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Interactive comment on "Inter-hemispheric seasonal comparison of Polar Amplification using radiative forcing of quadrupling CO_2 experiment" *by* Fernanda Casagrande et al.

Fernanda Casagrande et al.

fernanda.casagrande@inpe.br

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Thank you very much for your consideration. We really appreciate the comments and have learned a lot. In order to improve the analyses as you suggested and also following the indication from referee #1, we add new results: 1) analysis of polar amplification from observational data (Figure 1) and sea ice analysis from different CMIP5 models (Figure 3, Figure 4 and Table 1). This analysis provided greater robustness in the results, which were included here in several parts of the revised manuscript. Thus replacing, expressions as "we suggest" with more complete discussions. Also, appropriate changes were made in the revised manuscript (expanding discussion) according

to the suggestions. 1) Regarding the Climate models chosen, we chose models from different locations considered state-of-the-art climate models (North America - USA (2), Europe – German and France(2), Japan (1), Asutralia (1)). Harrison et al. (2015), in a Nature Climate Change publciation used seven state–of-the-art CMIP5 climate model to explain the evolution of CMIP5 papaeo-simulation to improve climate simulations. In our work, we used pratically the same models, adding – BESM-OA V2.5. Furthermore, GFDL-ESM2M was chosen because has a diferente atmospheric compent, but the same ocean component. 2) Regarding to use CMIP6, we've been working hard to finish our experiments, unfortunately, we are not done yet. 3) Other BESM-OA and state-of-the-art CMIP5 numerical experiments (as RCP and decennial) have been previously published in Casagrande et al. (2016) and Casagrande (2016). 4) We totally agree and appreciate the valuable suggestions. So we added new analyzes and figures. 5) We have improved both, introduction and conclusions on revised manuscript.

Figure 1. Polar Amplification using Long-term observations of Surface Air Temperatures (oC) at 2008-2018 (seasonal average) relative to 1979 -1989 (seasonal average) in (a) Winter (DJF) and (b) Summer (JJA). Source: Era Interim Reanalysis.

Figure 1 shows the enhanced surface warming at high latitudes compared to the rest of globe, with a slightly greater rate of warming in the 20th century. The observed Polar Amplification is not symmetric, most evidence is from Arctic region (during the boreal winter). According to Stocker et al., (2013), the enhanced warming at northern high latitudes was linked with decrease in snow cover and sea ice concentration, sea level rise and increase in land precipitation. Besides that, changes in atmospheric and ocean circulation (Chylek et al., 2019; Pedersen et al., 2016; Pithan and Mauritsen, 2014; Stocker et al., 2013; Yang et al., 2010; Graversen et al., 2008).

Following the reviewer's suggestion and in order to better discuss the relationship between enhanced warming at high latitudes (Figure 1) and sea ice changes, we include the Figure 3, Figure 4 and Table1.

Figure 3 (new - attached here) shows, under the largest future GHG (4xCO2), the spatial pattern of sea ice changes for both, Arctic and Antarctic (difference between sea ice concentration for the last 30 years of abrupt4xCO2 numerical experiment and the last 30 years of the piControl run). This new Figure complements and makes the discussion shown in Figure 1 (old manuscript) more robust. The maximum of the Arctic warming obtained from observations (new Figure 1) and different CMIP5 simulations (old Figure 1) occurs in boreal winter (DJF). According to Figure 1 (old manuscript), the following models, in descending order, appears as having greater amplification: MIROC – ESM, MPI-ESM, BESM-OA V2.5 and CSIRO-ACCESS. Similar response, for the same period is observed in Figure 3 and Figure 4, related to sea ice changes. The large decrease in sea ice concentration is more evident in models with great Polar Amplification, and for the same range of latitude (75o N – 90o N). The end of melting period (when sea ice reaches its minimum annual value) for all models shows sea ice-free conditions. Models that have strong Polar Amplification exhibit expressive changes in the sea ice annual amplitude with outstanding ice-free condition from may to December (MIROC-ESM) and June to December (MPI-ESM). Then, the end of melting period is expected early, likely, associated a large decrease in sea ice thickness and contributing to a delay in sea ice formation. We suggest, based in Figure 3 and Table 1, that, the Arctic will become covered only by first year sea ice (more vulnerable to melting), making the region more sensitive thermodynamically and dynamically to temperature changes. These new evidences presented here, corroborates with the theory, that the Polar Amplification is closely linked to sea ice albedo feedback. For Antarctica, however, the same physical processes cannot be used to explain the Polar Amplification (as discussed in the manuscript). Although, according to Figure 1 (old manuscript) and Figure 3 (new - attached here), there is a small indication of the contribution of sea ice albedo feedback in Antarctic Polar Amplification. Latitudes between 60oN and 65oN (greater Polar Amplification, models BESM-OAV2.5, MIROC-ESM and NCAR-CCSM4) for Austral winter also have trace of relation with abrupt changes in sea ice (Figure 3). Here, it is important to consider the contribution of the ice sheet in Polar Amplification

that is not represented by the most of CMIP5 current models. According to Salzmann (2017 the overall weaker warming in Antarctica is due to a more efficient ocean heat uptake in the southern ocean, weaker surface albedo feedback in combination with ozone depletion.

Figure 3. Sea ice concentration for the last 30 years of Abrupt4xCO2 numerical experiment minus the last 30 years of the piControl run for the following models: BESM-OA V2.5, NCAR-CCSM4, GFDL-ESM-LR, MPI-ESM-LR, CSIRO, IPSL and MIROC-ESM in March (left column) and September (right column).

Table 1. Sea ice area (million square kilometers) for the last 30 years of the abrupt 4xCO2 numerical experiment minus the last 30 years of the piControl run for the following models: BESM-OA V2.5, NCAR-CCSM4, GFDL-ESM-LR, MPI-ESM-LR, CSIRO, IPSL and MIROC-ESM. I Arctic (Antarctic) sea ice reach its annual maximum area in march (february) and the minimum period in September.

Figure 4. Climatology of maximum and minimum Sea ice area (million square kilometers) for the last 30 years of the abrupt 4xCO2 numerical experiment minus the last 30 years of the piControl run for the following models: BESM-OA V2.5, NCAR-CCSM4, GFDL-ESM-LR, MPI-ESM-LR, CSIRO, IPSL and MIROC-ESM. (a) Arctic, (b) Antarctic. Black color represents the maximum (minimum) period of sea ice concentration, march (february) month for Arctic (Antarctic). Gray color bar represents September month.

Specific comments:

Pg. 1; L. 8: “The numerical climate simulation from Brazilian Earth System Model (BESM) are...” – Replace “are” by “is” or “simulation” by “simulations”. Reply: ok

Pg. 1; Ls. 18, 19, 21, 24: Consider to add an article in the following cases – “warming at the surface”, “heat in the atmosphere.”, “for the cold season”, and “in the coming decades”. Also, for other instances in the manuscript. Reply: ok

Overall comment: For uncountable nouns, the use of the indefinite article “a” may be redundant. For instance: “a warming”, “a cooling”. This rule could be considered for the entire manuscript. Reply: ok

Pg. 2; Ls. 31: I guess the authors meant GHG rather “GHC Reply: ok

Pg. 2; Ls. 35–39: The sentence is confusing. It is kind of hard to get what the authors mean. Please, consider to rewrite it. For instance, “these two-poles inter-hemispheric asymmetries in the mean ocean circulation” but nothing was mentioned for the “Arctic mean circulation” Reply: ok

Pg. 2; L. 37: “According Marshall...” replace by “According to Marshall”. Please, check for the other instances in the text. Reply: ok

Pg. 2; Ls. 40–42: “Numerous...” but only Vaughan was cited. Numerous scientific publications based on both, observations and state-of-the-art Global Climate Model simulations for the high latitudes of the northern hemisphere have shown that AA is an intrinsic feature of the Earth’s climate system (Smith et al., 2019; Vaughan et al., 2013; Serreze and Barry, 2011; Screen and Simmonds, 2010).

Pg. 2; Ls. 45–46: “from between 1875 and 2008” – Drop “from”. Reply: ok

Pg. 2; Ls. 46–47: Add “the” in “latitudes of the northern hemisphere”. Reply: ok

Pg. 2; L. 55: Replace “this processes” by “these processes”; Also, it seems that the explanation “Ocean is becoming more like the Atlantic ocean” is not required. Reply: ok

Pg. 2; L. 59: “The large differences among the models is” – Replace “is” by “are”. Reply: ok

Pg. 3; Ls. 78–81: I was wondering why comparing the BESM results against only 5 other models rather than the entire ensemble of models? Also, since we are already in the CMIP6, why not make this study with experiments from this phase. In addition,

since the 4xCO2 seems a bit unrealistic, I think the use of the simulations forced by “1% per year CO2 increase (1pctCO2; Eyring et al., 2016)” would strength the manuscript.

Pg. 3; L. 81: “The paper was is organized”. Reply: ok

Pg. 3; L. 86: Missing “.” at the end of the sentence. Reply: ok

Pg. 3; L. 93: “an a instantaneous”; “the 21st”. There is a mistake with numbering sections as per Sec. 3. Reply: ok Reply: ok

Pg. 5; L. 129: “accesses”. Do you mean “assess”? Reply: ok

Pg. 5; L. 128–129: It does not seem to be the case since the discussion for Arctic and Antarctic is, in some instances, merged in Sec. 3 Reply: ok

Pg. 5; L. 135: Replace “assesses” by “assess”. Reply: ok

Pg. 6; L. 138: Replace “This procedure been largely” by “This procedure has been”. Also, the authors argued “largely” but cited only 2 references. Reply: ok

This procedure has been largely used by researchers since allows us to evaluate and compare potential warming and sensitivities between low and high latitudes as well as to compare differences between models (Van der Linden et al., 2019; Cvijanovic et al., 2015; Manabe et al., 2004; Holand and Bitz, 2003).

Pg. 6; L. 138: “Contrasting, the tropical warming for both, northern and southern hemisphere, is pretty similar with not so accentuated SAT increase in summer and for regions close to 30N.” – Not sure I agree with this statement. From Fig. 1, it is noticeable an increase in the SAT differences from about -60S to +60N. Could the authors add some words/explanation for that in the manuscript? Reply: ok

Pg. 6; L. 146–147: “. . . the overall weaker warming in Antarctica is due to a more efficient ocean heat uptake in the southern ocean”. I am wondering whether the authors could test this by looking at the SST data (or another output variable). For instance, is the Polar Amplification and respective seasonal cycle also observed in the SST data.

If so, what are the differences between Antarctic and Arctic? Maybe something could be shown in terms of albedo feedback. I think this is a better way to address the issue rather than “We expect...”. Reply: ok

Pg. 6; L. 155: “reaching a minimum at 70S” – I would rather say 60S. Reply: ok

Pg. 6; L. 160: “The main reason for winter (DJF) Arctic Amplification pointed by Serreze et al., (2009) is largely driven by changes in sea ice, allowing for intense heat transfers from the ocean to the atmosphere...”. I also think the authors could check this hypothesis with the CMIP datasets. Reply: ok

Pg. 6; L. 163: Replace “looses” by “loses”. Reply: ok

Pg. 7; L. 171: Replace “consequent” by “consequently”. Reply: ok

Pg. 7; L. 174–178: The referred teleconnection seems to be out of context here. Reply: ok

Pg. 7; L. 180: Replace “trend” by “tends”(?) Reply: ok

Pg. 7; L. 190: Replace “In the other hand” by “On the other hand” Reply: ok

Pg. 7; L. 197: Replace “Artic” by “Arctic”. Reply: ok

Pg. 7; L. 203: Replace “register” by “registered”. Reply: ok

Pg. 8; L. 209: Replace “previously version” by “previous version”. Reply: ok

Pg. 8; L. 208–212: Not sure the comparison between the two BESM versions makes sense in the scope of the manuscript. The paper compares different models but not different versions of the same model. As it is, it seems like an artifact for auto-citation. Reply: ok

Fig. 2 – I think this analysis should be performed for the ensemble of models. Fig. 3: This figure should be further improved. The labels are too small; it is missing the y-label and unity; the colorbar is not aligned with the figures. Reply: ok

Pg. 11; L. 275: Replace “a combination changes in winds” by “a combination of changes in winds” Reply: ok

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Interactive comment on Ann. Geophys. Discuss., https://doi.org/10.5194/angeo-2019-106, 2019.

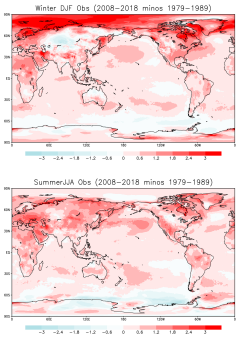

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Fig. 1.

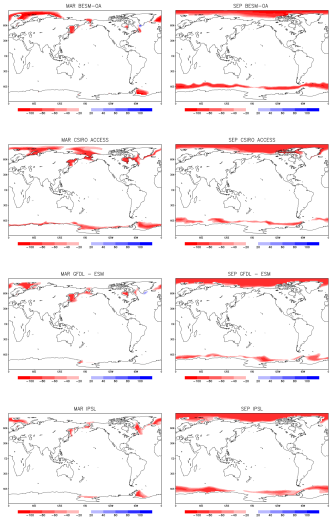

Fig. 2.

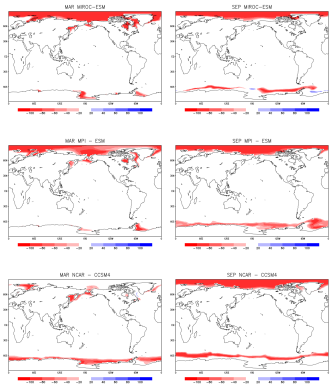

Figure 3. Sea ice concentration for the last 30 years of abrupt4xCO_2 numerical experiment minus the last 30 years of the piControl run for the following models: BESM-OA V2.5, NCAR-CCSM4, GFDL-ESM-LR, MPI-ESM-LR, CSIRO-ACCESS, IPSL and MIROC-ESM in March (left column) and September (right column).

Fig. 3.

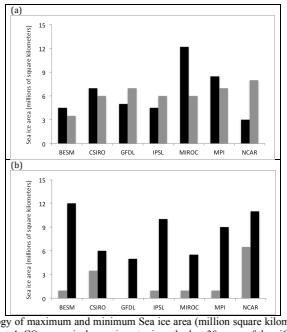

Figure 4. Climatology of maximum and minimum Sea ice area (million square kilometers) for the last 30 years of the abrupt 4xCO_2 numerical experiment minus the last 30 years of the piControl run for the following models: BESM-OA V2.5, NCAR-CCSM4, GFDL-ESM-LR, MPI-ESM-LR, CSIRO, IPSL and MIROC-ESM. (a) Arctic, (b) Antarctic. Black color represents the maximum (minimum) period of sea ice concentration, march (february) month for Arctic (Antarctic). Gray color bar represents September month.

Fig. 4.

CMIP5 Models	Arctic			Antarctic		
		March	Sept		Feb	Sept
BESM-OA	**piControl**	16	3.5	**piControl**	1	29
	4xCO$_2$	11.5	Ice-Free [Aug-Nov]	**4xCO$_2$**	Ice-Free	17
		March	**Sept**		**Feb**	**Sept**
CSIRO ACCESS	**piControl**	14	6	**piControl**	4.5	17
	4xCO$_2$	7	Ice-Free [Jul-Nov]	**4xCO$_2$**	1	11
	Arctic	**March**	**Sept**	**Antarctic**	**Feb**	**Sept**
GFDL –ESM2M	**piControl**	14	7	**piControl**	Ice-Free	9
	4xCO$_2$	9	Ice-Free	**4xCO$_2$**	Ice-Free [Feb-Mar]	4
		March	**Sept**		**Feb**	**Sept**
IPSL –CM5-LR	**piControl**	13	6	**piControl**	1	17
	4xCO$_2$	8.5	Ico-Free [Jul-Oct]	**4xCO$_2$**	Ice -Free [Jan-Mar]	7
		March	**Sept**		**Feb**	**Sept**
MIROC-ESM	**piControl**	13	6	**piControl**	1	14
	4xCO$_2$	0.8	Ice-Free [May-Dec]	**4xCO$_2$**	Ico free	8.5
		March	**Sept**		**Feb**	**Sep**
MPI –ESM	**piControl**	12	7	**piControl**	1	13
	4xCO$_2$	3.5	Ice-Free [Jun-Dec]	**4xCO$_2$**	Ice-Free [Jan-Apr]	4
		March	**Sept**		**Feb**	**Mar**
NCAR –CCSM4	**piControl**	13	8	**piControl**	7.5	22
	4xCO$_2$	10	Ice-Free [Aug-Oct]	**4xCO$_2$**	1	11

Table 1. Climatology of maximum and minimum Sea ice area (million square kilometers) for the last 30 years of the abrupt 4xCO_2 numerical experiment and the last 30 years of the piControl run for the following models: BESM-OA V2.5, NCAR-CCSM4, GFDL-ESM-LR, MPI-ESM-LR, CSIRO, IPSL and MIROC-ESM.

Fig. 5.