somewhat confusing. The general notion, I think, is the different degree of turbulent mixing in tropical, mid and polar latitudes. I recommend referring to, e.g., Po-Chedley et al. (2018), who draw a lucid and consistent picture of the latitudinal differences.

Reply: A paragraph was changed to include a more clear explanation (p. 9 l. 1-11).

- **p. 8, l. 16: "... as noted in yellow and blue shaded areas in Figure 4", this hint would better be given when the discussion of Figure 4 starts (l. 4) or, alternatively" in the figure caption.**

  Reply: It was removed.

- **p. 8, l. 22: This paragraph is either too short (different cloud feedback results from different methods being a highly complex issue) or too long (as these general issues are not necessarily within the scope of the paper). Please focus on what could be a reason for the specific behavior of BESM in this particular case.**

  Reply: Parts with comparison between regression and kernel methods was removed.

- **p. 8, l. 35: "This is due to ...", a rather technical reasoning (which continues throughout this paragraph). The reader would rather be interested in the physical reason. I the cloud cover response over sea (60°S) and over sea ice (Arctic) less well simulated by BESM compared to land areas? Or could it by that there is a problem with the cloud phase feedback (e.g., Mitchell et al., 1989; Tan et al., 2016) in BESM? I would find it sufficient, if some ideas could be formulated, with hints to future research.**

  Reply: (p. 9, l. 29) It is evident from figures presented in the manuscript, that BESM is an outlier for the cloud feedbacks. This is due to a strong shortwave component response over both the Arctic and the Southern Ocean near Antarctica. Considering the SW CRE/ΔT_{as} [as described by Cess et al. (1989)] and the individual components of feedbacks cloud mask, we can note that those higher values cloud feedback are mainly consequences of the sum of SW CRE/ΔT_{as} and the cloud masking for albedo feedback [-($\lambda_a - \lambda_a^c$)], as shown in Figure 1. For Arctic region, the major contributor for BESM be an outlier is the SW CRE, while for over the ocean near the Antarctic is the albedo feedback cloud mask. In this latter, since the radiative kernel for both all- and clear-sky are the same throughout the models, the difference among them is due to the albedo change [$\Delta a/\Delta T(K_a - K_a^{cs})$]. Over the both regions (Arctic and near Antarctic), an increase in cloud fraction above 850 hPa and a decrease below such level for BESM is observed, which means a low-level clouds upward shifting. Moreover, the increase in cloud cover above 850 hP is stronger than the reduction below principally over the (Figure 2a). As consequence, a negative SW CRE change is present in those regions (but not stronger for BESM comparatively to other models), that is the response to the increase in sun shading (Figure 2b). However, the SW cooling is smaller than the heating provided by LW radiation, as presented in the net effect (Figure 2d). The net radiation heating change is more intense around 60°S, that can be related to the more intense surface albedo change as well as the low-cloud lifting.

- **p. 8, l. 6: "stratocumulus region", this is presumably a different entity and not connected to the BESM peculiarities showing up in Figure 4.**
  Reply: This part was deleted.
- **p. 9, l. 10: The section 4.3 with its figures 6 and 7 (the scatter plots) is not very insightful to me. What are these correlation diagrams (especially Figure 6) supposed to teach the reader? Is this a standard diagnostic? Does the placement of BESM in the third quadrant reveal anything about this model in a physical sense? Please, give some reasoning for the figure's usefulness in the present paper. Interpretation**

of precipitation change patterns is more lucid; yet, it would be fine to know whether, e.g., the southward shift of the SPCZ in BESM does occur in other CMIP models too (even if not in the ensemble mean).
Reply: The diagrams helps understand the models temperature and precipitation dispersion. Moreover, it was used to answer if there is some general behaviour, such as: Do warmer/wetter models in piControl run present also a warmer/wetter in the abrupt4xCO2? Are there some physical limitations? Maybe the way it was presented is not clear, so we decided rewrite the paragraph.

- **p. 9, l. 27: "... near the equator compared to the subtropics ..."; ("as opposed to" suggests that the subtropics grow colder)**
Reply: Done.

- **The statement beginning on p. 10, l. 21 "This increase ..." sounds somewhat counter-intuitive and is, in my opinion, an oversimplification of what the cited papers actually say. Rather, the non-linear increase of water vapor available for condensation, as suggested by the Clausius-Clapeyron relation, is limited towards a more linear relation by tropospheric radiative cooling (Mitchell et al., 1987).**
Reply: New information was provided in order to make the sentence clear (p. 11 l. 26): "The slope of the linear regression is 2.5% of precipitation change per K. This is a value close to that found by Held and Soden (2006).This slope is much inferior to that expected for Clausius-Clapeyron relation, which is about 6,5% of precipitation chang per K. In fact, precipitation increasing is not governed by the availability of moisture but by the surface and tropospheric energy balance (Allen and Ingram, 2002, Mitchell et al. 1987)."

- **p. 10, l. 25: "ACCESS1-0 and HadGEM2-ES use ..." up to the end of this paragraph: that may all be true, but the reader would rather be interested whether this implies anything for BESM.**

Reply: Some discussion about ACCESS1-0 and HadGEM2-ES were suppressed.

- **p. 10, l. 32: "... (SLP) pattern ..."**
  Reply: Done.
- **p. 10, l. 30: This whole paragraph gives a lot of (by no means unfounded!) physical reasoning on tropospheric variability patterns, but in the end takes a simple similarity of the SLP mean response patterns from BESM and from the CMIP ensemble to indicate that BESM may well represent such variability patterns. This is a bold conclusion, which in my view would need backing from actual variability pattern analysis. Is such analysis planned?**
  Reply: The comparison between BESM and ensemble was removed. The BESM variability change is planned to be discussed in a future work.
- **p. 11, l. 23: "It is shown ...", this a very odd 'conclusion', as this statement is common knowledge motivating any research on global warming, and it is certainly not "... shown in this study". Even "... confirmed by this study" would be a summary much too weak for motivating publication of this paper. Please, find a more specific main conclusion that is directed towards the BESM performance.**
  Reply: New information was added.
- **p. 11, l. 31: Here, some information about the BESM radiation module and its evaluation would emphasize that the radiative feedbacks calculated from BESM output within the CMIP range indeed indicate a good representation of such feedbacks inside that model (see major issues).**
  Reply: New information was added.
- **p. 12, l. 5: You might delete "However,"; I see no contradiction of this sentence with the preceding one.**
  Reply: Done.

- **p. 12, l. 12: "... is not the aim for the BESM development", this whole paragraph is a very puzzling wrap-up of your paper (see general remarks).**
  Reply: New information was added.
- **Figure 3, Figure 8: Please ensure that this figure will appear larger in the eventual paper, otherwise it will be hard to decipher.**
  Reply: Done.
- **Caption of Figure 6: "Shaded areas"; this return in several other figure captions, too. You mean the white areas, don't you?**
  Reply: We mean areas fill in with colors.

Complete Figure Captions

Figure 1. SW Cloud feedback and the albedo and SW humidity feedbacks cloud mask-ing for the CMIP5 multi-model ensemble-mean (solid line) and BESM-OA2.5 (solid linewith dots). Inter-model standard deviations for each latitude are in yellow. In blue are the feedback limits based on the maximum and minimum values for each latitudeamong the models, not including BESM-OA2.5.

Figure 2. Vertical profiles of the zonal mean of the 4xCO2 - piControl mean difference-for the following variables: (a) Cloud fraction, Radiative heating-cooling rate (dT/dt) of(b) shortwave, (c) longwave and (d) sum of shortwave and longwave.

Interactive comment on Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-209, 2018.

Printer-friendly version

Discussion paper

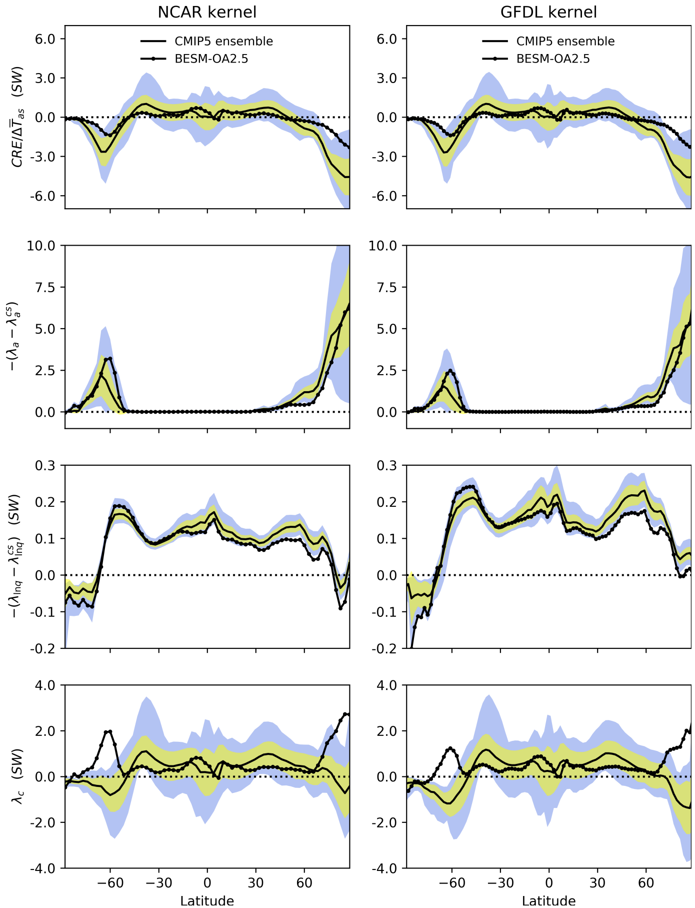
NCAR kernel
GFDL kernel
CMIP5 ensemble
BESM-OA2.5
6.0
3.0
0.0
-3.0
-6.0
$CRE/\Delta\overline{T}_{as}$ (SW)
10.0
7.5
5.0
2.5
0.0
$-(\lambda_a - \lambda_a^{cs})$
0.3
0.2
0.1
0.0
-0.1
-0.2
$-(\lambda_{lnq} - \lambda_{lnq}^{cs})$ (SW)
4.0
2.0
0.0
-2.0
-4.0
λ_c (SW)
−60
−30
0
30
60
Latitude

Fig. 1.

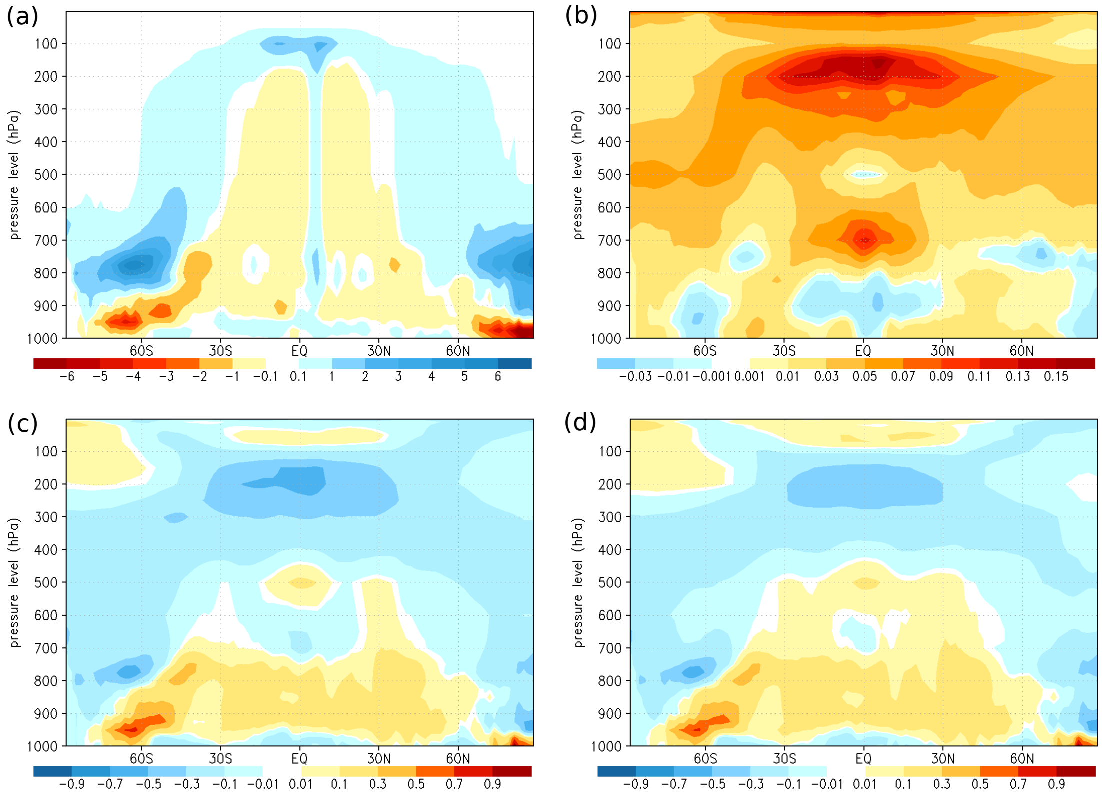
(a)
(b)
(c)
(d)
pressure level (hPa)
100
200
300
400
500
600
700
800
900
1000
60S
30S
EQ
30N
60N
−6 −5 −4 −3 −2 −1 −0.1 0.1 1 2 3 4 5 6
−0.03 −0.01 −0.001 0.001 0.01 0.03 0.05 0.07 0.09 0.11 0.13 0.15
−0.9 −0.7 −0.5 −0.3 −0.1 −0.01 0.01 0.1 0.3 0.5 0.7 0.9

Fig. 2.

~~Overview~~ Assessing the performance of climate change ~~in the~~ simulation results from BESM-OA2.5 ~~climate~~ in comparison to a CMIP5 model ensemble

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Abstract. The main features of climate change patterns, as simulated by the coupled ocean-atmosphere version 2.5 of the Brazilian Earth System Model (BESM-OA2.5) are contrasted with those of other 25 CMIP5 models, focusing on temperature, precipitation and atmospheric circulation. The climate sensitivity to quadrupling atmospheric CO_2 concentration is investigated from two techniques: ~~Gregory et al. (2004)~~ the linear regression (Gregory et al., 2004) and Radiative Kernel (Soden and Held, 2006; Soden et al., 2008) methods. Radiative kernels from both NCAR and GFDL are used in order to decompose the climate feedback responses of CMIP5 models and BESM-OA2.5 into different processes. Applying the ~~Gregory~~ linear regression method for equilibrium climate sensitivity (ECS) estimation, we obtain ~~values ranging from 2.07 to 4.74 K for the CMIP5 models and 2.96 K for BESM , which is~~ a value for BESM close to the ensemble mean value~~(3.30 K ± 0.76)~~. The study reveals that BESM has shown zonally averaged feedbacks estimated from Radiative Kernel within the ensemble standard deviation of the other CMIP5 models. The exceptions are found in the high-latitudes of the Northern Hemisphere and the ocean near Antarctic, where BESM shows values for lapse-rate~~and humidity feedbacks~~ , humidity feedbacks and albedo marginally out of the ~~limit between minimum and maximum~~ standard deviation of CMIP5 multi-model ensemble~~, as well as in the Arctic region and over the ocean near the Antarctic for cloud feedback~~ . For those areas, BESM also presented an strong positive cloud feedback being a outlier comparatively to all analyzed models. Moreover, BESM shows physically consistent changes in the pattern of temperature, precipitation and atmospheric circulation.

1 Introduction

The effects of increased atmospheric CO_2 concentration on the climate system has been studied over the last 120 years (Arrhenius, 1896; Callendar, 1938; Plass, 1956; Kaplan, 1960; Manabe and Wetherald, 1967, 1975; Manabe and Stouffer, 1980; IPCC, 2007, 2013; Pincus et al., 2016; Good et al., 2016, and many others). The human induced increase of atmospheric greenhouse gas (GHG) concentrations, commonly referred to sometimes given as the CO_2-equivalent concentration, contributes to a radiation imbalance at the Top-Of-Atmosphere (TOA), causing less outgoing radiation to leave the Earth System. The trapping of infrared radiation results in temperature rise at the lower levels of the troposphere, as well as an increase in ocean heating content. In addition, the increased GHG concentration can act as a trigger for climate feedback processes that will either amplify or damp the initial radiative perturbation (Cubasch and Cess, 1990). Earth system models (ESM) are the most advanced tools available for analyzing the coupled climate system (atmosphere, ocean, land, and ice) physical processes and their interactions, although they still exhibit important uncertainties in their projections of climate change (IPCC, 2013).

The equilibrium global-mean surface temperature change induced by doubling the CO_2 concentration in the atmosphere, referred to as the Equilibrium Climate Sensitivity (ECS), remains a centrally important measure of a model's climate response to CO_2 forcing. In the fifth Intergovernmental Panel on Climate Change (IPCC) assessment report (AR5), climate model estimates of the ECS range from 2 K to 4.5 K. For more than 40 years, this inter-model spread has been considered one of the most critical uncertainties for the evaluation of future climate changes (IPCC, 2013). This inter-model dispersion arises principally from differences in how climate models simulate climate feedback processes. Among them, the cloud feedback constitutes the largest source of spread for climate sensitivity estimates (Cess et al., 1989, 1990; Dufresne and Bony, 2008; Vial et al., 2013; Caldwell et al., 2016).

Beyond ECS, the response of precipitation to anthropogenic GHG emissions is a topic of great interest in climate science, given the potential consequences on both societies and ecosystems. Changes in precipitation can generally be decomposed into two processes: a thermodynamic component due to increased moisture and no circulation change, and a dynamic component due to circulation change and no moisture change (Bony et al., 2006)(Bony et al., 2006; Seager et al., 2010) . The thermodynamic component gives rise to the well-known 'wet-gets-wetter' and 'dry-gets-drier' pattern of precipitation changes (Held and Soden, 2006). Although this thermodynamic response is robust in theory and models, it is governed by the global-mean surface warming, and therefore uncertainty is likely to arise as in the inter-model spread for ECS (Gregory et al., 2004; Andrew described by Held and Soden (2006), which is associated with Clausius-Clapeyron relation (saturation-specific humidity increase exponentially with temperature) (Marvel and Bonfils, 2013). As to the dynamic component associated with circulation change, it sometimes yields strong deviations from the thermodynamic pattern of precipitation, and is known to dominate the uncertainty in total precipitation due to uncertainties in the regional circulation change (Xie et al., 2015).

The recent development of the Brazilian Earth System Model, ocean-atmosphere coupled version 2.5 (BESM-OA2.5) is an evolution of BESM-OA2.3 first presented by Nobre et al. (2013). The authors scrutinized the BESM-OA2.3 model behavior for decadal climate variability and climate change using extended runs with ensemble members totaling over 2000 years of model simulations. El Niño/Southern Oscillation (ENSO) interannual variability over the equatorial Pacific and the inter-hemispheric gradient mode over the tropical Atlantic on decadal time scale are reproduced by BESM-OA2.3. Veiga et al. (2018) showed that BESM-OA2.5 is able to simulate the general mean present-day climate state, as well as to reproduce the main climate variability, particularly over the Atlantic. Differences between BESM-OA2.3 and BESM-OA2.5 are discussed in the next section.

Here, we assess the main features of climate change patterns as simulated by BESM-OA2.5, with a focus on temperature (climate sensitivity and feedbacks), precipitation and atmospheric circulation. The recent development of the BESM-OA2.5 is a coordinated effort of the National Institute for Space Research (INPE) in Brazil in order to advance the understanding of the causes of the global and regional climate changes and their impacts on the socioeconomic sector. We evaluate how BESM's simulated climate change compares with Coupled Model Intercomparison Project phase 5 (CMIP5) models, discussing peculiarity of BESM climate response. The paper is structured as follows: section 2 presents the description of the new features of BESM2-OA2.5; section 3 presents the methodology, the results are presented in section 4; and section 5 presents the summary and conclusions.

2 Model Description

2.1 BESM-OA2.5

The coupled model BESM-OA2.5 is the result of coupling the Center for Weather Forecast and Climate Studies (CPTEC/INPE) Brazilian Atmospheric Model [BAM (Figueroa et al., 2016)] and the Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model version 4p1 (Griffies et al., 2004) via the Flexible Modular System (FMS) also from GFDL. The dynamical core and physical processes of the atmospheric component of BESM-OA2.5 is the same that used by Veiga et al. (2018). BAM is a hydrostatic model, which its dynamical core is based on the spectral transform method which employs the global spherical harmonic basis functions. The Eulerian Advection scheme option is used in this study but with two-time-level semi-Lagrangian scheme for the transport of moisture and microphysics prognostic variables, which are carried out completely on the model grid space. Simplified fast physical parametrizations are used here due to computationally efficiency requirements for long integrations in comparison that used in the operational Numerical Weather Prediction (NWP) model. The summary of the main differences in physical processes between BAM used in this paper and BAM NWP operational is listed in Table 1. The dynamical equations in BAM are discretized following a spectral transform with horizontal resolution truncated at triangular wavenumber 62 (approximately an equivalent grid size of 1.875°) and 28 layers unevenly spaced in the vertical sigma coordinate with the top level at around 2.73 hPa(if the surface pressure were considered as 1000 hPa). The oceanic component uses a tripolar grid at horizontal resolution of 1° in longitude, and in the latitudinal direction the grid spacing is 1/4° between 10°S-10°N, decreasing uniformly to 1° at 45° and to 2° at 90° in both hemispheres. The ocean grid has 50 vertical levels with a 10-m resolution in the upper 220 m, decreasing gradually to about 370 m at deeper levels.

Veiga et al. (2018) showed that BESM-OA2.5 is able to simulate the general mean climate state. However, substantial biases appear at the simulation associated with double ITCZ over the Pacific and Atlantic Oceans and regional biases in the precipitation over the Amazon and Indian regions. It is worth noting that BESM-OA2.5 shows improvement in ITCZ representation in comparison with the previews version (Nobre et al., 2013). BESM-OA2.5 also is capable to reproduce the most important large-scale interannual and decadal climate variabilities. The Atlantic Meridional Mode (Nobre and Srukla, 1996) is well simulated by the model in term of the spatial pattern and temporal variability, whereas this mode is poorly represented in most CMIP5 models (IPCC, 2013; Liu et al., 2013; Richter et al., 2014; Amaya et al., 2017). The Atlantic Meridional Overturning Circulation (AMOC) represented by BESM-OA2.5 has a mean circulation which is similar to the ensemble AMOC simulated by the CMIP5 models, but slightly lower than the averaged value based on observation. Moreover, the spatial structure of both the North Atlantic Oscillation (NAO) and the Pacific Decadal Oscillation (PDO) variability is well captured (Veiga et al., 2018) .

2.2 Comparison to previous version

The main differences between BESM-OA2.5 and the previous version BESM-OA2.3 described in Nobre et al. (2013) are in the atmospheric model . The current version of BESM uses the BAM defined by Figueroa et al. (2016), but with simpler and computationally cheaper parameterizations (as shown in Table 1).

and how some surface layer variables are estimated, which are important in the coupling between atmosphere and ocean. The total energy balance at the TOA is better represented in BESM-OA2.5 than in BESM-OA2.3, which results in an improvement that reduced to around 2 -4 W m^{-2} the mean global bias of -20 W m^{-2} presented by the latter. It should be noted that BESM-OA2.5 has a new set of parameterizations, mainly regarding a better microphysical processes representation. For instance, the previous model precipitation was parameterized only in terms of the large scale condensation. Moreover, BESM-OA2.5 underwent improvements in the representation of the wind, humidity and temperature in the surface layer, with the use of the similarity functions formulation presented by Jiménez et al. (2012). Based on Monin-Obukhov theory, the wind (u_{10m}), humidity (q_{2m}) and temperature (θ_{2m}) are estimated from the values of the first atmospheric model level and the surface, as described in Eq. (24), (25) and (26) of Jiménez et al. (2012). Furthermore, the similarity functions ψ_m and ψ_h depend on the stability regimes (Businger et al., 1971). For BESM-OA2.5, those regimes are associated with stable ($\zeta/L > 0$) and unstable ($\zeta/L \leq 0$) conditions (Arya, 1988). Those diagnostic variables are important for BESM because they are used in ocean-atmosphere coupling strategy.

One year long global simulations and 6 hourly outputs were done with BAM configured with surface layer schemes based on Arya (1988) and Jiménez et al. (2012), here called BAM-Arya (the original scheme) and BAM-Jimenez (the new scheme), respectively. The normalized root mean square error (RMSE) was computed with respect to the reanalysis NCEP-DOE (National Centers for Environmental Prediction – Department of Energy) version 2 (Kanamitsu et al., 2002). The normalized RMSE of the wind at 10 m, temperature and humidity at 2 m for the two surface layer schemes were investigated. Consistent improvements of BAM-Jimenez relative to BAM-Arya were noted in all the three variables over the oceanic regions, where these variables are used in ocean-atmosphere coupling. The normalized RMSE analysis over the continents presented less consistent results, with improved BAM-Jimenez representation of both winds and temperature, but degraded representation of the humidity field (figures not shown).

Veiga et al. (2018) showed that BESM-OA2.5 is able to simulate the general mean climate state. However, substantial biases appear at the simulation associated with double ITCZ over the Pacific and Atlantic Oceans and regional biases in the precipitation over the Amazon and Indian regions. It is worth noting that BESM-OA2.5 shows improvement in ITCZ representation in comparison with the previews version (Nobre et al., 2013). BESM-OA2.5 also is capable to reproduce the most important large-scale interannual and decadal climate variabilities, mainly that related to Atlantic Ocean. The Atlantic Meridional Mode (Nobre and Srukla, 1996) is well simulated by the model in term of the spatial pattern and temporal variability, whereas this mode is poorly represented in most CMIP5 models (IPCC, 2013; Liu et al., 2013; Richter et al., 2014; Amaya et al., 2017) . The Atlantic Meridional Overturing Circulation (AMOC) represented by BESM-OA2.5 has a mean circulation which is similar to the ensemble AMOC simulated by the CMIP5 models, but slighter lower than the averaged value based on observation. Moreover, the spatial structure of both the North Atlantic Oscilation (NAO) and the Pacific Decadal Oscillation (PDO) variability is well captured (Veiga et al., 2018).

3 Methodology

3.1 Experiments design

For the purpose of this study, climate simulations are performed using BESM-OA2.5 (hereinafter BESM) for the piControl (pre-industrial control scenario, run for 300 years with atmospheric CO_2 concentration invariant at 274 ppmv) and abrupt4xCO_2 (run for 150 years after the abrupt quadrupling of atmospheric CO_2 at year 150 of the piControl simulation) scenarios, which means a spin-up of 150 years. These two scenarios that are commonly employed in CMIP5 studies for climate change assessment (Taylor et al., 2012)(Taylor et al., 2012; Eyring et al., 2016). Climate change is evaluated from the difference between the abrupt4xCO2 and piControl experiments. In addition, BESM's results are compared with a selection of 25 CMIP5 models listed in Table 2. All models, including BESM, are interpolated at 2.5° x 2.5° longitude/latitude horizontal resolution. All CMIP5 models data are available in the Earth System Grid Federation (ESGF).

3.2 Estimates of climate change sensitivity

Here we estimate the climate feedback using two different techniques: Gregory et al. (2004) regression (Gregory et al., 2004) and Radiative Kernel (Soden et al., 2004, 2008) methods. This seemingly redundant procedure was done in order to document BESM climate change responses in face of others CMIP models through different ways. The Gregory method has a more straightforward computation, however it returns only a global-mean value. On the other hand, it is possible to obtain the seasonal feedback for every lat-lon point with Radiative Kernel method, besides the feedback can be decomposed into different processes. Moreover, with the Gregory et al. (2004) linear regression method, it is possible to estimate the ECS.

3.2.1 Linear forcing-feedback regression analysisof Gregory et al. (2004)

Gregory et al. (2004) The regression method to compute the thermal response to radiative forcing is applied for 26 CMIP5 models including BESM. The method consists of the linear regression between the annual change (considering abrupt4xCO2 minus piControl) of the global-mean near-surface temperature (ΔT_{as}) and the net radiation change (ΔR) at TOA.

If G is the radiative forcing imposed on the climate system (here, associated with an abrupt increase in atmospheric CO_2 concentration) and ΔR the resulting radiative imbalance in the global-mean net radiative budget at TOA, then at any time, the response of the climate system to this radiative imbalance responds to the radiative forcing according to the following equation:

$$\Delta R = \lambda \Delta \overline{T}_{as} + G \quad (1)$$

where λ (< 0) is the climate feedback parameter and $\Delta \overline{T}_{as}$ the global-mean near-surface temperature change. In a sufficiently long simulation (coupled atmosphere-ocean models take millennia), when the climate system reaches a new equilibrium (ΔR = 0), . For this method the ECS can be estimated as ECS $= -G/\lambda$ in a shorter simulation (typically of 150 year) without reach the thermodynamical equilibrium. As the ECS is the theoretical equilibrium temperature for doubling CO2, in a quadrupling of CO2 it is necessary to divide its result by 2 (Andrews et al., 2012).

By using this linear forcing-response framework, we can estimate climate sensitivity, radiative forcing, and feedback parameter following the method proposed by Gregory et al. (2004). The values of λ (slope) and G (y-intercept) are estimated through the ordinary least square regression of the global-annual-mean of ΔR against $\Delta \overline{T}_{as}$ in all-sky conditions. Using the same linear technique, we decompose the feedback parameter into shortwave (SW) and longwave (LW) radiation components and extract the clear-sky components we extract the clear sky radiative flux components from the BESM and CMIP data bases in order to estimate the cloud radiative forcing or cloud radiative effect (ΔCRE) defined as the difference between the all-sky and clear-sky feedback parameters (Andrews et al., 2012). Estimates of G, λ, ΔCRE, and ECS for all models are presented in the next section.

3.2.2 Climate feedbacks (Radiative Kernel)

The radiative kernel technique [as in Soden and Held (2006), Soden et al. (2008), Vial et al. (2013)] is used next to partition the feedback parameter λ into contributions from the temperature response (λ_T), water vapor ($\lambda_{\ln q}$), surface albedo (λ_a), and cloud (λ_c) feedbacks plus a residual term Re (Vial et al., 2013), and expressed in Eq. (2).

$$\lambda = \lambda_T + \lambda_{\ln q} + \lambda_a + \lambda_c + \mathrm{Re} \quad (2)$$

It is worth noting that in the regression method the radiative feedback is consistent with the actual radiative transfer scheme used in the climate model, while in the radiative kernel the feeckback is not integraly consistent. In fact, the kernel is obtained from another climate model that is not among the models analyzed. Model intercomparison is easily achieved using this method as the same kernel can be applied to all models (Soden and Held, 2006; Soden et al., 2008)(Soden and Held, 2006; Soden et al., 2008, 2018
. This however assumes that the kernel is independent of models and climate states and that uncertainties in the radiative transfer code used to compute them are small compared to the models' climate responses (Soden et al., 2008).

Following Vial et al. (2013), we decompose the total feedback parameter (λ) into contributions from λ_T, $\lambda_{\text{ln}q}$, λ_a, and λ_c as:

$$
\begin{aligned}
\lambda &= \sum_x \lambda_x + \text{Re} = \sum_x \frac{\partial R}{\partial x}\frac{dx}{d\overline{T}_{as}} + \text{Re} = \sum_x K_x \frac{dx}{d\overline{T}_{as}} + \text{Re} \\
\lambda &= \left(K_{T_s}\frac{dT_s}{d\overline{T}_{as}} + K_T\frac{dT}{d\overline{T}_{as}}\right) + \left(K_{\text{ln}q}\frac{d\text{ln}q}{d\overline{T}_{as}}\right) \\
&\quad + \left(K_a\frac{da}{d\overline{T}_{as}}\right) + \lambda_c + \text{Re}
\end{aligned} \tag{3}
$$

where the temperature feedback has been separated into the Planck feedback (vertically uniform tropospheric warming equal the surface warming) and lapse rate feedback (deviation from the tropospheric uniform warming):

$$
\begin{aligned}
\lambda_T = \lambda_p + \lambda_{lr} &= \left(K_{T_s}\frac{dT_s}{d\overline{T}_{as}} + K_T\frac{dT_s}{d\overline{T}_{as}}\right) \\
&\quad + \left(K_T\frac{dT}{d\overline{T}_{as}} - K_T\frac{dT_s}{d\overline{T}_{as}}\right)
\end{aligned} \tag{4}
$$

and where the water vapor feedback is computed assuming constant relative humidity (Soden et al., 2008; Shell et al., 2008; Jonko et al., 2013).

In Eq. (3), K_x (the radiative kernel for a variable x) and x [temperature (T_s and T, in K), natural logarithm of humidity (ln$q$, in kg/kg) and albedo (a, dimensionless)] are function of longitude, latitude, and pressure vertical coordinates in monthly climatology. To obtain tropospheric averages, the water vapor and temperature feedbacks are vertically integrated from surface up to the tropopause, defined as being 100 hPa in the Equator, and varying linearly to 300 hPa in the Poles. The stratospheric temperature and water changes is not accounted for calculating the feedbacks, and they are shifted to the residuum.

We used both GFDL and National Center for Atmospheric Research (NCAR) radiative kernels to estimate climate feedbacks. More details on how the radiative kernels are obtained can be found in Soden et al. (2008) and Shell et al. (2008).

Due to the non-linearities involving clouds and net radiation at TOA (Soden et al., 2008), the cloud feedback is not calculated directly from these radiative kernels, which represents one of the key limitations of the kernel method. Instead, the cloud feedback is ~~estimated~~ approximated using the cloud radiative forcing (ΔCRE) corrected for non-cloud feedbacks as in Soden et al. (2004, 2008). After the calculation of non-cloud feedbacks for both all-sky and clear-sky (~~subscript cl~~superscript cs) conditions, we thus estimate the cloud feedback (λ_c) as:

$$
\begin{aligned}
\Delta\text{CRE} &= \Delta R - \Delta R^{cs} \\
\Delta\text{CRE}_k &= (G - G^{cs})_{CO_2} - \Delta\overline{T}_{as}\sum_x(\lambda_x - \lambda_x^{cs}) \\
\Delta\text{CRE}_a &= \Delta\text{CRE} - \Delta\text{CRE}_k \\
\lambda_c &= \frac{\Delta\text{CRE}_a}{\overline{T}_{as}}
\end{aligned} \tag{5}
$$

Where, ~~ΔR_{cl}~~ ΔR^{cl} is the clear-sky net radiation flux at TOA. Following Soden et al. (2008), $(G - G_{cl})_{CO_2}$ was considered being equal to 2x0.69 W m^{-2} . Finally, a 30-year mean relative to the period from 120th to 150th year of each scenario was used for all feedbacks estimation.

3.3 Changes in the atmospheric circulation and precipitation

Monthly mean climatologies are computed for the last 30 years of piControl and abrupt4xCO2 runs, and the projected climate response to CO_2 increase is evaluated from the difference between these abrupt4xCO2 and piControl monthly mean climatologies. The statistical significance of this difference is calculated based on the t-Student test. The significance level used is of 90%. Furthermore, in order to evaluate how similar two spatial pattern are, we used the spatial inner product calculated as $\sum(A_i \cdot B_i)/(|A| \cdot |B|)$, where A and B are the 2-D variables and i is the spatial index related to their lat-lon coordinates.

4 Results

4.1 G, λ, ΔCRE and ECS estimated by Gregory method

Figure 1 shows the linear regressions of ΔR , ΔLW (clear-sky) and ΔSW (clear-sky) against $\Delta\overline{T}_{as}$ for BESM. These linear regressions based on all-sky data are used to estimate ECS, G and λ, here in Figure 1 the regressions are also based on clear-sky data to obtain ΔCRE (as mentioned in the previous section). BESM features G = 8.62 W m^{-2}, λ = -1.45 W m^{-2} K^{-1}, ΔCRE = -0.13 W m^{-2} K^{-1}, and ECS = 2.96 K.

The parameters G, λ, ΔCRE and ECS computed for all models are shown in Table 3. The ~~results for ECS found here are similar~~ climate sensitivities of 26 CMIP5 coupled models (including BESM-OA2.5) were assessed as it was performed by Andrews et al. (2012) for 15 CMIP5 coupled models. In the present work, we included the following models: ACCESS1-0, ACCESS1-3, bcc-csm1-1, BESM-OA2.5, BNU-ESM, CCSM4, FGOALS-g2, FGOALS-s2, GISS-E2-H, GISS-E2-R, e inmcm4. For the 15 same models, we found similar results to those of Andrews et al. (2012), which range between 2.07 to 4.74 K. The possibly small differences we attribute to the interpolation of the data as detailed in previous section. G and λ vary from 5.01 to 8.95 W m^{-2} and from -1.66 to -0.60 W m^{-2}K^{-1}, respectively. Inter-model spread in G among the models are due to differences in the radiative codes used, as well as the rapid adjustment processes of the troposphere and surface (Collins et al., 2006; Gregory and Webb, 2008; Andrews and Forster, 2008). The spread in the ECS is more influenced by λ than G (Figure 2), as was also suggested by Andrews et al. (2012). The correlation coefficient between ECS and λ is -0.82, which is significant at 1% of confidence interval (Figure 2b). On the other hand, the correlation between ECS and G is -0.01, witch is not statistically significant (Figure 2a). Thus, the ratio of climate restoration (associated with λ) better explains the dispersion in ECS than the initial radiative imbalance triggered by the CO_2 increase (related to G). Despite BESM presenting one of the highest G among all the CMIP5 models, it shows a response to doubling CO_2, which is inside the warming range of 3.30±0.76 K presented by the models of the ensemble.

ΔCRE for BESM is -0.13, while CMIP5 models have ΔCRE varying from -0.50 to 0.70 W m^{-2} K^{-1}. This term does not consider the masking effects of clouds as the ΔCRE$_a$ estimated by the radiative kernel method (Eq. 5). Therefore, ΔCRE cannot be interpreted as a change in the cloud properties alone.

4.2 Climate Feedbacks estimated by Radiative Kernel method

Figure 3 shows the global-mean feedbacks for lapse-rate, water vapor, lapse-rate plus water-vapor, albedo, and cloud (SW, LW, and total) for each CMIP5 model. The Both radiative kernels are used to test whether the results are sensitive to the particular choice of radiative kernel, and whether inter-model differences are greater than the distribution of the radiatively active constituents of the base model. It is worth clarifying that positive/negative values of feedbacks contribute to the amplification/damping of global warming. The strongest positive feedback (Figure 3) is due to the water vapor (mean value: 1.39 W m^{-2}K^{-1}), followed by clouds (mean value: 0.96 W m^{-2}K^{-1}), and surface albedo (mean value: 0.32 W m^{-2}K^{-1}). The Planck feedback global-mean is negative with an average of -3.60 W m^{-2}K^{-1} (not shown in Figure 3) followed by lapse-rate feedback with -0.77 W m^{-2}K^{-1}.

For all models in Figure 4, there is an almost constant Planck feedback about -4 W m^{-2} K^{-1} from 90°S to 60°N, with a notable increased ensemble standard deviation in the subantarctic latitude (around 60°S). The exception is in the Arctic region where mean value reaches -10 W m^{-2} K^{-1} with almost the same increased standard deviation. BESM in the subantarctic and Arctic latitudes presented one of the lowest values for Planck feedback, revealing that BESM has a stronger vertically homogeneous warming among the CMIP5 models. Furthermore, for those same region BESM showed greater lapse-rate feedback, corroborating that BESM does not have a higher contrast between surface and upper troposphere temperatures as other models.

As described in Soden et al. (2008), both lapse-rate and water vapor feedbacks partially compensate each other. In the tropics, negative values of the lapse-rate feedback predominate, while in the Polar regions the signal is the opposite (Figure 4). The faster The stronger increase in upper troposphere temperature than near-surface temperature in all models (shown in Figure 4) results in a negative lapse-rate feedback in the Tropics. On the other hand, the high-latitude warming is more close to the surface, which reflect in a positive lapse-rate feedback. Considering the Clausius-Clapeyron relation, the upper troposphere with an increased temperature could allow more water vapor concentration, leading to a positive water vapor feedback. The opposite is also true, e.g. positive lapse-rate feedback could exist as a result of a lower warming and humidity at the upper troposphere than near the surface, which can be associated with a negative water vapor feedback. Hence, the However, recently Po-Chedley et al. (2018) showed that the correlation between lapse-rate and water vapor feedbacks can be combined as shown in Figure 3. Nevertheless, the is more related to the patter of surface warming than the covariation of the local tropical lapse-rate and water vapor feedbacks. For water vapor feedback constitutes a strong positive feedback and the sum of them also results in a positive effectit is observed a greater dispersion in the Tropics, with BESM systematically presenting values below of the ensemble mean for the same latitude band. This behavior extends throughout the Northern Hemisphere.

The albedo feedback is important in regions where there is a reduction in sea-ice and snow cover near the Polar Regions (Figure 4). The positive signal of the albedo feedback implies that the reduction in albedo corresponds to an increase in both the radiation budget at the TOA (due to the reduction of upward shortwave radiation) and temperature near the surface. The albedo feedback shows a large dispersion among models in northern high latitudes, as noted in yellow (standard deviation) and blue (limits between minimum and maximum) shaded areas in Figure 4. It is emphasized that not only the albedo feedback contributes to the Arctic Amplification. In fact, as discussed by Pithan and Mauritsen (2014), the albedo feedback is the second main contributor to Arctic Amplification, while the largest contributor is the temperature feedback. The explanation for the importance of temperature feedback during the surface warming, is in the fact that more energy is radiated back to space in low latitudes, compared with the Arctic. BESM shows an albedo feedback greater than the ensemble standard deviation over Southern ocean around 60°S. This same latitude is where Planck and lapse-rate feedbacks are out of models limits for BESM. Also, as a consequence of sea-ice melting, that region experienced a stronger increase in atmosphere temperature comparatively to the ensemble spread. Those negative values are more evident over the Tropical Pacific and North Atlantic oceans.

Regarding cloud feedbacks, most of the inter-model spread arise from the SW component (figures 3 and 4). This dispersion is also noted in the standard deviation and in the limit between minimum and maximum of zonally averaged cloud feedback shown in Figure 4. The SW cloud feedback ranges from -0.28 to 1.40 W $m^{-2}K^{-1}$, while the LW cloud effect ranges from 0.10 to 0.96 W $m^{-2}K^{-1}$. The combined SW and LW cloud effects result in a positive cloud feedback ranging from 0.35 to 1.69 W $m^{-2}K^{-1}$. This result is similar to that found by Soden et al. (2008) for CMIP3 [IPCC AR4, IPCC (2007)] models, where they presented a near neutral and positive cloud feedback. ΔCRE computed by using the Gregory et al. (2004) methodology (Section 4.1) is related to the cloud feedback (estimated from corrected ΔCRE - Section 4.2), even though ΔCRE and λ_c could present opposite signals for some models. For instance, BESM shows -0.13 BESM presents positive values of around 0.5 W $m^{-2}K^{-1}$ and 0.95for both SW and LW cloud feedback, which results in a total cloud feedback of 1.0 W $m^{-2}K^{-1}$ for ΔCRE and λ_c, respectively. (Figure 3). The highest positive values are in regions with strong albedo feedback (Figure 4).

Overall, BESM lies within the range of CMIP5 models, with global-mean values of 1.24 W $m^{-2}K^{-1}$, 0.95 W $m^{-2}K^{-1}$, 0.27 W $m^{-2}K^{-1}$, -3.57 W $m^{-2}K^{-1}$ and -0.71 W $m^{-2}K^{-1}$ for water vapor, cloud, albedo feedbacks, Planck and lapse-rate feedbacks, respectively. However, differences between BESM and the other models are found in the high latitudes, where BESM exhibit lapse-rate and humidity feedbacks marginally out of range of values set by the CMIP5 multi-model ensemble (Figure 4). It is also evident from figures 4 and 5 that BESM is an outlier for the cloud feedbacks. This is due to a strong shortwave component response over both the Arctic and the Southern Ocean near Antarctica. Even though BESM presents an acceptable radiation closure at TOA (less than 2 W m^{-2} bias), it is deficient in representing shortwave radiation over the Arctic and the Southern Ocean, as a result of negative biases of middle and high clouds in the extratropics as shown by Casagrande et al. (2016). Therefore, it is plausible that such a deficiency in cloud representation could cause the high positive values in SW cloud feedback . It is worth highlighting that the cloud feedback is one of the biggest causes of uncertainty in climate projections (IPCC, 2013). BESM has also a larger negative cloud feedback in the stratocumulus regions compared to the CMIP5 ensemble (figures 4 and 5). This, combined with its anomalous positive high latitude cloud feedback, is qualitatively consistent with the results presented in McCoy et al. (2016) showing an anti-correlation across models in Considering the SW CRE [as described by Cess et al. (1989)] and the individual components of feedback cloud mask, we can note that those higher values in cloud feedback are mainly consequences of the sum of SW CRE and the high latitude optical depth feedback and the lower latitude cloud amount feedback . effect of cloud masking for albedo feedback $[-(\lambda_a - \lambda_{ac})]$, as shown in Figure 6. For Arctic region, the major contributor for BESM be an outlier is the SW CRE, while for over the ocean near the Antarctic is the albedo feedback cloud mask. In this latter, since the radiative kernel for both all- and clear-sky are the same throughout the models, the difference among them is the albedo change $[\Delta a/\Delta\bar{\bar{T}}_{as}(K_a - K_a^{cs})]$. Over the both regions (Arctic and near Antarctic), an increase in cloud fraction above 850 hPa and a decrease below that level for BESM is observed, which means a low-level clouds upward shifting . Moreover, the increase in cloud cover above 850 hP is stronger than the reduction below (Figure 7a). As consequence, a negative SW CRE change is present in those regions (but not stronger for BESM comparatively to other models), that is the response to the increase in sun shading (Figure 7b). However, the SW cooling is smaller than the heating provided by LW radiation, as presented in the net effect (Figure 7d). The net radiation heating change is more intense around 60°S, that can be related to the more intense surface albedo change, as well as the low-cloud lifting. Despite of the lost of SW energy at surface (related to the increased sun shading), which results in a SW cloud radiative effect negative, it is overcome by the albedo feedback cloud mask, that contribute to a cloud feedback positive over those two regions.

4.3 Changes in temperature, atmospheric circulation and precipitation

Figure 6 8 shows the annual mean for surface temperature change between the abrupt4xCO2 and piControl scenarios for the ensemble of 25 CMIP5 models and BESM. It is clearly seen in Figure 6 8 that despite the generalized increase of the air temperature over most of the globe in both panels, BESM shows a generally lower temperature increase, principally over the continental areas. The CMIP5 ensemble shows a mean continental temperature increase of 6.78 K, while BESM shows 5.57 K. Notwithstanding, the spatial pattern of temperature increase is similar, as measured by the spatial inner product (as described in the previous section) between the two upper panels in Figure 78, which results in the value of 0.96 (values near 1 mean that both variables have similar spatial pattern, whereas values near 0 mean that there are few spatial correspondences between variables). One point of interest of the scientific community is the relative low temperature increase over the subpolar North Atlantic, also refered as warming hole (Drijfhout et al., 2012). In the CMIP5 ensemble mean, the North Atlantic does not show a decrease of temperature, but it is the region with the smallest temperature increase globally; while BESM shows an area of temperature decrease in this region. Such a decrease is also present in other 6 analyzed models (CSIRO-Mk3-6-0, FGOALS-s2, GFDL-ESM2G, GFDL-ESM2M, GISS-E2-R, and inmcm4). This results are consistent with Drijfhout et al. (2012), who showed that both observations and CMIP5 models present maximum cooling in the center of the subpolar gyre. Those authors argue that there are evidences that both subpolar gyre and AMOC adjust in concert with different time lags.

The regions with the largest temperature increase in the abrupt4xCO2 scenario are the Polar Regions, mainly over the North Pole. The equatorial Pacific shows an increase in temperature in the abrupt4xCO2 scenario when compared with the piControl, both in the CMIP5 ensemble and BESM. Such changes in the Pacific mean state is in line with the IPCC-AR5, in which it is shown that the Pacific Ocean becomes warmer near the equator as opposed compared to the subtropics in the CMIP5 projections (Liu et al., 2005; Gastineau and Soden, 2009; Cai et al., 2015). The scatter plot of global average of abrupt4xCO2 versus piControl presented in Figure 6 8 is an additional information that helps to understand the models dispersion around the mean value. It indicates Even though there is a predominance of models in either quadrants 1 or 3 (top-right and bottom-left, respectively)~~and half of that in quadrants 2 and 4 (top-left and bottom-right, respectively). This is indicative of the general tendency for~~ , it is not possible to note a linear relationship. It means that models with warmer/cooler mean climates in the piControl runs ~~to~~ aparently does not present a corresponding warmer/cooler climate for the abrupt4xCO2 experiments~~; but not always. As it is the case for 1/3 of all the models considered, BESM falls out of quadrants 1 or 3.~~ .

Figure ~~7~~ 9 shows the precipitation changes between abrupt4xCO2 and piControl scenarios for multi-model ensemble and BESM. The results are approximately similar to Held and Soden (2006), with wet regions becoming wetter (near-equatorial and subpolar regions) and dry regions becoming drier (centered around 30° in both hemispheres). The precipitation pattern in the CMIP5 ensemble has increased precipitation over the equatorial Pacific, which can be related to the equatorial Pacific warming pattern shown in the temperature change (Figure ~~6~~8). Also, the CMIP5 ensemble shows a decrease in precipitation in northern South America. BESM precipitation pattern is similar to the spatial patterns in the CMIP5 ensemble, yet with some notable discrepancies. For example, the decrease in precipitation over the South Pacific shown in the CMIP5 ensemble plot is extended into the Indonesian region in BESM. It is also worth noting in the BESM simulation that the South Pacific convergence zone (SPCZ) shifts southward in the abrupt4xCO2, compared to piControl. Over South America, the precipitation change pattern is similar to that which occurs during El Niño years (Kayano et al., 1988; Marengo and Hastenrath, 1993; Grimm and Tedeschi, 2009), with increased precipitation over southeastern South America and decreased precipitation over northern/northeastern South America, in both the multi-model ensemble and BESM. The scatter plot in Figure ~~7~~ 9 suggests a linear relationship between experiments, meaning that models that have a larger (smaller) global average precipitation in piControl scenario show a larger (smaller) precipitation in abrupt4xCO2 scenario. In the scatter plot of Figure ~~7~~9, BESM has value near the center, which means that it presents global averaged precipitation values similar to the average of all the models used in the ensemble.

Figure ~~8~~ 10 depicts the scatter plot of ECS versus the change in precipitation between Abrupt4xCO2 and piControl (ΔPr), for all models considered. It is worth noting that all the models present increased global-mean precipitation for the quadrupling of atmospheric CO_2 with piControl pre-industrial CO_2 concentrations (positive values in y-axis in Figure ~~8~~10). The apparent linear relationship between differences (abrupt4xCO2 minus piControl) in global-mean precipitation and ECS is also evident in Figure ~~8~~10, in which warmest models tend to have highest changes in precipitation. ~~This increase in precipitation with warming is~~ The slope of the linear regression is 2.5% of precipitation change per K, which is close to that found by Held and Soden (2006).This slope is much inferior to that expected for Clausius-Clapeyron relation, which is about 6,5% of precipitation chang per K. In fact, precipitation increasing is not governed by the ~~increase in atmospheric radiative cooling (Allen and Ingram, 2002; Held and Soden, 2006; Thorpe and Andrews, 2014).~~ availability of moisture but by the surface and tropospheric energy balance, including in this process the surface radiative heating, surface latent heat flux and radiative cooling of troposphere (Allen and Ingram, 2002).

MRI-CGCM3, ACCESS1-0, and HadGEM2-ES show greater deviation from the linear fit shown in Figure ~~8~~10. Also, BESM is marginally out of the residual standard error interval, with 9.5% increased precipitation (the error limit is 9.2%). ACCESS1-0 and HadGEM2-ES use the same atmospheric model (Bi et al., 2013; Dix et al., 2013), which could explain the lower increase in precipitation in both coupled models. ~~Another reason could be that these two models present a better representation of the~~

~~SW absorption by water vapor in their shortwave radiative transfer scheme, as shown in Figure 4 of DeAngelis et al. (2015), which leads to smaller precipitation response (per unit global warming).~~

As in the case of temperature and precipitation changes, we are also interested in understanding the alteration in the BESM atmospheric circulation (compared to other models) considering a quadrupling of CO_2 concentration. The sea level pressure (SLP) response patterns shown in Figure ~~9~~ 11 depict a poleward shift of the subtropical high pressure cells for both the CMIP5 ensemble and BESM. Furthermore, when the models are subjected to the increase of atmospheric CO_2 concentration, a decrease in SLP over the Polar regions is evident. This SLP decrease over the Polar regions and the increase in mid-latitudes indicate a positive trend of Arctic Oscillation (AO) and Antarctic Oscillation (AAO) episodes, which have already been reported in the studies of Fyfe et al. (1999), Cai et al. (2003), Miller et al. (2006). It is also interesting to note the statistically significant SLP decrease (increase) over the eastern (western) Pacific, a pattern that might be indicative of an ENSO-like pattern in scenarios with increased CO_2 concentration. This pattern is coherent with those depicted in Figure ~~6~~ 8 for SST changes in a $4xCO_2$ scenario. ~~As for the case for near-surface temperature, the spatial inner product between multi-model ensemble and BESM has a high value (0.95) for SLP changes. This is an indication that BESM has a climate spatial response consistent with that presented by the other CMIP5 models ensemble.~~

Results for piControl scenario (contours in Figure ~~10~~12) show that the Southern Hemisphere subtropical jet, depicted by the core of maximum eastward zonal wind, is localized around 35°S, 200-150 hPa, in both the CMIP5 ensemble and BESM. We note that regions with the strongest positive values (anomalous eastward wind) in all levels show a southward displacement in both panels of Figure ~~10~~ 12 (BESM and the CMIP5 ensemble). This is consistent with the poleward displacement of high SLP center shown in Figure ~~9~~11. Also, as the high-pressure centers experienced a poleward shift, the pressure gradients are intensified in subpolar areas, and consequently increased near-surface wind velocity is a result, following the geostrophic approximation $[u \approx -(1/f\rho)(\partial p/\partial y)]$, where f is the Coriolis parameter and ρ is the air density.

Figure ~~11~~ 13 shows the average 5°N – 5°S (Walker circulation) differences between abrupt4xCO2 and piControl for omega (shades) and zonal wind and vertical velocity (vectors). According to the pattern of omega in piControl (contours), the multi-model ensemble and BESM show subsidence over an extensive area in the Pacific (150°E – 90°W), which intensity is reduced in the abrupt4xCO2 simulation, as indicated in Figure ~~11~~ 13 (blue). This is coherent with near-surface temperature patterns (Figure ~~6~~8), which show an equatorial warming pattern in the mean state (e.g. during El Niño years a weakening of the Walker circulation occurs). Furthermore, there are positive values in the difference between the two scenarios over South America (around 75°W), consistent with the decrease of precipitation in tropical South America, in both BESM and the CMIP5 ensemble (Figure ~~7~~9).

5 Conclusions

piControl and abrupt4xCO2 scenarios for 25 CMIP5 models have been contrasted with those generated by the BESM-OA2.5 model~~. It is shown in this study that the abrupt increase in atmospheric CO_2 concentration is associated with the rise in the global-mean temperatureand changes in~~ , based on their climate sensitivity parameters such as the Equilibrium Climate

Sensitivity (ECS) and climate feedbacks. Also, the changes in the temperature, atmospheric circulation and precipitation patterns were investigated.

~~Taking into account a quadrupling of pre-industrial CO_2 concentration, we demonstrate that BESM is in line with CMIP5 ensemble in terms of climate sensitivity as well as global and zonally averaged climate feedbacks. For instance, applying the Gregory et al. (2004) method for climate sensitivity estimation~~Applying the linear regression method (Gregory et al., 2004), we obtain ECS for the 25 CMIP5 models analyzed ranging from 2.07 to 4.74 K, with BESM showing 2.96 K, close to the ensemble mean value (3.30 ± 0.76). BESM has one of the biggest radiative forcing (G) with 8,62 W m^{-2}K, which is related to the radiative code transference and the rapid adjustment process (Collins et al., 2006; Gregory and Webb, 2008; Andrews and Forster, 2008) . Both G and the climate sensitivity (λ) define the ECS with this method, however, only λ presents a significant correlation with ECS, corroborating with Andrews et al. (2012) results.

To go further in the analysis, the radiative kernel method is used to separate the climate feedback into Planck, lapse-rate, water vapor, albedo and cloud feedbacks. ~~BESM has shown zonally averaged feedbacks within the ensemble standard deviation of the other CMIP5 models. The exception being in~~ Two regions presented considerable standard deviation for Plank, lapse-rate and albedo: the Arctic region and over the ocean near the Antarctic~~for cloud feedback~~. Over those regions, BESM-OA2.5 ~~shows larger values~~ also shows cloud feedback values larger than the zonal mean plus standard deviation for the analyzed models, ~~mainly due to deficiencies noted in the shortwave radiation component of~~ reaching near 3 W $m^{-2}K^{-1}$ while the zonal mean is around 0 W $m^{-2}K^{-1}$. For BESM-OA2.5 ~~. Despite BESM's good total (shortwave plus longwave) radiation closure at TOA, it shows deficiency in representing shortwave radiation over the Arctic and the ocean near the Antarctic (Casagrande et al., 2016)~~ was observed a shift upward of the low-cloud cover and an increase in cloud cover between 850 and 700 hPa, what is responsible for a sun shading at surface, increasing the outgoing SW radiation at the TOA. Moreover, BESM-OA2.5 presented a greater albedo change than other models, specially in the subantarctic area. Despite of the lost of SW energy at surface, which results in a negative SW cloud radiative effect, it is overcome by the albedo feedback cloud mask, that contribute to a positive cloud feedback over those regions.

Atmospheric circulation patterns in BESM-OA2.5 are similar to patterns in the multi-model ensemble and in other studies regarding near-surface temperature (IPCC, 2007, 2013). For precipitation, the thermodynamic component evidences the well-known 'wet-gets-wetter' and 'dry-gets-drier' pattern of precipitation changes (Held and Soden, 2006). ~~However,~~ BESM-OA2.5 along with the CMIP5 ensemble have consistent weakening of Walker circulation, principally in the Pacific and over northern South America, which has been reported in previous studies (Collins et al., 2010; DiNezio et al., 2012; Huang and Xie, 2015; Cai et al., 2015). Regarding SLP, both BESM and the CMIP5 ensemble indicate a poleward displacement of the subtropical high pressure systems, as shown in other studies (Fyfe et al., 1999; Cai et al., 2003; Miller et al., 2006). In line with such displacement, the subtropical jet is also shifted polewards, and it is more evident in the Southern Hemisphere.

~~The BESM (version 2.5) results show climate sensitivity and thermodynamical responses similar to the other CMIP5 ensemble, but it is not the aim for the BESM development. More than that, BESM has the objective of being~~ BESM-OA2.5 is an additional climate model with ability of reproduce changes that are physically understood in order to study the global climate system. In this sense, ~~a new version of~~ the BESM results contributed to better understand the inter-model spread in cloud feedback. Furthermore, BESM is under development in order to overcome the present extra-tropical and tropical climate simulation deficiencies, as reported in Casagrande et al. (2016) and Veiga et al. (2018), respectively. ~~Notwithstanding, the inter-model spread in climate sensitivity discussed here, mainly that regarding the cloud feedback, remains a scientific challenge for the future.~~

Code and data availability

The BESM-OA2.5 source code is freely available after signature of a license agreement. Please contact Paulo Nobre to obtain the source code and data of BESM-OA2.5.

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

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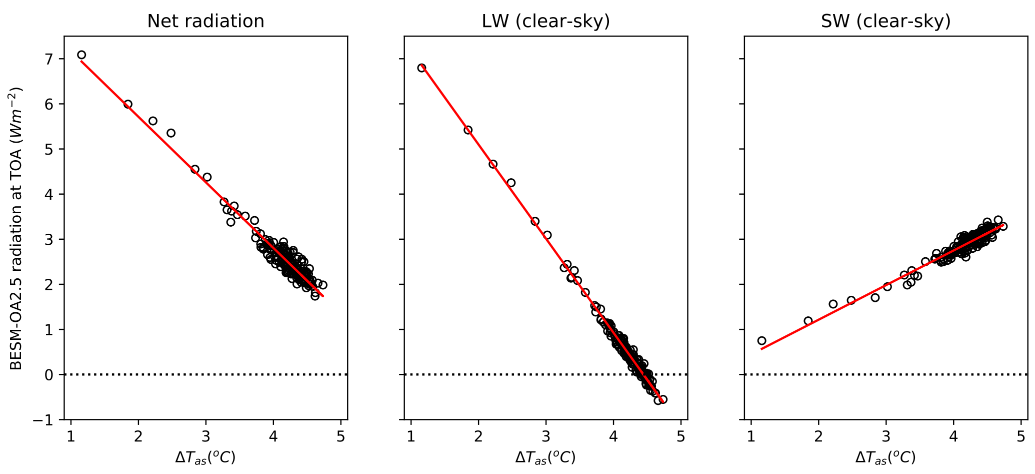


Figure 1. Annual global-mean linear regression between $\Delta\overline{T}_{as}$ and: (a) Net radiation, (b) ΔLW (clear-sky) (c) ΔSW (clear-sky) for BESM-OA2.5

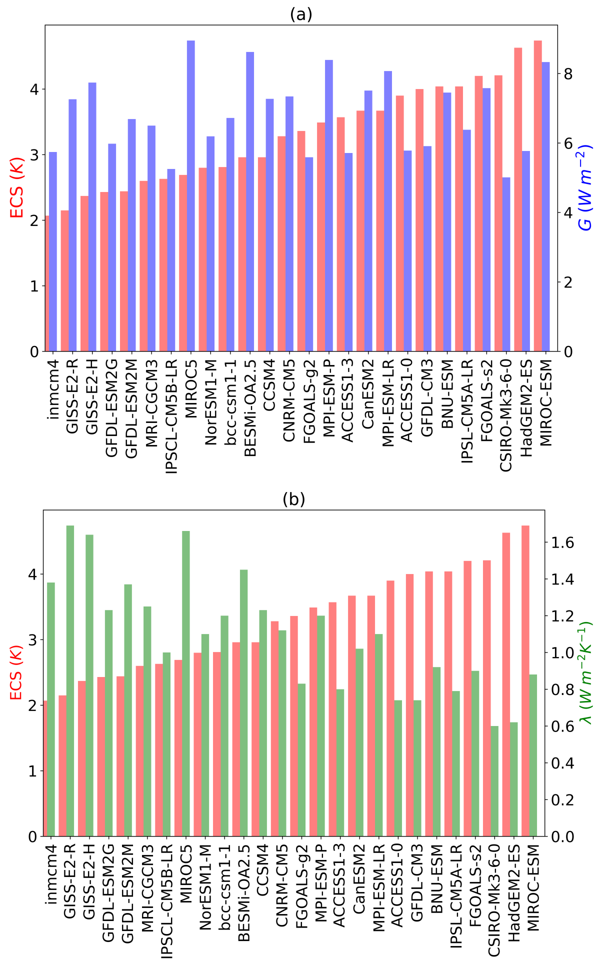


Figure 2. (a) ~~ECS~~ Equilibrium Climate Sensitivity (ECS, in red) and ~~G~~ Radiative forcing (G, in blue) values with ECS increasing from left to right; (b) ECS (red) and ~~λ~~ climate sensitivity (λ, in green) with ECS increasing from left to right.

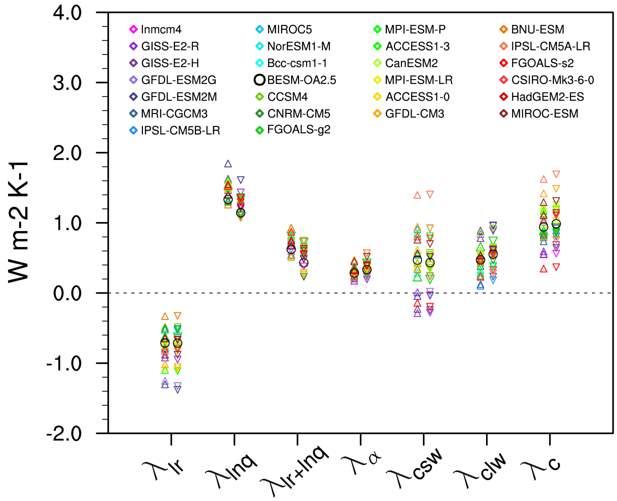


Figure 3. Global-mean feedbacks for 25 CMIP5 models and BESM-OA2.5 (circle). Changes in abrupt4xCO2 relative to piControl are averaged over years 120-150. The triangles mean estimated feedback values using NCAR radiative kernel whereas upside-down triangles mean estimated feedback values using GFDL radiative kernel.

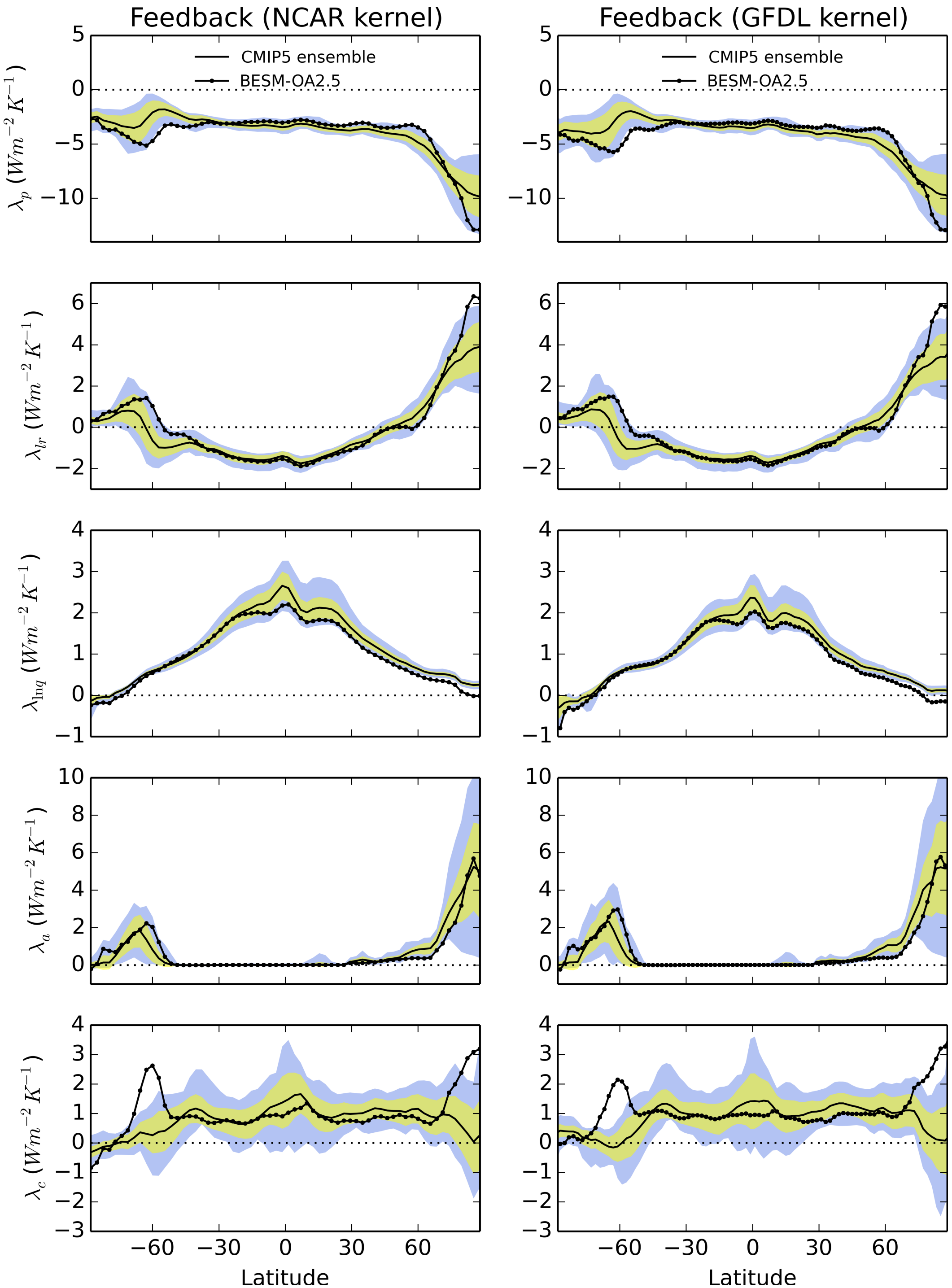


Figure 4. Feedbacks for the CMIP5 multi-model ensemble-mean (solid line) and BESM-OA2.5 (solid line with dots). Inter-model standard deviations for each latitude are in yellow. In blue are the feedback limits based on the maximum and minimum values for each latitude among the models, not including BESM-OA2.5. All feedbacks are based on the averaged over years 120-150.

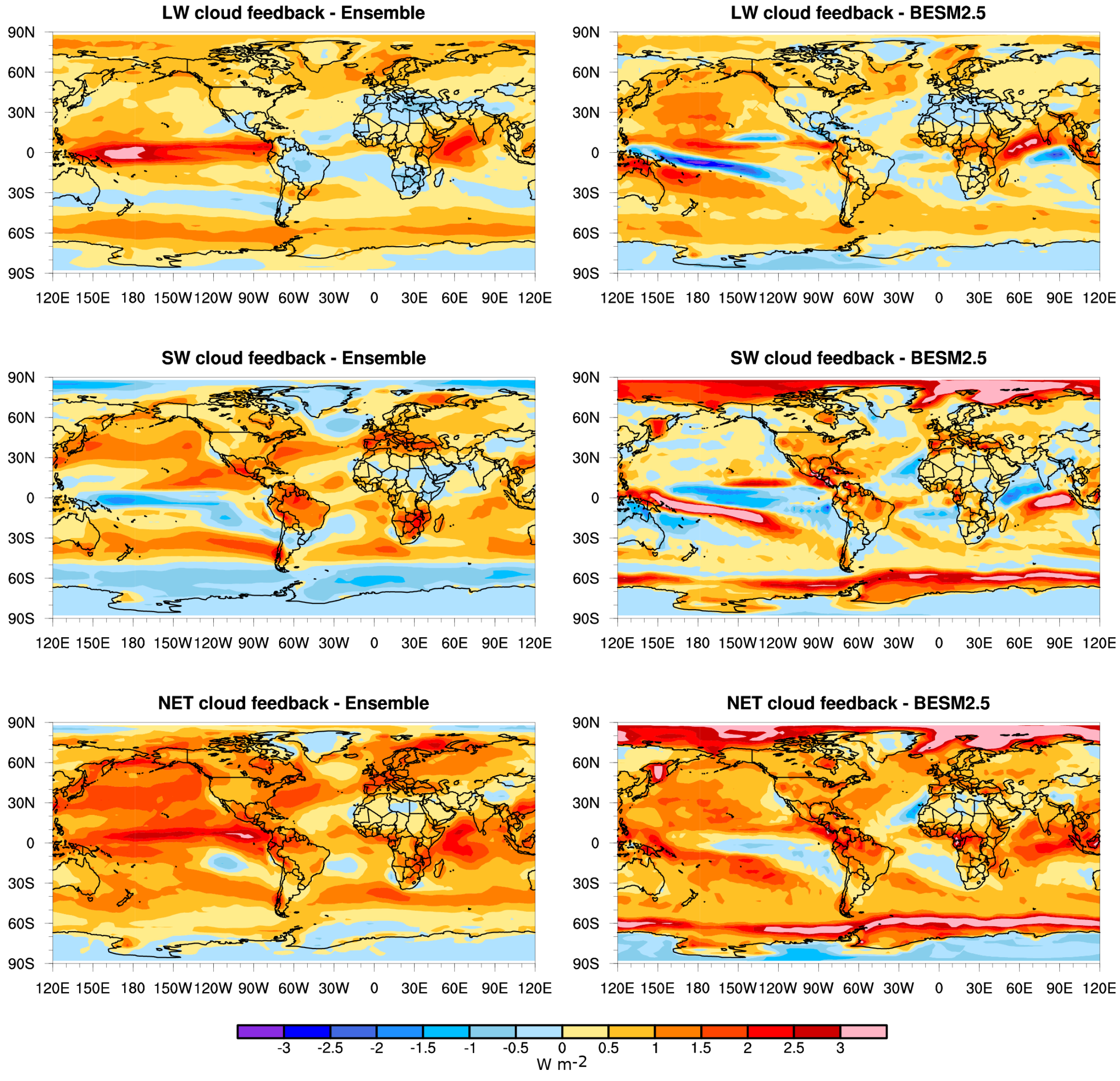


Figure 5. Cloud feedbacks using NCAR radiative kernel for CMIP5 ensemble (left column) and BESM-OA2.5 (right column). Those results are based on the averaged over years 120-150.

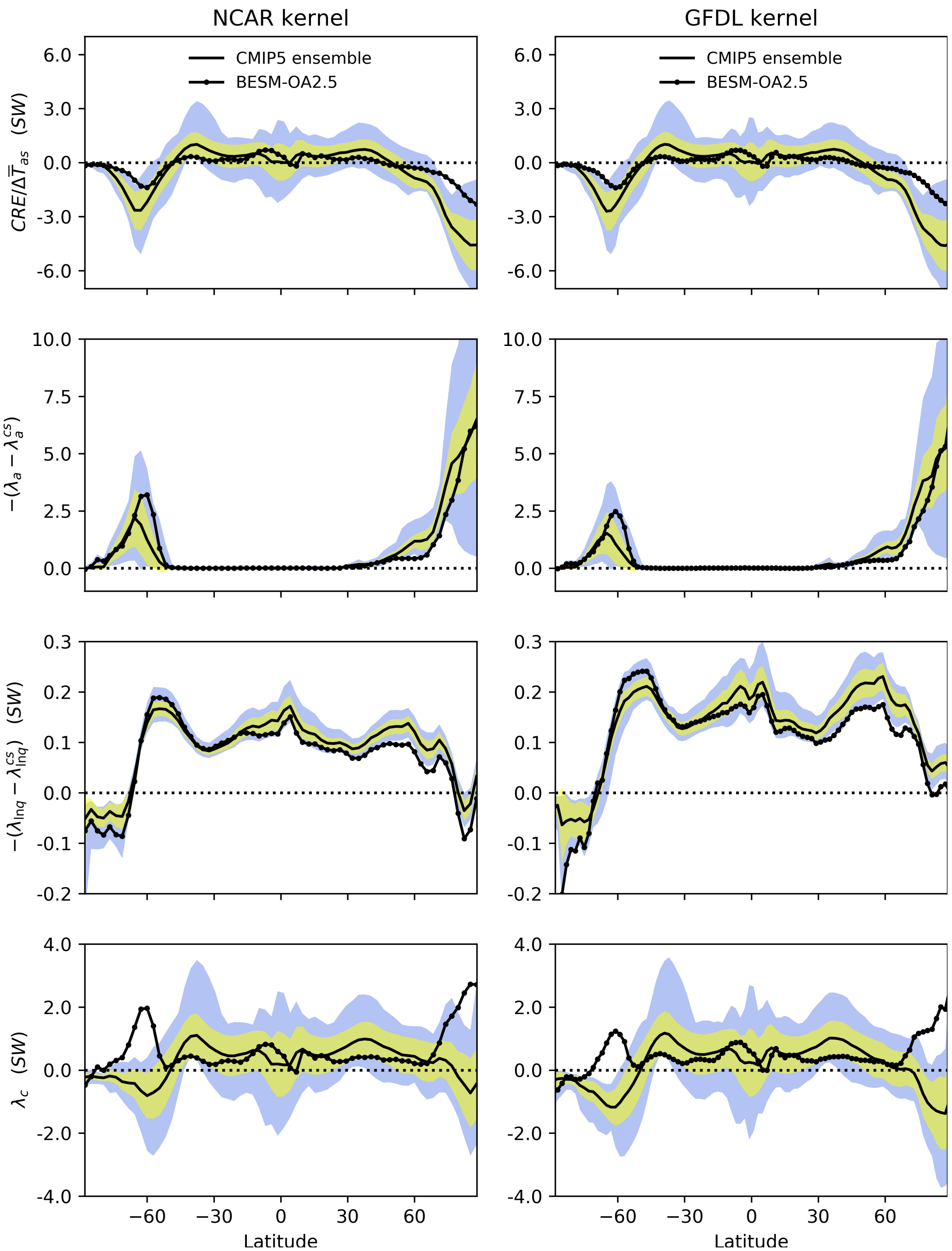


Figure 6. SW Cloud feedback and the albedo and SW humidity feedbacks cloud masking for the CMIP5 multi-model ensemble-mean (solid line) and BESM-OA2.5 (solid line with dots). Inter-model standard deviations for each latitude are in yellow. In blue are the feedback limits based on the maximum and minimum values for each latitude among the models, not including BESM-OA2.5.

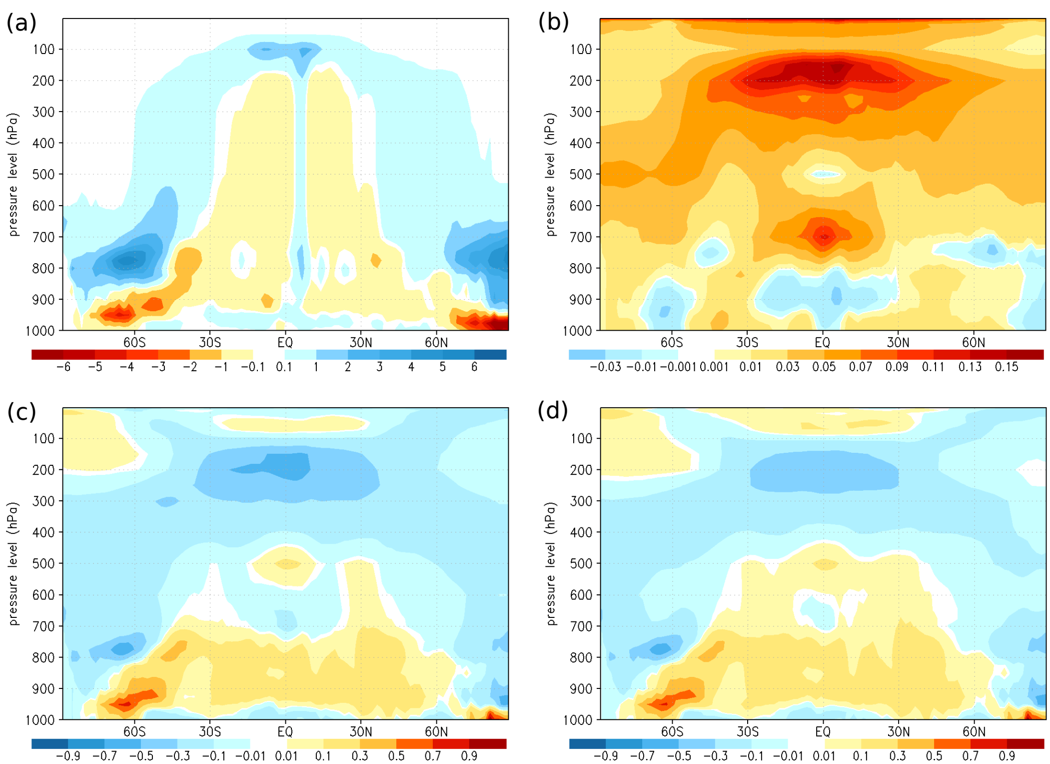


Figure 7. Vertical profiles of the zonal mean of the 4xCO2 - piControl mean difference for the following variables: (a) Cloud fraction, Radiative heating/cooling rate (dT/dt) of (b) shortwave, (c) long wave and (d) sum of shortwave and longwave for BESM-OA2.5.

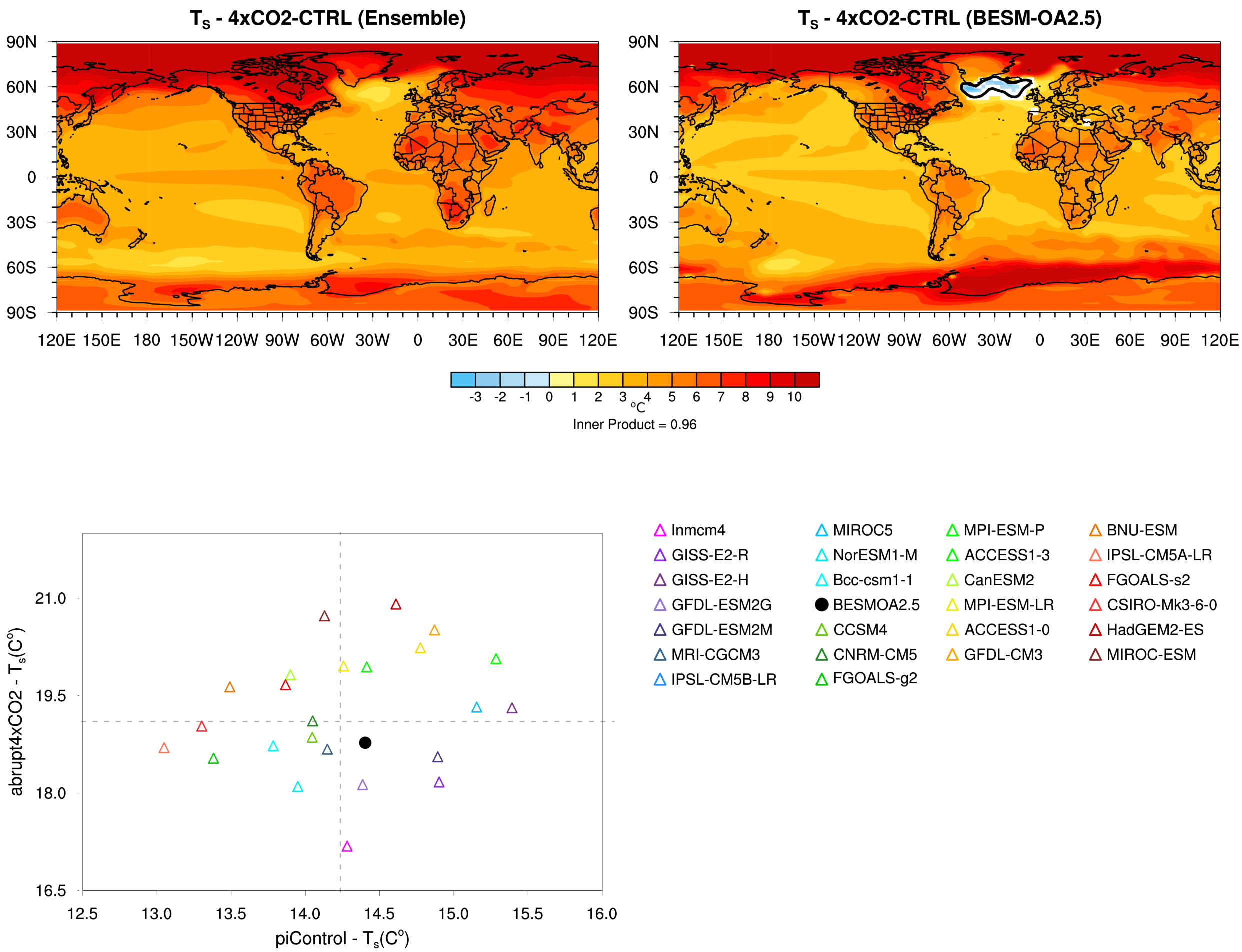
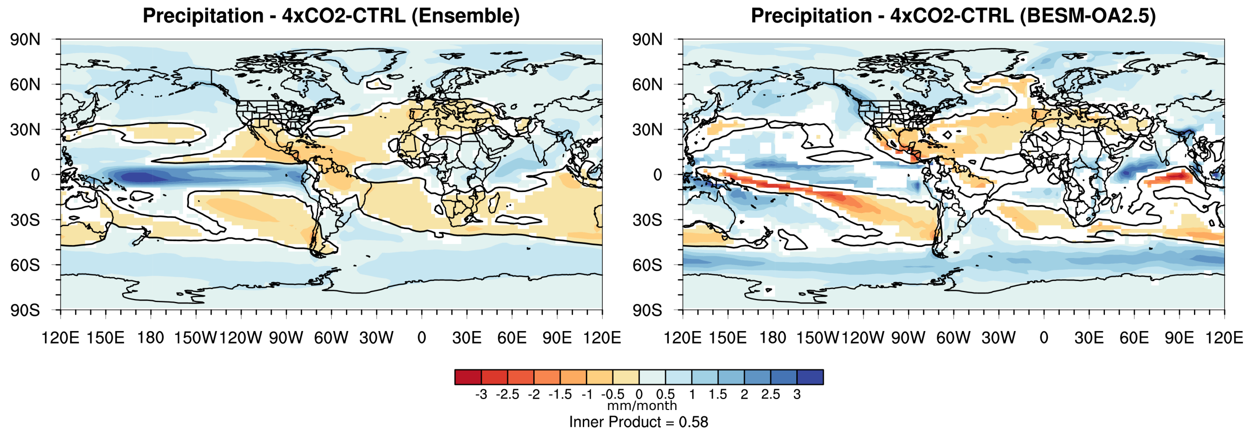


Figure 8. Difference (averaged over years 120-150) of surface temperature between abrupt4xCO2 and piControl simulations in (a) CMIP5 ensemble and (b) in BESM-OA2.5; and (c) scatter plot of global average of surface temperature for the CMIP5 models used in ensemble and BESM-OA2.5 (black dot). Shaded areas in (a) and (b) have level of confidence greater than 90%; the black line represents the isoline of zero temperature difference.



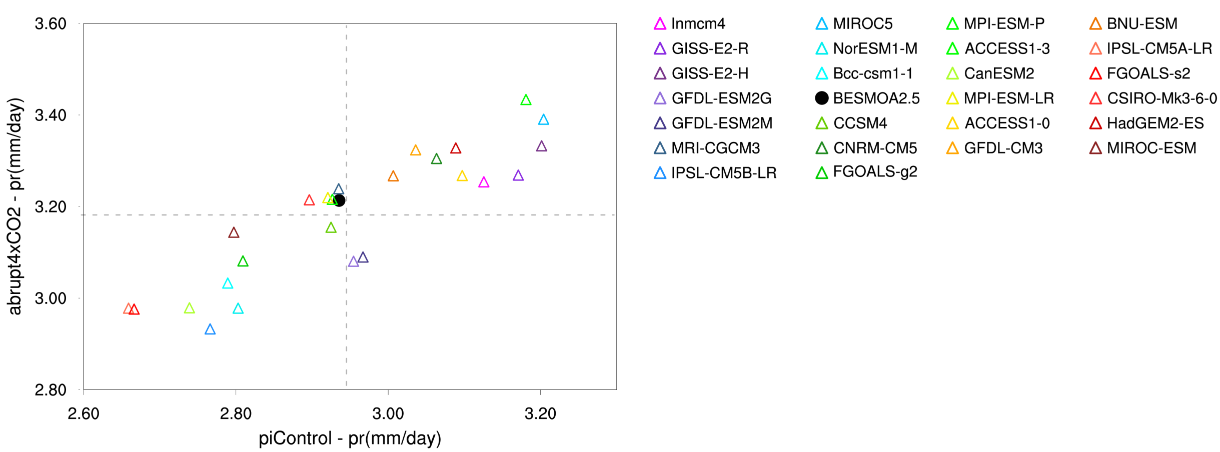


Figure 9. Difference (averaged over years 120-150) of precipitation (in mm/month) between abrupt4xCO2 and piControl simulations in (a) CMIP5 ensemble and (b) in BESM-OA2.5; (c) scatter plot of precipitation global average for CMIP5 models used in the ensemble and BESM-OA2.5 (black dot). Shaded areas in (a) and (b) have level of confidence greater than 90%; the black line represents the isoline of zero precipitation difference.

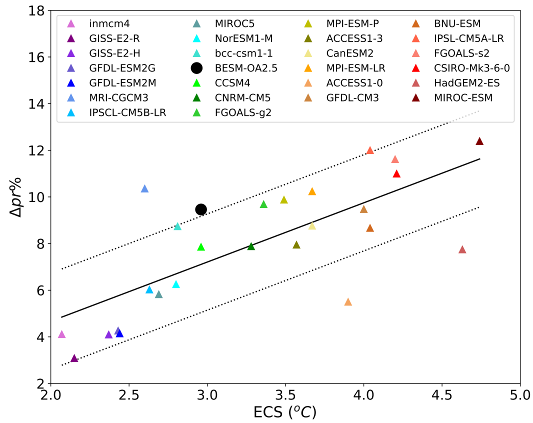


Figure 10. Scatter plot between ECS and $\Delta Pr(\%)$ for all models considered. The solid black line is the linear fit between ECS and perceptual change in precipitation. As in Figure 2, models are sorted according their ECS value. The dash lines represent the error limits considering the residual standard error.

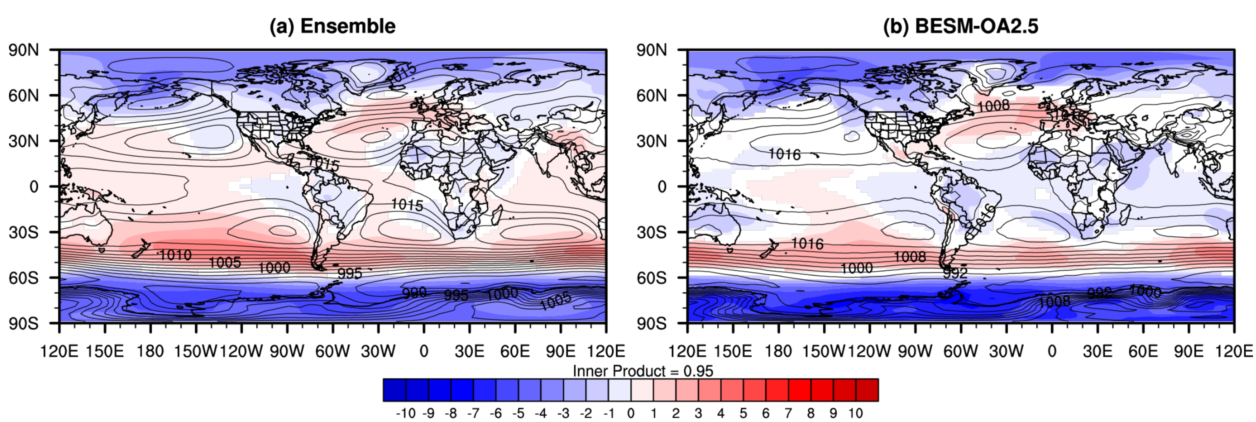
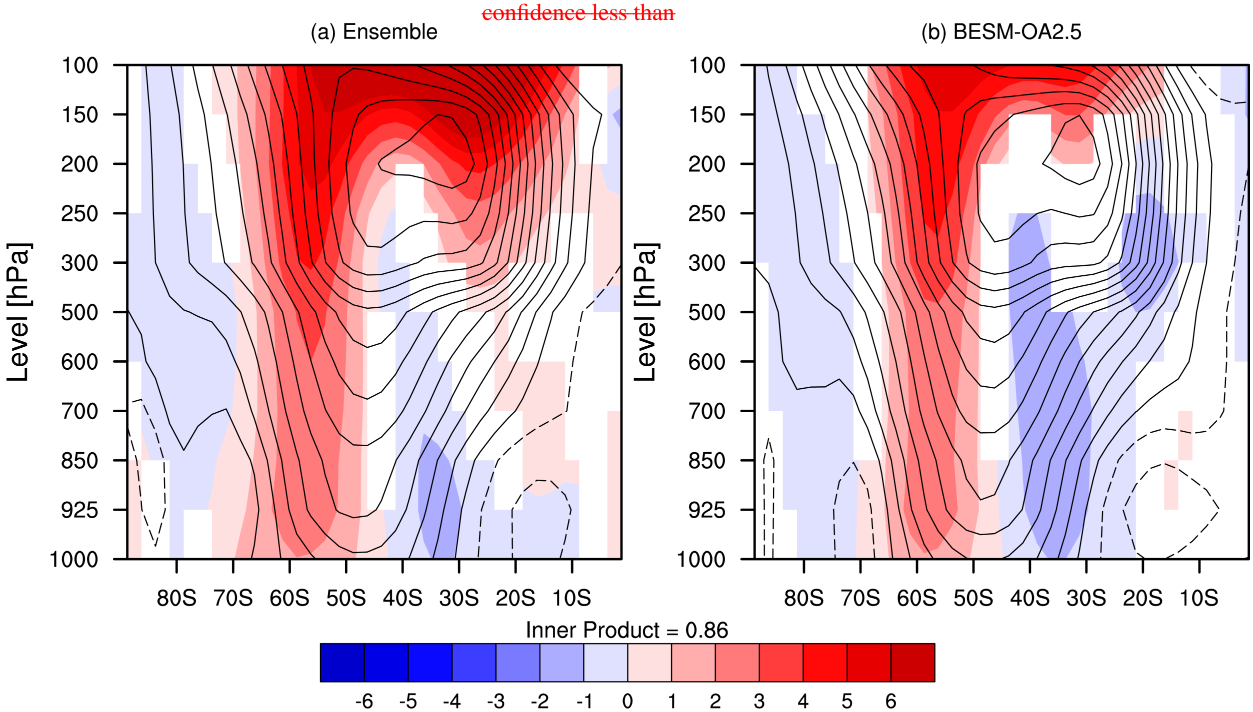


Figure 11. Difference (averaged over years 120-150) of sea level pressure (SLP) in hPa between two scenarios (abrupt4xCO2 minus piControl, shaded), and SLP during piControl (contours) in CMIP5 models ensemble (first column) and BESM-OA2.5 (second column). White areas have level of confidence less than 90%.

~~Vertical profile of the difference (averaged over years 120-150) of zonal mean wind (in m/s) between two scenarios (abrupt4xCO2 minus piControl, shaded), and piControl (contours) for (a) ensemble of CMIP5 models and for (b) BESM-OA2.5. White regions have level of confidence less than~~

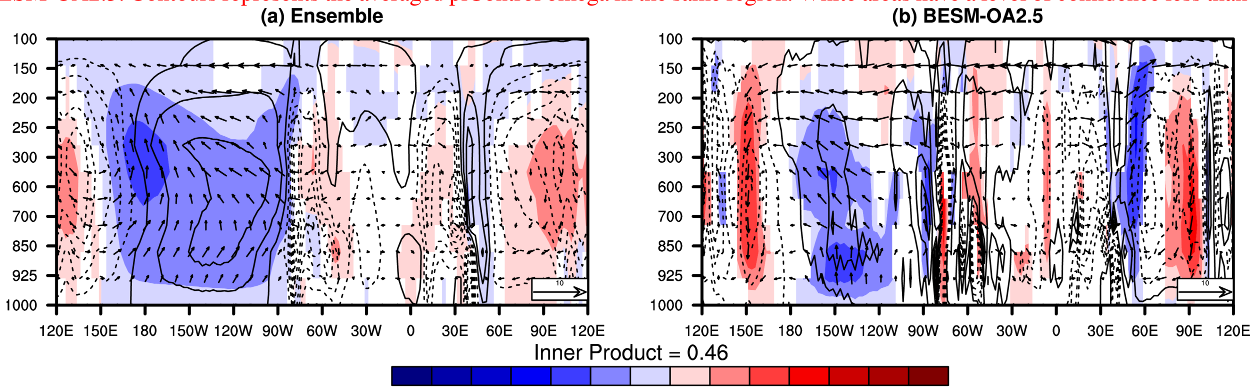


~~90%.~~

Figure 12. Vertical profile of the difference (averaged over years 120-150) of zonal mean wind (in m/s) between two scenarios (abrupt4xCO2 minus piControl, shaded), and piControl (contours) for (a) ensemble of CMIP5 models and for (b) BESM-OA2.5. White regions have level of confidence less than 90%.

Difference (averaged over years 120-150) between abrupt4xCO2 and piControl for omega (shades) in Pa/s and zonal-vertical winds (vectors), averaged between 5°S and 5°N, for (a) CMIP5 ensemble

and (b) BESM-OA2.5. Contours represents the averaged piControl omega in the same region. White areas have a level of confidence less than



90%.

Figure 13. Difference (averaged over years 120-150) between abrupt4xCO2 and piControl for omega (shades) in Pa/s and zonal-vertical winds (vectors), averaged between 5°S and 5°N, for (a) CMIP5 ensemble and (b) BESM-OA2.5. Contours represents the averaged piControl omega in the same region. White areas have a level of confidence less than 90%.

Table 1. Atmospheric physical parameterizations used in BAM (Figueroa et al., 2016) BESM-OA2.5~~and BAM~~.

Physical Parameterization	BAM	BESM-OA2.5
Shortwave radiation	RRTMG (Iacono et al., 2008)	Clirad (Taraso
Longwave radiation	~~Harshvardhan (Harshvardhan et al., 1987) RRTMG (Iacono et al., 2008)~~ RRTMG (Iacono et al., 2008)	Harshvardhan
Cloud microphysics	~~Ferrier (Ferrier et al., 2002) Morrison (Morrison et al., 2005)~~ Morrison (Morrison et al., 2005)	Ferrier et al. (2
Land surface model	~~SSib (Xue et al., 1991)~~ Ibis [Foley et al. (1996) modified by Kubota (2012)]	SSib (Xue et a
Planetary Boundary Layer	Modified Mellor and Yamada (1982) scheme	Holtslag and B
Shallow Convection	UW shallow convection (Park and Bretherton, 2009)	Tiedtke (1984)
Deep Convection	Modified Grell and Dévényi (2002)ensemble scheme	Modified Grell
Gravity wave	Webster et al. (2003) scheme with low-level blocking	Alpert et al. (1
Total Cloud cover fraction	Based on Probability Density Function (PDF)	Slingo (1987)

Table 2. Models belonging to CMIP5 used in this study.

Number	Model	Institution, country
1	ACCESS1-0	CSIRO-BOM, Australia
2	ACCESS1-3	
3	bcc-csm1-1	BCC, China
4	BNU-ESM	BNU, China
5	CanESM2	CCCma, Canada
6	CCSM4	NCAR, USA
7	CNRM-CM5	CNRM-CERFACS, France
8	CSIRO-Mk3-6-0	CSIRO-QCCCE, Australia
9	FGOALS-g2	LASG-CESS, China
10	FGOALS-s2	LASG-IAP, China
11	GFDL-CM3	
12	GFDL-ESM2G	NOAA-GFDL, USA
13	GFDL-ESM2M	
14	GISS-E2-H	NASA-GISS, USA
15	GISS-E2-R	
16	HadGEM2-ES	MOHC, England
17	inmcm4	INM, Russia
18	IPSL-CM5A-LR	IPSL, France
19	IPSL-CM5B-LR	
20	MIROC-ESM	MIROC, Japan
21	MIROC5	
22	MPI-ESM-LR	MPI-M, Germany
23	MPI-ESM-P	
24	MRI-CGCM3	MRI, Japan
25	NorESM1-M	NCC, Norway

Table 3. CO2 Forcing (W m^{-2}) (G), Net Feedback (W m^{-2} K^{-1}) (λ), Climate Response (W m^{-2} K^{-1}) (ΔCRE), and Equilibrium climate sensitivity (K) (ECS) values.

Model	G	λ	ΔCRE	ECS
ACCESS1-0	5.78	-0.74	0.11	3.90
ACCESS1-3	5.71	-0.80	0.27	3.57
bcc-csm1-1	6.72	-1.20	-0.06	2.81
BESM-OA2.5	8.62	-1.45	-0.13	2.96
BNU-ESM	7.45	-0.92	-0.27	4.04
CanESM2	7.51	-1.02	0.16	3.67
CCSM4	7.27	-1.23	-0.15	2.96
CNRM-CM5	7.34	-1.12	-0.19	3.28
CSIRO-Mk3-6-0	5.01	-0.60	0.25	4.21
FGOALS-g2	5.59	-0.83	-0.08	3.36
FGOALS-s2	7.58	-0.90	-0.45	4.20
GFDL-CM3	5.91	-0.74	0.49	4.00
GFDL-ESM2G	5.98	-1.23	-0.21	2.43
GFDL-ESM2M	6.69	-1.37	-0.31	2.44
GISS-E2-H	7.74	-1.64	-0.50	2.37
GISS-E2-R	7.26	-1.69	-0.46	2.15
HadGEM2-ES	5.77	-0.62	0.37	4.63
inmcm4	5.74	-1.38	-0.10	2.07
IPSL-CM5A-LR	6.38	-0.79	0.70	4.04
IPSL-CM5B-LR	5.25	-1.00	0.29	2.63
MIROC5	8.95	-1.66	-0.43	2.69
MIROC-ESM	8.33	-0.88	0.14	4.74
MPI-ESM-LR	8.07	-1.10	-0.06	3.67
MPI-ESM-P	8.39	-1.20	-0.04	3.49
MRI-CGCM3	6.50	-1.25	-0.05	2.60
NorESM1-M	6.19	-1.10	-0.08	2.80
Mean	6.84$\pm$1.09	-1.09$\pm$0.31	-0.03$\pm$0.30	3.30$\pm$0.76