Response to reviewer 3

Review of manuscript wcd-2021-26:

Dynamical drivers of Greenland blocking in climate models

by

Clio Michel et al.

In this study, the HAPPI large ensemble simulations are used to investigate the representation of Greenland blocking (GB) in the HAPPI models and the extent to which GB occurrence is associated with the occurrence of Rossby wave breaking, specifically cyclonic Rossby wave breaking (CWB) over the Labrador Sea / the south of Greenland (70-30W, 50-70N). It is found that most of the 5 HAPPI models considerably underestimate GB frequency; the best agreement with ERA-Interim GB frequency is seen in ECHAM6 and especially the MIROC5 models. Models also tend to underestimate CWB frequency, especially so MIROC5. An analysis of the relationship between CWB and GB occurrence shows that these two phenomena are closely associated in ERA-Interim and ECHAM6, but much less so in MIROC5, leading the authors to conclude that a different dynamical driver of GB must be acting in MIROC5.

Global climate models (GCMs) have long-standing biases in the representation of atmospheric blocking, which are still seen in the latest generation of GCMs. Studies into the nature of blocking (biases) in GCMs therefore remain important, and the present study illustrates an intriguing difference between two GCMs in how they represent GB and CWB. I therefore recommend the study for publication in WCD. I would like to make one suggestion for further analysis, other than that my comments are minor/presentational.

We are grateful to the reviewer for the careful review. Our answers to the comments are below in blue color.

1)

The authors conclude that the dynamical link between CWB and GB is present but not the main ingredient triggering GB in MIROC5. This is, of course, very interesting and nicely illustrated in the paper but the question about the character of GB in MIROC5 is left open. Given the large negative CWB bias in MIROC, many blocking events will occur without CWC in that model.

I would like to suggest the following additional analysis: The authors have derived a set of days (or events) when CWC and GB occurs, respectively. This could be used to derive $2x^2$ contingency tables of co-occurrence of CWC and GB with frequency counts (No-No, No-Yes, Yes-No, Yes-Yes) for each of ECHAM, MIROC, and ERA-Interim. Furthermore, composites could then be shown with respect to three sets of these events (No-Yes, Yes-No, Yes-Yes), and potentially these could be more illustrative than the current Figures 5 and 6 – it is difficult to be sure, but I would like to encourage the authors to try if they have not already done so.

We thank the reviewer for the suggestion of this additional analysis that we have performed and whose results are described below.

In order to define the Greenland blocking category, we use the Greenland blocking days as defined in the manuscript. The no CWB category contains the days when the CWB index defined in the manuscript is equal to 0 and the CWB category includes all days with a positive CWB index. The contingency Table R1 clearly shows that, for MIROC5, Greenland blocking (GB) occurs as frequently with CWB as without CWB (51 versus 50 days), whereas for ECHAM6.3-LR and ERA-Interim most of Greenland blocking occurs with CWB. This difference may arise from the lack of CWB in MIROC5. However, the composites of 500-hPa geopotential for the category GB - no CWB (first row column (b) in Figs. R1, R2, and R3) exhibits a westward shift of the anticyclonic pattern. This may reflect the blocking at a later stage of its lifetime as recently shown by Drouard et al. (2021) for the blocking of cyclonic type typical over Greenland (with CWB southwest of the region chosen for the index calculation as seen on Fig. R3c second row but only for ERA-Interim). Whether or not CWB occurs during Greenland blocking, the low-level zonal wind is always stronger south over the North Atlantic (columns (a) and (b) of fourth row in Figs. R1, R2, and R3).

We think that the composites in the original manuscript and this additional analysis complement each other: Fig. 4 of the original manuscript shows the atmospheric state during Greenland blocking days, Fig. 5 of the original manuscript demonstrates that Greenland blocking can happen with CWB southwest of Greenland, and the above analysis nicely illustrates that MIROC5 has many days with Greenland blocking without CWB in the box chosen. Therefore, we have decided to include the contingency table in the manuscript but to leave out the composites that will be added to the supplement.

Table R1: Ensemble mean and spread of the number of days in each category for ECHAM6.3-LR and MIROC5 (2nd and 3rd columns) and total number of days in each category for ERA-Interim (4th column). Unit: days. The CWB/no CWB categories distinguish the days for which the spatially averaged CWB frequency, as defined in Section 2.4 of the original manuscript, is greater than 0 / equals 0. GB stands for Greenland Blocking. The GB/no GB categories distinguish the blocked days from the non-blocked days as defined in Section 2.3 of the original manuscript.

	ECHAM6.3-LR		MIROC5		ERA-Interim	
	CWB	no CWB	CWB	no CWB	CWB	no CWB
GB	36.2 ± 14.9	10.0 ± 6.0	51.2 ± 13.6	49.8 ± 15.2	77	26
no GB	431.9 ± 20.5	333.9 ± 22.6	323.4 ± 20.1	385.6 ± 24.4	406	303



Figure R1: Ensemble mean of the composites of the 500-hPa geopotential (Z500), AWB, CWB, 850-hPa zonal wind (u850) and blocking for three categories (GB - CWB, GB - no CWB, and no GB - CWB) whose mean numbers of days are found in the contingency table for ECHAM6.3-LR. The first four top rows shows the anomalies in shading and the total field in contours and the bottom row shows the blocking frequency in shading. The numbers in the bottom right corner of each panel show the number of members that have days in the category. Here all members have at least one day in all categories. GB stands for Greenland Blocking.



Figure R2: As Fig. R1 but for MIROC5.



Figure R3: Composites of the 500-hPa geopotential (Z500), AWB, CWB, 850-hPa zonal wind (u850) and blocking for three categories (GB - CWB, GB - no CWB, and no GB - CWB) whose numbers of days are found in the contingency table for ERA-Interim. The first four top rows shows the anomalies in shading and the total field in contours and the bottom row shows the blocking frequency in shading. The number 1 in the bottom right corner of each panel points out that this is ERA-Interim and not an ensemble. GB stands for Greenland Blocking.

2) abstract

Make clear early on that this study is about the winter season.

We will add this information in the abstract.

3) page 1, line 23

Surely there are also more wide-ranging impacts of GB due to its association with the NAO and temperature anomalies across much of the Northern Hemisphere? Please add a brief discussion and some references; Chen et al. 2017 looks like a good start.

We thank the reviewer for the reference suggestion. We will modify this part of the introduction to take into account the reviewer's comment.

4) page 3, line 63 What does "enhanced" mean here? With respect to which reference? Maybe it can simply be omitted.

As suggested, we will remove the word "enhanced" there.

5) page 4, line 121 Typo: occur*s*

Will be corrected.

6) page 5, line 152

If I understand correctly, these 30 estimates are from overlapping time periods and therefore strongly dependent. Is this considered in the significance testing?

No, the dependency between the short period and the whole 40 years was not taken into account with this t-test. The aim of this test was to justify the use of the period 2006-2015 instead of the 40-yr climatology to calculate the biases. For this limited purpose the chosen method seems adequate/sufficient. However, we have repeated the same analysis bootstrapping 100 times 30 non consecutive winters (with replacement) within ERA-Interim as shown in Fig. R4 and the conclusions are identical.

7) Section 3

It is nice to see from this section and the Supplement that the authors have conducted thorough model evaluation. A question that keeps coming up is what constitutes a "good enough" evaluation result to justify pursuing the main aim of the study. Where the authors clear about this before conducting the evaluation? I understand this question is hard and slightly philosophical, but, if possible, a short discussion of this point with respect to this study would be greatly appreciated!

Ideally, it would have been great to be able to understand the reason for the good representation of blocking in MIROC5, despite the strong biases in RWB. However, the HAPPI simulations were not designed to study the biases in depth with mainly daily variables not available to our knowledge, but we think that the large ensembles were a great asset to study blocking.

Many studies have evaluated blocking bias in climate models, but only few tried to understand the reasons behind the biases. Here, we highlight that such reasons might depend on the considered models. We hope that the results will help the modellers to design numerical experiments and consider these dynamical aspects and not only the mean state when they create/evaluate/tune the models.

We will add 1-2 sentences in the conclusion section.

8) page 7, line 208 "Similar standard deviation ..." – similar to ERA or to each other?

We meant similar to ERA-Interim. The sentence will be changed.



Figure R4: (a-e) Bias in winter (DJF) blocking frequency for the five models (ensemble mean of the blocking frequency minus ERA-Interim) and (f) ERA-Interim DJF blocking climatology for 2006-2015 (in frequency, as %). Black Dark gray lines show the smoothed 2, 4 and 6% contours for ERA-Interim (2006-2015). The black box shows the main region of Greenland blocking in ERA-Interim. Biases that are not significant at the 10% significance level are dotted and there is no dot where there is no blocking.

9) page 7, line 215

"More frequent . . . " than what? Rephrase this sentence to make clearer that you are talking about a model bias.

We agree with the reviewer and will make the sentence clearer.

10) Table 1

Given the central role of CWB, I suggest adding columns for CWB frequency to this table.

As far as we understand this suggestion, we calculate the ensemble mean of the CWB index for each model (all winter days and all members are taken into account). The index represents the area of the box covered by CWB and a value of 100% would mean that every grid point in the box has CWB. All values can be found in Table R2 here below. As expected from the bias shown in Fig. 4 of the original manuscript, MIROC5 exhibits low values for the present and future experiments but ECHAM6.3-LR exhibits values close to ERA-Interim's.

Table R2: Ensemble mean of the DJF CWB index (in %) as defined in Section 2.4 for the five HAPPI models and both present and future experiments along with the DJF mean of the CWB index for ERA-Interim (2006-2015).

Model/Reanalysis	Experiment	Mean CWB index	
CAM4-2degree	Present	7.6	
CanAM4	Present	10.1	
ECHAM6.3-LR	Present	11.6	
MIROC5	Present	4.7	
NorESM1-HAPPI	Present	8.4	
CAM4-2degree	Future	7.4	
CanAM4	Future	10.4	
ECHAM6.3-LR	Future	11.5	
MIROC5	Future	4.7	
NorESM1-HAPPI	Future	8.2	
ERA-Interim	2006-2015	11.1	

11) page 9, line 237"zonal wind" - I would add the direction ("westerly").

Will be added.

12) Section 4.2

Please consider if some of the supplemental material referred to could be promoted to the main manuscript.

We would like to give the readers the opportunity to see the results from all the models, but would like to keep the focus in the paper on the comparison between ECHAM6.3-LR and MIROC5. Therefore, most of the results for the other models are included only in the supplement. However, we will have now some additional information in the main manuscript in form of tables: the contingency table and table R2.

13) page 10, line 291 Please add the CMIP6 results, which are now also available (Davini & D'Andrea, 2020).

Will be added.

14) page 11, line 305 Please add appropriate figure cross-reference(s) here (Figures 5 & 7, I think).

Will be added.

15) page 11, line 330 "for the reasons cited above" ... please refer to the (sub)section here and/or add a brief reminder of what these reasons are.

The reasons are stated in the two sentences before this one. We have anyway added the reasons in parenthesis in this sentence.

16) Section 6

Please add a brief summary/conclusions from Section 5.

Yes, we will add a short paragraph to sum up the results of Section 5.

References

Chen, X., & Luo, D. (2017). Arctic sea ice decline and continental cold anomalies: Upstream and downstream effects of Greenland blocking. Geophysical Research Letters, 44(7), 3411–3419. https://doi.org/10.1002/2016GL072387

Davini, P., & D'Andrea, F. (2020). From CMIP3 to CMIP6: Northern Hemisphere Atmospheric Blocking Simulation in Present and Future Climate. Journal of Climate, 33(23), 10021–10038. https://doi.org/10.1175/J D-19-0862.1