Dear Editor, Dear Marco,

First we would like to thank reviewers for their relevant comments which have helped us to improve our manuscript.

Responses to each individual reviewer have been posted on TCD.

The main changes in respect to the original version are:

- The introduction has been improved by mentioning effect of clouds on surface melting, using the various references suggested by the reviewer #1;
- Melt anomalies are now discussed in the results section, as suggested by reviewer #2;
- Hatched zone representing non-significant differences in the different figures are now black hatched to increase visibility.

All the minor corrections and improvements suggested by reviewers have been taken into account in the revised version of the manuscript.

All the best,

Alison Delhasse

We first would like to thank the reviewer comments which will help to improve our manuscript.

Overview This manuscript examines the inability of GCMs to reproduce recent high-latitude Northern Hemisphere circulation changes and the effect this has on model projections of future GrIS SMB. They force the MAR regional climate model with a number of different reanalysis and GCM boundary conditions, provided by the ERA-Interim reanalysis and three GCMs for the past climate and by the GCMs for the future climate. These sensitivity experiments ultimately show that GrIS SMB will be subject to much more significant future decreases if the recent (post-2000) shift toward negative sum TCD Interactive comment Printer-friendly version Discussion paper mer NAO continues. They also show that GCMs that project temperature increases but do not capture recent circulation changes show a smaller decrease in SMB. Overall, this work makes a useful contribution to our understanding of the effect of circulation changes on GrIS SMB and how well this is reproduced in GCMs. There are a few minor problems with the authors' characterization of recent circulation changes and the presentation of their methods and results. These issues and the recommended corrections are described in detail in the specific comments below.

Major comments

In the introduction, the authors partially attribute the recent increase in GrIS melt and mass loss to an increase in incoming solar radiation (p. 1–2). Similarly, in section 3.2 (p. 6), they state that "The current observed melt increase since the 2000's is partly due to the increase in downward shortwave radiation (SWD) caused by more frequent anticyclonic situations enhancing the melt-albedo feedback". In both cases, a single reference (Hofer et al., 2017) is provided. However, that study's claim – that decreasing summer cloud cover is driving the recent GrIS mass loss acceleration – is contradicted by a number of other works, which have demonstrated the important role of clouds and poleward moisture transport in providing melt energy during summer melt events. See, for example, see the Bennartz et al. 2013, Van Tricht et al. 2016, and Solomon et al. 2016 papers that show that clouds enhanced melt and/or reduced meltwater refreezing during recent major melting events. Also see the Neff et al. 2014, Bonne et al. 2015, Fausto et al. 2016, and Mattingly et al. 2016 papers, which together show that poleward moisture transport played a critical role in forcing the extreme July 2012 GrIS melt event, and that these types of moisture transport events have increased during the same 2000–2016 period discussed in this study.

The paper should be modified to more fairly reflect the breadth of the literature on this topic, noting that while one paper found a decreasing trend in summer cloud cover after 2000, most other studies on the topic have pointed to the key role played by poleward transport of warm, moist air and the resultant cloud cover in forcing GrIS melt events. Including this information will also help align the characterization of recently observed circulation changes with the authors' statement that "both simulations forced by warmer reanalysis suggest a SWD decrease as well as in GCM-forced simulations with a warmer climate as a result of an increased cloud cover. This effect combined with a higher free atmosphere temperature explains then the increase in downward longwave radiation (LWD) in a warmer climate" (p. 6, lines 9–12).

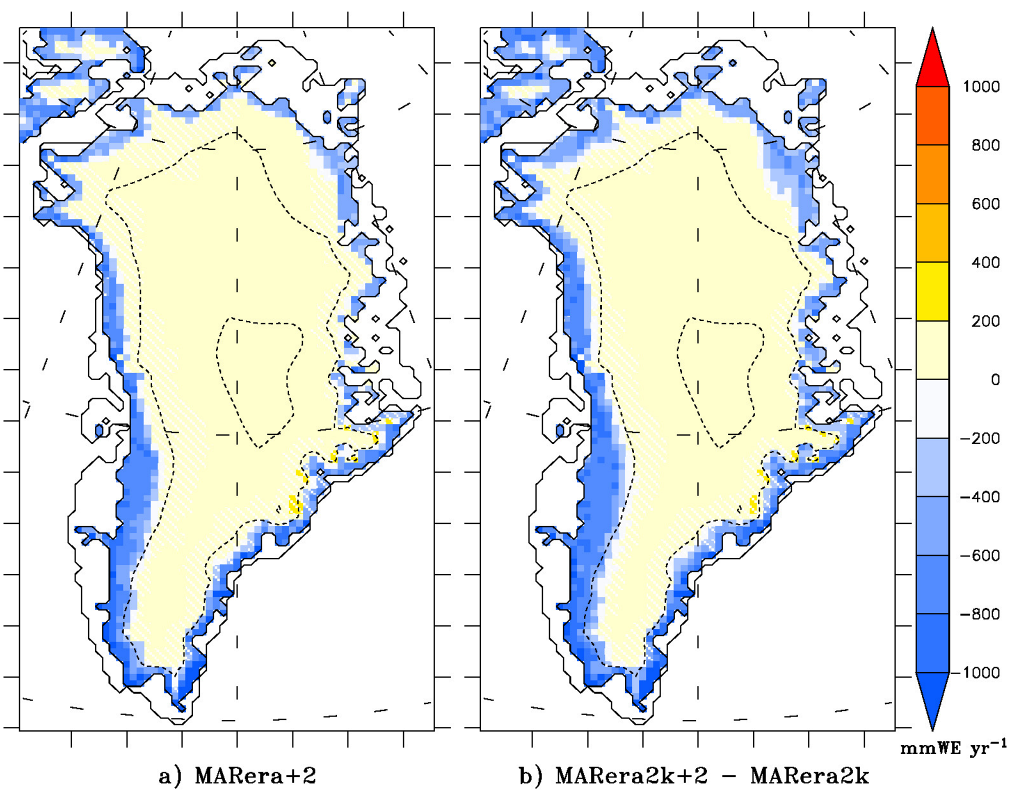
These relevant remarks will be taken into account to improve our introduction where the antagonist role of clouds over the ablation zone (where they rather cold the climate) and over the accumulation zone (where they rather warm the climate) will be discussed in more details, as well as our discussion of results (Section x.y).

Section 2.2.1, p. 3: More detail is needed here about the ERA-Interim atmospheric temperature forcing. Are the ERA-Interim atmospheric temperatures increased in a uniform manner at all vertical levels? Are they only increased near the surface? Or are they increased at 850 hPa, 700 hPa, 600 hPa, and 500 hPa, in a manner analogous to the temperature anomaly calculations for the GCMs (section 2.2.2)?

More details should be given in the sentence p3, line 5-6. We suggest then to reformulate our sentence “ Then, we performed sensitivity experiments in which ERA-Interim atmospheric temperatures were increased by respectively +1 °C, +1.5 °C and +2 °C at the MAR atmospheric lateral boundaries (hereafter referred to as warmer reanalysis).”
to
“Then, we performed sensitivity experiments in which ERA-Interim atmospheric temperatures were increased by respectively +1 °C, +1.5 °C and +2 °C at each of the 24 vertical sigma level of the MAR atmospheric lateral boundaries (hereafter referred to as warmer reanalysis).”

Figure 2 should be altered to include both positive and negative SMB anomalies (Fig. 2a) and differences (Fig. 2b) on a diverging color scale (like Figures S5 through S7 in the supplement). In addition to the areas of negative SMB anomalies / differences along the margins of the GrIS, the color scale is likely concealing areas of less intense positive anomalies / differences in the interior GrIS.

Adapted figure:



How is the statistical significance of anomalies calculated? (i.e. pg. 4, line 22; pg. 6, line 2)

Anomalies and/or differences are significant if they are greater than the standard deviation (i.e. interanual variability of the annual SMB) of the simulation of MAR forced by unaltered ERA-Interim over 1980-1999 as explained p4, line 22 and in the legends of both figures.

The manner in which SMB anomalies in the experiments are discussed is confusing. On pg. 5 (lines 4–10), the SMB anomalies in the MARera2K+x experiments are described as having “significantly more negative” SMB anomalies and an “enhanced decrease in SMB” compared to the warmer reanalysis and GCM-forced experiments. However, in the Conclusions (pg. 7, lines 27–31), the SMB anomalies in the experiments with warming and a circulation change (i.e. the MARera2K+x experiments) are first described as having SMB anomalies that are “two times higher on average”, then are described as having a “higher decrease in SMB”. The language in the Results and/or the Conclusions should be edited to be consistent, and to make the nature of the SMB anomalies clarified.

To be consistent, we will change “ ... two times higher on average ...” in “ ... two times more negative on average...” in p7, line 27.

Minor comments

p. 1, l. 10: change “is similar” to “are similar”
p. 1, l. 13: change “atmospheric conditions will persist” to “atmospheric conditions persist”
p. 1, l. 20: change “have been attributed” to “has been attributed”
p. 1, l. 21: misspelled “heighten”
p. 2, l. 1: change “solar radiations” to “solar radiation”
p. 2, l. 7: change “rises” to “raises”
p. 2, l. 18: change “relatively” to “relative”
p. 2, l. 19: change “consists in” to “consists of”
p. 2, l. 20: change “radiations” to “radiation” and “precipitations” to “precipitation”
p. 4, l. 8: change “Like with” to “As with”
p. 7, l. 19: change “First experiments consisted in” to “The first experiments consisted of”
Supplement: change “relatively” to “relative” throughout Table S2

Ok, thanks. All of these will be taken into account in the revised version of our paper.

We first would like to thank the reviewer for his comments which will help to improve our manuscript.

Substantive Comments

1. As mentioned by reviewer #1, additional information on how temperature perturbations are applied to the ERA-Interim forcing are necessary to better understand the results. Were the temperatures increased only at the surface or at each MAR atmospheric vertical level? This should be clearly mentioned. Section 2.1 should also explicitly state how many atmospheric vertical levels are used in these simulations.

As explained in the responds to reviewer #1, more details will be given in the sentence p3, line 5-6. We suggest then to reformulate our sentence "*Then, we performed sensitivity experiments in which ERA-Interim atmospheric temperatures were increased by respectively +1 °C, +1.5 °C and +2 °C at the MAR atmospheric lateral boundaries (hereafter referred to as warmer reanalysis).*"
to
"*Then, we performed sensitivity experiments in which ERA-Interim atmospheric temperatures were increased by respectively +1 °C, +1.5 °C and +2 °C at each of the 24 vertical sigma level of the MAR atmospheric lateral boundaries (hereafter referred to as warmer reanalysis)*."

2. Section 2.1 should also briefly discuss how the snow pack was initialized for the different sensitivity experiments. Is the initial state of the snow pack similar for each sensitivity experiment (MAR forced by ERA-Interim and GCM scenarios)?

The reference simulations have been initialized with snowpacks from previous MAR simulations (forced by ERA and by the 3 GCMs) and started in 1970 to give time to MAR to be independent of the initial snow condition. To remove the dependence of the snowpack initialization in the ERA-Interim forced sensitivity experiments, we have started these simulations in 1970 with warmer ERA-40.

3. In Section 2.2.2, the authors should explain in more detail why these three specific GCMs were selected. The authors should also clarify why the 20-yr periods experiencing +1, +1.5 and +2 ºC are sometimes very different for the three GCMs, i.e. especially for CanESM2.

As explain p3 l 21-22, the three selected GCMs are the best representing the general circulation at 500 hPa (impacting the precipitation amount and pattern simulated by MAR) and the JJA (June-July-August) temperature at 700 hPa (impacted the melt amount simulated by MAR) over Greenland compared to ERA-Interim over 1980 – 1999.We refer to Fettweis et al. (2013) for more details in this choice of GCMs

The 20-yr periods experiencing +1, +1.5 and +2 ºC are very different following the used GCM because there is offset in the warming projected by each GCM: For instance, CanESM2 projects a faster warming notably due to the melting of the Arctic sea ice with respect to the other GCMs. Again, this is also well shown and discussed in Fettweis et al. (2013).

4. At P5 L3-5, the authors state that capturing the circulation change results in a massive runoff increase "nearly two times higher" relative to the reference period. This is an interesting result that is not further discussed. The authors should consider discussing the potential mechanisms driving this significant runoff increase. See also the corresponding point comment at P7 L4-6.

See point comment at P7 L4-6.

Point Comments

P1 L4: Add “North” before “Atlantic”.
L8: For consistency, replace “forced with” by “forced by”. This comment holds for the whole manuscript.
L23: The authors could add: “[…] snow grain metamorphism and further decreasing surface albedo […]”.

Ok, thanks. All of these will be taken into account in the revised version of our paper.

P2 L1: The authors could add: “[…] in summer leads to longer exposure of bare ice at the GrIS margins […]”.

OK, thanks.

L4-7: The authors certainly mean that as GCMs fail to capture the current circulation change, the resulting recent melt increase modeled by RCMs forced by GCM “historical climate” is underestimated compared to observations. Could the authors clarify this and reformulate?

GCMs do not simulate any circulation change for both the historical scenario (prior to 2006) and RCPs scenarios, so that the melt increase observed since the 2000’s is underestimated when RCM’s are forced by these GCM as Fettweis et al. (2013a) showed that 70% of the recent melt increase is explained by the NAO shift. We therefore propose to reformulate L4-7 (p2):

“*Such an amplification in surface melt is well represented by Regional Climate Models (RCMs) when they are forced by reanalysis (Ettema et al., 2009; Fettweis et al., 2011, 2017; Noël et al., 2015, 2018). However, as General Circulation Models (GCMs) do not presently predict any circulation changes (Belleflamme et al., 2012; Fettweis et al., 2013b), the melt increase currently observed is underestimated when RCMs are forced by GCM scenarios (e.g., Fettweis et al., 2011, 2013b; Rae et al., 2012).*”

to

“Such an amplification in surface melt is well represented by Regional Climate Models (RCMs) when they are forced by reanalysis which capture the current circulation change (Ettema et al., 2009; Fettweis et al., 2011, 2017; Noël et al., 2015, 2018). However, as General Circulation Models (GCMs) do not presently predict any circulation changes (Belleflamme et al., 2012; Fettweis et al., 2013b), the melt increase currently observed is underestimated when RCMs are forced by GCM scenarios starting from 2000’s (e.g., Fettweis et al., 2011, 2013b; Rae et al., 2012).”

L21-27: This paragraph should better be moved to Section 2.1. Section 2.2 could start at L27: “We performed two sets […]”.

OK, thanks.

Information about the number of atmospheric vertical levels and initialization of the snow pack could be briefly discussed in Section 2.1, see also substantive comments.

See Substantive Comment 1 for the number of atmospheric vertical levels (i.e, 24 levels) and Substantive Comment 2 for the initialization of the snowpack.

P3 Sections 2.2.1 and 2.2.2 could be titled "ERA-Interim forcing" and "GCM forcing", respectively.

OK, thanks.

L18: How are temperature in the free atmosphere estimated at 850-700 hPa when these pressure levels cross the surface topography of the GrIS interior?

If the topography is higher than the altitude of the level pressure, the pixel is not taken into account for the average temperature.

P4 L25-28: I do not fully understand the analogy between SMB anomalies in Noël et al. (2014) and the present study. Could the authors clarify and reformulate?
I also suggest: "These differences at the ice sheet margins are similar to SMB anomalies found […], who obtained insignificant impact […]".

Although we made the analogy between forcing MAR by reanalyses warmer by 1, 1.5 and 2°C over the 1980-1999 period and by GCMs over a climate warmer by 1, 1.5 and 2°C compared to their reference climate over 1980-1999, experiments based on warmer reanalyses differ from corresponding experiments based on GCM because sea surface conditions (SSC, namely SIC and SST) remains unchanged in the warmer reanalysis forced sensitivity experiments but correspond to a warmer climate in the GCM forced simulations. SSC in MARera+x are thus representative of a colder ocean (more SIC and less SST) than the SSC from MARnor, MARcan and MARmir experiments. On the other hand, Noël *et al*. (2014) evaluated the influence of warmer SSC on the Greenland SMB by increasing (resp. decreasing) SST (resp. SIC) of ERA-Interim. Differences at the ice sheet margins (Fig. 1) are similar to the SMB anomalies found by Nöel *et al* (2014). We therefore assume that weak anomalies between MARera+x and MARmir (or MARnor or MARcan) result from the SSC unchanged in MARera+x.

We will modify L25-28:

"However, these differences on the ice sheet margins correspond to the same anomalies found by Noël et al. (2014) who evaluated the (not significant) impact of warmer SSC on the current SMB. Therefore, we can reasonably assume that these differences in anomalies mainly result from SSC not modified in experiments based on warmer reanalysis compared to GCM-forced simulations using future SSC."

to

"These weak differences are caused by the sea surface conditions (SSC) which were not modified in experiments based on warmer reanalyses while the GCM-forced simulations use future SSC and corresponds to what found by Noël et al. (2014) who showed that same unsignificant anomalies warmer SSC."

P5 L5: I understand: "The SMB anomaly in MARera2k+1 […] more negative than the warmer reanalysis over the reference period (MARera+1, resp. MARera+2) and the corresponding GCM-forced future experiments (Table 2)", could the authors clarify?

The SMB anomaly MARera2k+1 (resp. MARera2k+1.5) is significantly more negative than warmer reanalysis experiments and GCM-forced future experiments relative to a climate warmer by +1.5 °C (resp. +2 °C).

L6-7: Could the authors consider: "This suggests that capturing the recent circulation change simulated by warmer reanalysis in GCM-forced experiments would enhance the projected SMB decrease." Then at L9: "This is illustrated […] of +2 °C over 2000-2016 (Fig. 2b), i.e. including the recent circulation change, compared to the reference circulation over […]".

OK, thanks.

P6 L9: I read 3.7 W/m² in Table 2. The authors certainly mean "~4W/m2".

OK, thanks.

L9-11: The second part of this sentence is poorly written (i.e. after as well as), could the authors reformulate?

We will rewrite

"However both simulations forced by warmer reanalysis suggest a SWD decrease as well as in GCM-forced simulations with a warmer climate as a result of an increased cloud cover (Franco et al., 2013)."

to

"However both simulations forced by warmer reanalysis as well as in GCM-forced simulations with a warmer climate suggest a SWD decrease as a result of an increased cloud cover (Franco et al.,2013)"

P7 L1: Table 2 shows that absorbed SWD is more than two times higher for 2000-2016 compared to the reference period. I suggest: "is more than two times".

OK, thanks.

L4-6: As mentioned in the substantive comments, this is an interesting result which is unexploited. The authors should briefly elaborate on how increased melt lead to enhanced runoff, the authors could refer to Machguth et al. (2016).

We have calculated same anomalies than runoff for the production of meltwater (ME):

Anomaly	Temperature increase (°C)	MARera+x	MARera2k+x	Mean 3 models
Annual mean SMB (Gt)	+0	0	**-205**	
	+1	-84	**-326**	-118
	+1,5	-146	**-408**	-164
	+2	**-206**	**-492**	**-197**
Annual mean RU (Gt)	+0	0	**211**	
	+1	**142**	**393**	**141**
	+1,5	**236**	**508**	**215**
	+2	**328**	**626**	**283**
Annual mean ME (Gt)	+0°C	**0**	**195**	
	+1°C	**133**	**352**	**135**
	+1,5°C	**210**	**440**	**203**
	+2°C	**291**	**534**	**261**

And we suggest to modify the flowing sentences by adding some details (in blue) in paragraph starting P5 L12 and ending P6 L13:

"As runoff (RU) and snowfall (SF) mainly drive the GrIS SMB (Box et al., 2004), we discuss in the following the anomalies relative to these two components only. Like for SMB anomalies, RU and SF anomalies are computed as differences between the corresponding mean value for a given experiment and the mean value for the reference period using the unaltered large-scale forcing (Table 2). Even though non-significant, an increase in SF is observed for all experiments associated with temperature rising in response to a higher air capacity for holding water vapor (Fettweis et al., 2013a). Moreover, mean RU anomalies increase with the temperature rising in all warming experiments, most significantly for the experiments using warmer reanalysis over 2000 – 2016 when the circulation change has occurred. It can thus be concluded that runoff is mainly responsible for the SMB discrepancies between the different sensitivity experiments in a warmer climate. Melt (ME) is also amplifying as RU with the circulation change. However, RU anomalies are systematically higher than ME anomalies which means RU increase more than ME. It can be explain by two factors (Machguth et al., 2016): (1) there is less pore place available for meltwater storage in warmer firn and, (2) bare ice area (in the ablation zone) is larger in warmer climate, so there is less meltwater storage which amplifies the runoff increase. The future decrease of the ice sheet meltwater capacity retention was notably shown by Van Angelen et al. (2013).

Due to the enhanced positive melt-albedo feedback since the 2000's, SWD absorbed by the surface is two times higher in simulations with warmer reanalysis over 2000 – 2016 than over the reference period. Due to a lower albedo, the surface absorbs more energy, amplifying the melt increase which further decreases the albedo, potentially reaccelerating melting in addition to a decrease of the ice sheet capacity to refreeze meltwater. This positive feedback triggered by more frequent anticyclonic summer situations over Greenland causes a runoff increase nearly two times higher in simulations over 2000 – 2016 than in the simulations over the reference period, i.e. before the circulation change."

L31: Following my previous comment, melt is not a direct component of SMB. It is the runoff increase that drives the decrease in SMB.

We will rewrite :
"*As a result, the melt increase is enhanced and is responsible for the higher decrease in SMB.*"

to

"*As a result, the runoff increase is enhanced and is responsible for the higher decrease in SMB.*"

Stylistic suggestions

P1 L5: Remove "in a warmer climate".
L6--9: I would suggest to reformulate as follows: "We compare GrIS […] MAR forced by perturbed ERA--Interim reanalysis over 1980--2016, i.e. with a temperature increase of +1, +1.5, +2 °C relative to 1980--1999, to future […] forced by three GCMs over selected periods experiencing a similar temperature increase."
L11: Remove "However,"
L18: I would suggest: "multiple melting records have been broken [...] "
L19: Replace "have been" by "can be"
L20: Maybe "resulting from" instead of "gauged through".
L21: Maybe "enhanced" instead of "heighten".

P2 L3: Remove “when they are” and add “climate” before reanalysis.
L7--8: I would suggest: “This raises the question of how RCM--based projections of future GrIS SMB are affected by the GCM forcing if the recent shift to negative NAO phases in summer persists through the next decades.”
L9: Maybe: “we use the Modéle Atmosphérique Régional (MAR), especially developed for modeling the SMB of polar regions, to perform [...] with perturbed ERA--Interim reanalysis (+1, +1.5,+2 °C) and three [...]”.
L18: Relative to the version [...].
L19: “consist of”.
L20: “radiation [...] precipitation”.
L23: Replace “a global forcing dataset such as reanalysis” by “climate reanalyses”.
L27: Remove “only” and replace “in relation to” by “with respect to”.

P3 L9: “[...] lateral boundaries is conserved by estimating the specific humidity changes as a function of temperature increase”.
L10--11: Either “[...] with warmer [...] atmospheric conditions” or “[...] with higher [...] atmospheric temperature”.
L6--13: I suggest: “Therefore we compare anomalies of these GCM--forced [...] and ~+2 °C to the corresponding GCM--forced [...]. As for the sensitivity experiments [...], the mean SMB anomalies associated with these GCMs [...] x equals 1, 1.5 or 2 corresponds to +1 °C [...] warming (Appendix [...]). Contrary to ERA--Interim forced experiments, no humidity correction [...] and the SSC are directly prescribed from RCP4.5 [...]”. The authors certainly mean humidity correction” at L12?

P4 L16--19: I would suggest: “[...] future SMB projections, we evaluate analogies between MAR forced by warmer reanalysis and by GCM future scenarios over periods experiencing a similar warmer climate. Figure 1 shows the difference in SMB anomalies between MARera+1 (resp. +2) and MARmir+1 (resp.+2,using MIROC5 as forcing) over 1980--1999 [...]”.
L28: “Because GCMs fail [...]”
L29: “similar SMB anomalies as MAR”,
L31: I guess the authors mean “a circulation change on the projected GrIS SMB”.

P5 L3: The authors could remove “in summer” as it is already suggested by “JJA temperature” at L4.
L13: “As for SMB anomalies,”

P7 L12: I would suggest: “The goal [...] the impact of unresolved recent atmospheric circulation change in GCMs on RCM--based projections of future GrIS SMB.”
L22: “for which a similar temperature increase of”.
L23: “by these GCMs in the free atmosphere.”
L24: Replace “that the results are similar ”by “similar results”.
L28: Maybe: “suggests that capturing the circulation change leads to SMB anomalies two times higher on average for a similar [...]”.
L32: “The results […] suggest”

P8 L2--3: “of examining whether GCMs can predict [...] if so, evaluate [...]”.

Ok, thanks. All of these will be taken into account in the revised version of our paper.

Figures and Tables

Table1: For consistency, replace 1± 0.39 by 1.00 ± 0.39 in the second row of the second column.
Table2: The authors should consider to explicitly mention MARera and MARera2k instead of/in addition to ERA-Interim in column 3 and 4.
Figure1: To improve readability, could the hatches be displayed in a darker color e.g. grey?
Figure2: As this figure also shows anomalies, a red-to-blue color scale centered on 0 should be used.As for Figure1, hatches could also be displayed in grey for better visibility.

Appendix A1 and A2: For consistency, replace “forced with” by “forced by”. The same applies to the two similar tables in the Supplementary Material.

Ok, thanks. All of these will be taken into account in the revised version of our paper.

References

Fettweis, X., Franco, B., Tedesco, M., van Angelen, J. H., Lenaerts, J. T. M., van den Broeke, M. R., and Gallée, H.: Estimating Greenland ice sheet surface mass balance contribution to future sea level rise using the regional atmospheric climate model MAR, The Cryosphere, 7, 469–489, https://doi.org/10.5194/tc-7-469-2013, 2013a.

Machguth, H., Macferrin, M., Van As, D., Box, J. E., Charalampidis, C., Colgan, W., … Van De Wal, R. S. W. (2016). Greenland meltwater storage in firn limited by near-surface ice formation. Nature Climate Change, 6(4), 390–393. https://doi.org/10.1038/nclimate2899

Van Angelen, J. H., Lenaerts, J. T. M., Van Den Broeke, M. R., Fettweis, X., & Van Meijgaard, E. (2013). Rapid loss of firn pore space accelerates 21st century Greenland mass loss. Geophysical Research Letters, 40(10), 2109–2113. https://doi.org/10.1002/grl.50490

Brief communication: Impact of the recent atmospheric circulation change in summer on the future surface mass balance of the Greenland ice sheet

Alison Delhasse [1], Xavier Fettweis [1], Christoph Kittel [1], Charles Amory [1], and Cécile Agosta [1,2]

[1]Laboratory of Climatology, Department of Geography, University of Liège, Liège, Belgium

[2]Laboratoire des Sciences du Climat et de l'Environnement, Gif-sur-Yvette, France

Correspondence to: Alison Delhasse (alison.delhasse@uliege.be)

Abstract. Since the 2000's, a change in the atmospheric circulation over North Atlantic resulting in more frequent blocking events has favored warmer and sunnier weather conditions over the Greenland Ice sheet (GrIS) in summer enhancing the melt increase. This circulation change is not represented by General Circulation Models (GCMs) of the 5th Coupled Model Intercomparison Project (CMIP5) which do not predict any circulation change for the next century over the North Atlantic. The goal of this study is to evaluate the impact of an atmospheric circulation change (as currently observed) ~~in a warmer climate on future~~ on projections of the future GrIS surface mass balance (SMB). We compare GrIS SMB estimates ~~from~~ simulated by the regional climate model MAR forced by ~~warmer~~ perturbed reanalysis (ERA-Interim with a temperature correction of +1 °C, +1.5 °C and +2 °C at the MAR lateral boundaries) over 1980 – 2016 to ~~future projections of~~ projections of the future GrIS SMB from MAR simulations forced ~~with~~ by three GCMs over ~~a future period~~ selected periods for which a similar temperature increase of +1 °C, +1.5 °C and +2 °C is projected by the GCMs in comparison to 1980 – 1999. Mean SMB anomalies produced with ~~warmer~~ perturbed reanalysis over the climatologically stable period 1980 – 1999 ~~is~~ are similar to those produced with MAR forced ~~with~~ by GCMs over future periods characterized by a similar warming over Greenland. However, over the two last decades (2000 – 2016) when ~~a circulation change~~ an increase in the frequency of blocking events has been observed in summer, MAR forced ~~with warmer~~ by perturbed reanalysis suggests that the SMB decrease could be amplified by a factor of two if such atmospheric conditions ~~will~~ persist compared to ~~future~~ projections forced by GCMs for the same temperature increase but without any circulation change.

1 Introduction

Starting in the late 1990's, the surface mass balance (SMB, i.e. the difference between mass sources and sinks at the surface) of the Greenland Ice Sheet (GrIS) has been decreasing through a rise in surface meltwater runoff (Fettweis et al., 2013a; van den Broeke et al., 2016). Since the 2000's, multiple melting records have been ~~observed~~ broken over the GrIS (Tedesco et al., 2013; Hanna et al., 2014; Fettweis et al., 2017) and 70% of this melt increase ~~have been~~ can be attributed to an atmospheric circulation change gauged through a shift of the summer North Atlantic Oscillation (NAO) index to negative values (Fettweis et al., 2013b). These changes have favoured anticyclonic conditions (i.e. more frequent blocking events) in summer over Greenland which ~~heigthen~~ enhance the melt-albedo feedback through three main ways (Box et al., 2012): (1) an increase in advection of warm air along the western coast of the ice sheet enhancing the surface sensible heat flux, thus strengthening snow grain metamorphism and further decreasing surface albedo (Tedesco et al., 2016); (2) a decrease in snowfall rates in summer leading to longer exposure of bare ice at the GrIS margins (Noël et al., 2015) ; and (3) an increase in incoming ~~solar radiations~~ radiation resulting in more surface heating~~(Hofer et al., 2017); and (3) a decrease in snowfall rates in summer (Noël et al., 2015).~~ . For this last feature, the debate about the contribution of shortwave and longwave radiations is still ongoing as the role of clouds is opposite between the ablation zone (more sensitive to shortwave anomalies) and the accumulation zone (more sensitive to longwave anomalies). Hofer et al. (2017) points out the importance of increasing incoming solar radiation while other studies allocate the increase in surface heating and melting to longwave radiation notably due to the transport of water vapor (Neff et al., 2014; Bonne et al., 2015) and liquid low-level clouds (Bennartz et al., 2013). These processes reduce meltwater refreezing and then enhance meltwater runoff (Van Tricht et al., 2016).

Such an amplification in surface melt is well represented by Regional Climate Models (RCMs) ~~when they are forced by reanalysis~~ forced by climate reanalysis which capture the current circulation change (Ettema et al., 2009; Fettweis et al., 2011, 2017; Noël et al., 2015, 2018). However, as General Circulation Models (GCMs) do not presently predict any future circulation ~~changes (Belleflamme et al., 2012; Fettweis et al., 2013b)~~change (Belleflamme et al., 2012; Fettweis et al., 2013b; Hanna et al., in review, the melt increase currently observed is underestimated when RCMs are forced by GCM scenarios starting from 2000's (e.g., Fettweis et al., 2011, 2013b; Rae et al., 2012). This ~~rises~~ raises the question of how ~~future projections of the GrIS SMB could be~~ RCM-based projections of future GrIS SMB are affected by the ~~use of future GCM scenarios to force a RCM if the current shift of the summer NAO to negative phases will continue in~~ GCM forcing if the recent shift to negative NAO phases in summer persists through the next decades?

To address this issue, we ~~have used the regional atmospheric climate model MAR (~~use the Modèle Atmosphérique Régional ~~)~~ (MAR), especially developed for polar regions~~and performed~~ , to perform a sensitivity study based on the analysis of MAR-derived GrIS SMB anomalies resulting from various forcing experiments with ERA-Interim reanalysis and three GCMs from the CMIP5 database (The 5th phase of the Climate Model Intercomparison Project; Taylor et al., 2012).

2 Data and methodology

2.1 The regional climate model MAR

The model MAR is a RCM specifically developed for simulating polar climate specificities (e.g., Amory et al., 2015; Gallée et al., 2015; Lang et al., 2015), furthermore abundantly evaluated over the Greenland ice sheet (e.g., Fettweis et al., 2011, 2017). In this study, we use the version 3.8 of MAR, and refer to Fettweis et al. (2017) for a more detailed description of MAR. ~~Relatively~~ Relative to the version 3.5 used in Fettweis et al. (2017) and in addition to usual bug fixes and improved computation efficiency, the main improvement of MAR v3.8 consists ~~in~~ of an increase of the cloud life time, partly correcting the underestimation of downward longwave ~~radiations~~ radiation and the overestimation of inland ~~precipitations found~~ precipitation described in Fettweis et al. (2017).

Table 1. 20-yr periods corresponding to an increase in temperature of $\sim$+1 °C, $\sim$+1.5 °C and $\sim$+2 °C for the three selected GCMs (MIROC5, NorESM1 and CanESM2). The exact increase in temperature and the standard deviation for these periods compared with 1980 – 1999 are shown.

	MIROC5		NorESM1		Can ESM2	
	Temp. increase (°C)	Period	Temp. increase (°C)	Period	Temp. increase (°C)	Period
$\sim$+0 °C	~~0~~0.00±0.54	1980 – 1999	~~0~~0.00±0.41	1980 – 1999	~~0~~0.00±0.57	1980 – 1999
$\sim$+1 °C	~~1~~1.00±0.39	2007 – 2027	0.99±0.52	2014 – 2034	1.00±0.41	1997 – 2017
$\sim$+1.5 °C	1.52±0.52	2019 – 2039	1.51±0.57	2023 – 2043	1.49±0.60	2006 – 2026
$\sim$+2 °C	1.97±0.64	2029 – 2049	2.00±0.55	2033 – 2053	1.99±0.49	2016 – 2036

2.2 ~~Forcing experiments~~

MAR requires prescription of atmospheric fields (temperature, ~~relative~~ specific humidity, wind speed, pressure) at its lateral boundaries as well as sea surface conditions (SSC, defined as sea ice concentration and sea surface temperature) from ~~a global forcing dataset such as~~ climate reanalysis or GCM outputs. Using ERA-Interim reanalysis (Dee et al., 2011) to force MAR, Fettweis et al. (2013a) have shown that the period 1980 – 1999 is characterized by a stable climate and general circulation over Greenland, before a circulation shift occurred in summer at the end of the 1990's. In this study, we thus consider the period 1980 – 1999 as a reference (Fettweis et al., 2013a), and discuss ~~only~~ mean GrIS annual SMB anomalies ~~in relation~~ with respect to this reference period.

2.2 Forcing experiments

We performed two sets of sensitivity experiments according to the large-scale forcing used, as described below.

2.2.1 ~~Forcing with the~~ ERA-Interim ~~reanalysis~~forcing

MAR was first forced ~~with~~ by the ERA-Interim reanalysis every 6 hours at a spatial resolution of 25 km over 1979 – 2016. Two distinct periods are considered: the reference period 1980 – 1999, and the period 2000 – 2016 for which a different atmospheric circulation has been observed in summer on average by comparison with the reference period ~~(Fettweis et al., 2013b, 2017)~~(Fettweis et al., 2 Then, we performed sensitivity experiments in which ERA-Interim atmospheric temperatures were increased by respectively +1 °C, +1.5 °C and +2 °C at ~~the~~ each of the 24 vertical sigma levels of the MAR atmospheric lateral boundaries (hereafter referred to as ~~warmer~~ perturbed reanalysis). The mean SMB anomalies of these sensitivity experiments are referred to as MARera+1, MARera+1.5 and MARera+2 respectively for anomalies averaged over 1980 – 1999, and MARera2k, MARera2k+1, MARera2k+1.5 and MARera2k+2 for corresponding anomalies averaged over 2000 – 2016 (Appendix A, Table A1). Note that the relative humidity at the lateral boundaries was conserved by modifying the specific humidity according to temperature changes in order to obtain precipitation fields consistent with warmer ERA-Interim atmospheric temperatures. However, SSC from ERA-Interim reanalysis remained unchanged in the sensitivity experiments.

2.2.2 ~~Forcing with CMIP5 GCMs~~GCM forcing

We performed three additional experiments in which MAR was forced over 1980 – 2060 with three GCMs from the CMIP5 database, using the Historical scenario over 1980 – ~~2006~~ 2005 and the future RCP4.5 scenario (Moss et al., 2010) over ~~2006~~ 2005 – 2060. Then, for each GCM, three 20-yr periods (different for each GCM) characterized by a climate of about $\sim$+1 °C, $\sim$+1.5 °C and $\sim$+2 °C warmer on average than the ~~Historical climate~~ climate over the reference period (as represented by the GCM) of 1980 – 1999 were considered (Table 1). The differences between the GCM periods are only due to the timing required to reach each relative warming. Note that each warming was computed as the mean JJA (June-July-August) temperature anomaly compared to 1980 – 1999 over the computation domain (~~100W- 0W, 55N-85N~~100°W- 0°W, 55°N-85°N) at four vertical levels in the free atmosphere (850 hPa, 700 hPa, 600 hPa and 500 hPa).

The three GCMs used are CanESM2, NorESM1 and MIROC5, identified in Fettweis et al. (2013b) as the CMIP5 GCMs best representing the general circulation at 500 hPa ~~and the JJA (June-July-August)~~ (influencing the precipitation amount and pattern simulated by MAR) and the JJA temperature at 700 hPa over Greenland (influencing the melt amount simulated by MAR) compared to ERA-Interim over 1980 – 1999. However, some discrepancies remain between MAR forced by these GCMs and MAR forced by ERA-Interim over 1980 – 1999. For instance, MAR underestimates runoff and overestimates snowfall when forced by NorESM1 compared to MAR forced by ERA-Interim (Fettweis et al., 2013a). This is also confirmed by a recent study comparing melt energy budgets from MAR forced by ERA-Interim, MIROC5, NorESM1 and CanESM2 (Leeson et al., 2018). ~~Therefore,~~ This is why the SMB obtained with ~~warmer~~ perturbed reanalysis cannot be directly compared to the SMB obtained with GCM forcing data because of these divergences over the reference period.

~~This is why only~~ Therefore we compare anomalies of these ~~GCMs-forced future~~ GCM-forced projections during the 20-yr future periods of $\sim$+1 °C, $\sim$+1.5 °C and $\sim$+2 °C ~~are discussed respectively in relation~~ to the corresponding GCM-forced MAR climate over the reference period (1980 – 1999) and not directly to MAR forced by ERA-Interim over 1980 – 1999. ~~Like~~ As for the sensitivity experiments using the ERA-Interim reanalysis as forcing, the mean SMB anomalies ~~relative to~~ associated with these GCMs experiments are respectively referred to as MARcan+x for CanESM2, MARmir+x for MIROC5 and MARnor+x for NorESM1 where x equals 1, 1.5 or 2 ~~according to a climate warmer by~~ corresponds to a warming of respectively +1 °C, +1.5 °C and +2 °C (Appendix A, Table A2). ~~The main difference with the~~ Contrary to ERA-Interim forced experiments~~is that no~~, no humidity correction has been applied at the MAR lateral boundaries and the SSC ~~used are those~~ are directly prescribed from the RCP4.5 scenario projected by the respective GCM.

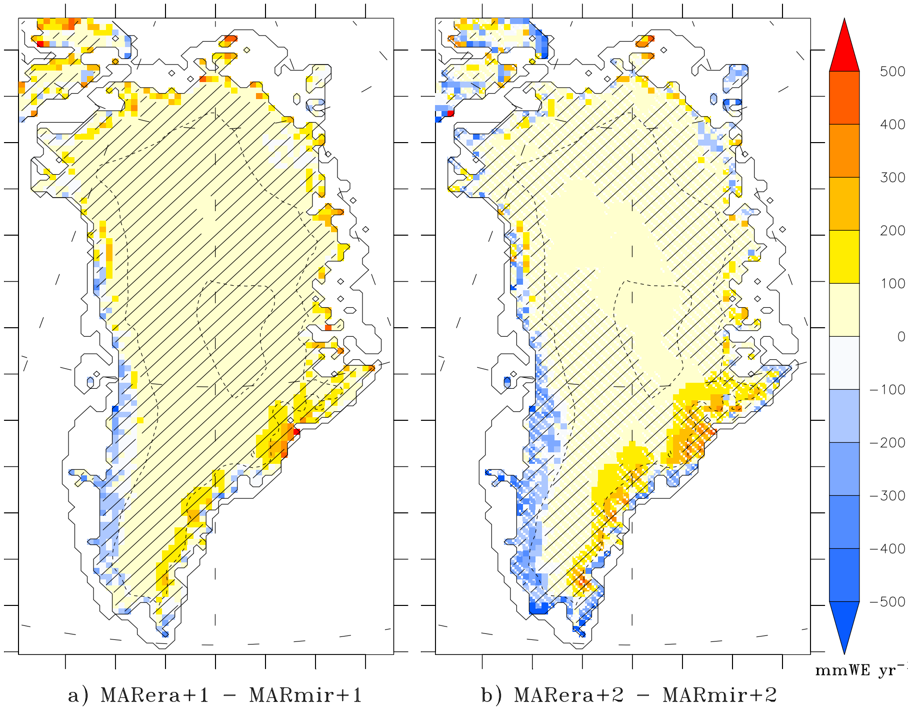


Figure 1. Differences of mean anomalies of annual SMB (in mmWE y^{-1}) between a) MARera+1 and MARmir+1 and b) MARera+2 and MARmir+2. Areas where anomaly differences are smaller than the inter-annual variability (i.e. the standard deviation) of the simulation of MAR forced by unaltered ERA-Interim over 1980 – 1999 are hatched. Dashed lines are equal altitude lines of 2000 m and 3000 m. See Appendix A Table A1 and Table A2 for abbreviations.

3 Results

3.1 Analysis of warming experiments without circulation change

Before assessing the impact of the current circulation change on ~~future~~ SMB projections, ~~the relevance of the analogy made between forcing with warmer reanalysis at MAR boundaries and forcing with GCM future scenarios predicting a similarly warmer climateneeds to be evaluated. In Figure 1 , we compare two different anomalies (here using MIROC5 as forcing): SMB anomaly~~ we evaluate analogies between MAR forced by perturbed reanalysis and by GCM scenarios over future periods experiencing a similar warmer climate. Figure 1 shows difference in SMB anomalies between MARera+1 (resp. +2) ~~; SMB anomaly~~ and MARmir+1 (resp. +2~~)~~

, using MIROC5 as forcing) over 1980 – 1999 when the mean general circulation in summer is similar in both ERA-Interim and GCMs.

Even if the differences are mainly not statistically significant (i.e. lower than the inter-annual variability of the simulation of MAR forced by unaltered ERA-Interim over 1980 – 1999), the runoff anomalies are generally higher if MAR is forced by

GCMs rather than by corresponding ~~warmer~~ perturbed reanalysis. GCM-forced simulations also predict a higher precipitation increase along the south-east of the ice sheet. ~~However, these differences on the~~ These weak differences are caused by the SSC which were not modified in experiments based on perturbed reanalysis while the GCM-forced simulations use future SSC. Anomalies at the ice sheet margins ~~correspond to the same~~ (Fig. 1) are similar to the SMB anomalies found by Noël et al. (2014) who evaluated the (~~not significant) impact of warmer~~ insignificant) impacts of SSC on the ~~current SMB . Therefore, we can reasonably assume that these differences in anomalies mainly result from SSC not modified in experiments based on warmer reanalysis compared to GCM-forced simulations using future SSC. While~~ SMB of the Greenland ice sheet. We therefore assume that anomalies between MARera+x and MARmir (or MARnor or MARcan) result from the SSC unchanged in MARera+x. Because GCMs fail to represent the circulation change observed in summer over Greenland since 2000's, MAR forced by ~~warmer~~ perturbed reanalysis over 1980 – 1999 simulates similar SMB anomalies ~~than~~ as MAR forced by GCMs over the corresponding ~~warmer future~~ future warmer periods. Therefore, evaluating MAR forced by ~~warmer~~ perturbed reanalysis over 2000 – 2016 allows us to evaluate the likely impact of a warmer climate induced by ~~a circulation change on the~~ an increase of blocking events (as currently observed) on the projected GrIS SMB.

3.2 Influence of a potential future circulation change

Over 2000 – 2016, the JJA temperature in the ERA-Interim reanalysis has increased by 0.7 °C in the free atmosphere (mean 850-500 hPa temperature integrated over the computation domain) ~~in summer~~ compared to 1980 – 1999. This offset in temperature has thus to be taken into account when comparing the anomalies of the different warming experiments. The SMB anomaly MARera2k+1 (resp. MARera2k+1.5) is significantly more negative ~~than warmer reanalysis~~ (up to a factor of two) than perturbed-reanalysis experiments and GCM-forced future experiments relative to a climate warmer by +1.5 °C (resp. +2 °C) (Table 2). This ~~means that~~ suggests that capturing the recent circulation change ~~associated with warmer reanalysis enhances the decrease in SMB~~ simulated by perturbed-reanalysis experiments would enhance the projected SMB decrease compared to the decrease projected for a warmer climate without any circulation change. This is illustrated in Figure 2 where the decrease in SMB is amplified for an equal increase in temperature of +2 °C ~~for the recent circulation~~ over 2000 – 2016 (Fig. 2b), i.e. including the recent circulation change, compared to the decrease for the reference circulation over 1980 – 1999 (Fig. 2a). Additional 2D-representations of these differences for GCM experiments are available in supplementary materials.

As runoff (RU) and snowfall (SF) mainly drive the GrIS SMB (Box et al., 2004), we mainly discuss in the following the anomalies relative to these two components~~only. Like~~ . As for SMB anomalies, RU and SF anomalies are computed as differences between the corresponding mean value for a given experiment and the mean value for the reference period using the unaltered large-scale forcing (Table 2). Even though non-significant, an increase in SF is observed for all experiments associated with ~~temperature rising~~ a rise in temperature in response to a higher air capacity for holding water vapor (Fettweis et al., 2013a). Moreover, mean RU anomalies increase with the temperature ~~rising~~ rise in all warming experiments, most significantly for the experiments using ~~warmer~~ perturbed reanalysis over 2000 – 2016 when the circulation change has occurred. It can thus be concluded that runoff is mainly responsible for the SMB discrepancies between the different sensitivity experiments in a warmer climate. As for RU, melt (ME) anomalies are also amplified with the circulation change (Table 2). However, RU

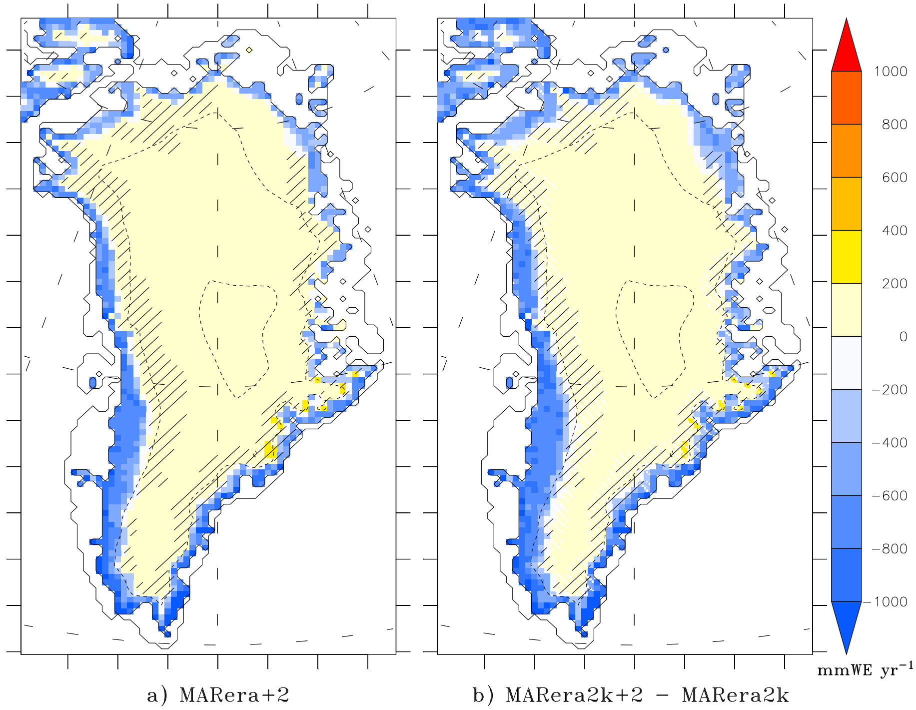


Figure 2. a) Mean anomalies of annual SMB (mmWE y^{-1}) of MAR forced with by warmer ERA-Interim warmer of +2 °C compared to MAR forced with by unaltered ERA-Interim over 1980 – 1999. b) Differences between mean anomalies of annual SMB (mmWE y^{-1}): MARera2k+2 - MARera2k. Areas where anomaly differences are smaller than the inter-annual variability (i.e. the standard deviation) of the simulation of MAR forced by unaltered ERA-Interim over 1980 – 1999 are hatched. Dashed lines are equal altitude lines of 2000 m and 3000 m. See Appendix A Table A1 and Table A2 for abbreviations.

anomalies are systematically higher than ME anomalies. This can be explained by two factors (Machguth et al., 2016): (1) there is less pore place available for meltwater storage in warmer and then more saturated firn and, (2) the bare ice area (in the ablation zone) is larger in warmer climate reducing the potential surface for meltwater storage which also amplifies the meltwater runoff increase. The future decrease of the ice sheet meltwater retention capacity has notably been discussed by Van Angelen et al. (2013).

The current observed melt increase since the 2000's is partly due to the increase in downward shortwave radiation (SWD)caused by more frequent anticyclonic situations enhancing the melt-albedo feedback (Hofer et al., 2017). On average over the ice sheet, SWD is downward shortwave radiation (SWD) and downward longwave radiation (LWD) are respectively almost 4 Wm^{-2} and 3 W mWm^{-2} higher over the 2000 – 2016 period than over the reference period (Table 3). This concords with Hofer et al. (2017)'s conclusions which argue that the current observed melt increase since the 2000's is a combination of the increase in SWD and LWD. However both simulations forced by warmer reanalysis suggest a SWD decrease perturbed reanalysis as well as in GCM-forced simulations with a warmer climate suggest a strong SWD decrease as a result of an

Table 2. Mean GrIS integrated anomalies of annual SMB (Gt ~~.~~y^{-1}), runoff (RU)~~and~~, snowfall (SF) and melt (ME) compared to 1980 – 1999. Anomalies from GCM-forced simulations are given as averaged. Anomalies greater than the 1980 – 1999 standard deviation (i.e. ~~,~~ greater than the inter-annual variability) of the simulation of MAR forced by unaltered ERA-Interim are shown in bold.

		Forcing		
	Temperature increase (°C)	ERA-Interim 1980 – 1999 (MARera)	ERA-Interim 2000 – 2016 (MARera2k)	Mean of the 3 GCMs
Annual mean SMB (Gtyr^{-1})	+0	0	**-205**	0
	+1	-84	**-326**	-118
	+1.5	-146	**-408**	-164
	+2	**-206**	**-492**	**-197**
Annual mean RU (Gtyr^{-1})	+0	0	**-211**	0
	+1	**142**	**393**	**141**
	+1.5	**236**	**508**	**215**
	+2	**328**	**626**	**283**
Annual mean SF (Gtyr^{-1})	+0	0	-8	0
	+1	37	28	13
	+1.5	56	46	29
	+2	**75**	**63**	51
Annual mean ME (Gtyr^{-1})	+0	0	**195**	0
	+1	**133**	**352**	**135**
	+1.5	**210**	**440**	**203**
	+2	**291**	**534**	**261**

~~increased cloud cover(Franco et al., 2013)~~increasing cloud cover, as already discussed in Franco et al. (2013). This effect combined with a higher free atmosphere temperature explains then the increase in ~~downward longwave radiation (LWD)~~ LWD in a warmer climate (Hofer et al., 2017).

Due to the enhanced positive melt-albedo feedback since the 2000's, SWD absorbed by the surface is more than two times higher in simulations with ~~warmer~~ perturbed reanalysis over 2000 – 2016 than over the reference period. Due to a lower albedo (in particular in the ablation zone), the surface absorbs more energy, amplifying ~~melt~~ the melt increase which further decreases the albedo, potentially reaccelerating melting in addition to a decrease of the ice sheet capacity to refreeze meltwater. This positive feedback triggered by more frequent anticyclonic summer situations over Greenland causes a runoff increase nearly two times higher in simulations over 2000 – 2016 than in the simulations over the reference period~~, i. e. before the circulation change.~~ .

Table 3. Mean GrIS integrated anomalies of summer energy fluxes ($W.m^{-2}$) and summer surface 2-m temperature (°C) compared to 1980 – 1999. Anomalies from GCM-forced simulations are given as averaged. Anomalies greater than the 1980 – 1999 standard deviation (i.e., greater than the inter-annual variability) of the simulation of MAR forced by unaltered ERA-Interim are shown in bold.

		Forcing		
	Temperature increase (°C)	ERA-Interim 1980 – 1999 (MARera)	ERA-Interim 2000 – 2016 (MARera2k)	Mean of the 3 GCMs
JJA mean SWD (Wm^2)	+0	0.0	**3.7**	0.0
	+1	-2.7	0.9	-0.7
	+1.5	**-4.2**	-0.6	-2.4
	+2	**-5.8**	-2.2	-3.9
JJA mean LWD (Wm^2)	+0	0.0	**3.2**	0.0
	+1	**4.8**	**8.1**	**4.5**
	+1.5	**7.2**	**10.6**	**7.3**
	+2	**9.7**	**13.2**	**9.4**
JJA mean absorbed SWD (Wm^2)	+0	0.0	**5.4**	0.0
	+1	1.9	**7.5**	2.0
	+1.5	**3.0**	**8.8**	2.8
	+2	**4.0**	**10.0**	**3.9**
JJA mean T2m (°C)	+0	0.00	**1.24**	0.00
	+1	**0.97**	**2.20**	**1.07**
	+1.5	**1.45**	**2.68**	**1.62**
	+2	**1.93**	**3.15**	**2.01**

In the absence of a circulation change, the increase in near-surface temperature (T2m) is only due to the temperature increase prescribed at the MAR lateral boundaries (Table 3). With a circulation change, the increase in T2m is higher and no more uniform as a result of enhanced warm air advection along the West GrIS (see Fig. S1 in supplementary material). Such more frequent anticyclonic conditions, resulting from more frequent blocking events (Hanna et al., in review, 2018), explain the increase in cloud cover at the north of the ice sheet and the associated LWD increase shown in Hofer et al. (2017) in this area, while sunnier conditions dominate in the southern part.

4 Conclusions

The goal of this study is to assess the impact of ~~the non-representation by GCMs of the~~ unresolved recent atmospheric circulation change ~~observed in summer over Greenland since the 2000's on~~ in GCMs on RCM-based projections of future GrIS SMB~~projections when these GCMs are used to force a RCM at its lateral boundaries~~. For this purpose, we used the RCM MAR and performed forcing sensitivity experiments with the ERA-Interim reanalysis and large-scale fields from 3 selected GCMs of the CMIP5 database to investigate the influence of a warmer atmosphere in the context of a circulation change inducing more frequent blocking events.

We used the annual SMB produced with each original forcing over the climatologically stable period of 1980 – 1999 as a reference, to compute mean annual SMB anomalies relative to each forcing experiment.

~~First experiments consisted in~~ The first experiments consisted of increasing the atmospheric temperature in the ERA-Interim reanalysis by +1 °C, +1.5 °C and + 2 °C at the MAR lateral boundaries over two distinct periods, i.e. 1980 – 1999 and 2000 – 2016, respectively before and after the shift in the summer NAO index. Additional forcing experiments were then performed using the three selected GCMs to force MAR over the reference period and over 20-yr future periods for which a ~~similarly warmer climate~~ similar temperature increase of ∼+1 °C, ∼+1.5 °C and ∼+2 °C is predicted by these GCMs in the free atmosphere.

The comparison between SMB anomalies relative to ~~warmer~~ perturbed reanalysis and GCM future experiments revealed ~~that the results are similar~~ similar results for each corresponding warming experiment, since for each GCM the atmospheric circulation remains unchanged over time. This allowed us to evaluate the likely impact of a warmer climate induced by a circulation change on the GrIS SMB by comparing SMB anomalies relative to ~~warmer~~ perturbed reanalysis over 2000 – 2016 with GCM-forced future SMB anomalies. This comparison suggests that ~~SMB anomalies are, this time,~~ capturing the circulation change leads to SMB anomalies two times higher on average with a circulation change than without for a similar atmospheric warming. These higher anomalies are explained by more frequent summer anticyclonic situations over GrIS leading to an increase in SWD and warm air advection along the west coast, both promoting a decrease in albedo. As a result, the ~~melt~~ runoff increase is enhanced and is responsible for the higher decrease in SMB.

The results of this study ~~suggests~~ suggest that previous estimates of ~~future GrIS SMB~~ GrIS melt projections produced using CMIP5 data as forcing (e.g., Rae et al., 2012; Fettweis et al., 2013a) could be significantly ~~overestimated~~ underestimated if the current summer atmospheric circulation pattern over Greenland persists. In the context of the forthcoming 6th phase of the Coupled Model Intercomparison Project, our conclusions highlight the importance of examining ~~if~~ whether GCMs predict circulation changes in the next decades and, if so, of evaluating their potential influence on ~~future~~ projections of the future GrIS SMB. Another remaining scientific challenge of particular interest for GrIS SMB projections is to establish if the increasing frequency of blocking events could be linked to global climate change.

Appendix A: Description of the abbreviations used in this study

Table A1. Abbreviation description of reanalysis sensitivity experiments

MARera+1	Anomalies between MAR forced ~~with~~ by the ERA-Interim reanalysis warmer of +1 °C over 1980 – 1999 and MAR forced ~~with~~ by the unaltered ERA-Interim reanalysis over 1980 – 1999
MARera+1.5	Anomalies between MAR forced ~~with~~ by the ERA-Interim reanalysis warmer of +1.5 °C over 1980 – 1999 and MAR forced ~~with~~ by the unaltered ERA-Interim reanalysis over 1980 – 1999
MARera+2	Anomalies between MAR forced ~~with~~ by the ERA-Interim reanalysis warmer of +2 °C over 1980 – 1999 and MAR forced ~~with~~ by the unaltered ERA-Interim reanalysis over 1980 – 1999
MARera2k	Anomalies between MAR forced ~~with~~ by the ERA-Interim over 2000 – 2016 and MAR forced ~~with~~ by the unaltered ERA-Interim reanalysis over 1980 – 1999
MARera2k+1	Anomalies between MAR forced ~~with~~ by the ERA-Interim reanalysis warmer of +1 °C over 2000 – 2016 and MAR forced ~~with~~ by the unaltered ERA-Interim reanalysis over 1980 – 1999
MARera2k+1.5	Anomalies between MAR forced ~~with~~ by the ERA-Interim reanalysis warmer of +1.5 °C over 2000 – 2016 and MAR forced ~~with~~ by the unaltered ERA-Interim reanalysis over 1980 – 1999
MARera2k+2	Anomalies between MAR forced ~~with~~ by the ERA-Interim reanalysis warmer of +2 °C over 2000 – 2016 and MAR forced ~~with~~ by the unaltered ERA-Interim reanalysis over 1980 – 1999

Table A2. Abbreviation description of GCM sensitivity experiments

MARmir+1	Anomalies between MAR forced ~~with~~ by MIROC5 over a warmer 20-yr period of +1 °C relatively to the reference period 1980 – 1999 and MAR forced ~~with~~ by MIROC5 over the reference period
MARmir+1.5	Anomalies between MAR forced ~~with~~ by MIROC5 over a warmer 20-yr period of +1.5 °C relatively to the reference period 1980 – 1999 and MAR forced ~~with~~ by MIROC5 over the reference period
MARmir+2	Anomalies between MAR forced ~~with~~ by MIROC5 over a warmer 20-yr period of +2 °C relatively to the reference period 1980 – 1999 and MAR forced ~~with~~ by MIROC5 over the reference period
MARnor+1	Anomalies between MAR forced ~~with~~ by NorESM1 over a warmer 20-yr period of +1 °C relatively to the reference period 1980 – 1999 and MAR forced ~~with~~ by MIROC5 over the reference period
MARnor+1.5	Anomalies between MAR forced ~~with~~ by NorESM1 over a warmer 20-yr period of +1.5 °C relatively to the reference period 1980 – 1999 and MAR forced ~~with~~ by MIROC5 over the reference period
MARnor+2	Anomalies between MAR forced ~~with~~ by NorESM1 over a warmer 20-yr period of +2 °C relatively to the reference period 1980 – 1999 and MAR forced ~~with~~ by MIROC5 over the reference period
MARcan+1	Anomalies between MAR forced ~~with~~ by CanESM2 over a warmer 20-yr period of +1 °C relatively to the reference period 1980 – 1999 and MAR forced ~~with~~ by MIROC5 over the reference period
MARcan+1.5	Anomalies between MAR forced ~~with~~ by CanESM2 over a warmer 20-yr period of +1.5 °C relatively to the reference period 1980 – 1999 and MAR forced ~~with~~ by MIROC5 over the reference period
MARcan+2	Anomalies between MAR forced ~~with~~ by CanESM2 over a warmer 20-yr period of +2 °C relatively to the reference period 1980 – 1999 and MAR forced ~~with~~ by MIROC5 over the reference period

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

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Brief communication: Impact of the recent atmospheric circulation change in summer on the future surface mass balance of the Greenland ice sheet

Alison Delhasse [1], Xavier Fettweis [1], Christoph Kittel [1], Charles Amory [1], and Cécile Agosta [1,2]

[1]Laboratory of Climatology, Department of Geography, University of Liège, Liège, Belgium

[2]Laboratoire des Sciences du Climat et de l'Environnement, Gif-sur-Yvette, France

Correspondence to: Alison Delhasse (alison.delhasse@uliege.be)

Abstract. Since the 2000's, a change in the atmospheric circulation over North Atlantic resulting in more frequent blocking events has favored warmer and sunnier weather conditions over the Greenland Ice sheet (GrIS) in summer enhancing the melt increase. This circulation change is not represented by General Circulation Models (GCMs) of the 5th Coupled Model Intercomparison Project (CMIP5) which do not predict any circulation change for the next century over the North Atlantic. The goal of this study is to evaluate the impact of an atmospheric circulation change (as currently observed) on projections of the future GrIS surface mass balance (SMB). We compare GrIS SMB estimates simulated by the regional climate model MAR forced by perturbed reanalysis (ERA-Interim with a temperature correction of +1 °C, +1.5 °C and +2 °C at the MAR lateral boundaries) over 1980 – 2016 to projections of the future GrIS SMB from MAR simulations forced by three GCMs over selected periods for which a similar temperature increase of +1 °C, +1.5 °C and +2 °C is projected by the GCMs in comparison to 1980 – 1999. Mean SMB anomalies produced with perturbed reanalysis over the climatologically stable period 1980 – 1999 are similar to those produced with MAR forced by GCMs over future periods characterized by a similar warming over Greenland. However, over the two last decades (2000 – 2016) when an increase in the frequency of blocking events has been observed in summer, MAR forced by perturbed reanalysis suggests that the SMB decrease could be amplified by a factor of two if such atmospheric conditions persist compared to projections forced by GCMs for the same temperature increase but without any circulation change.

1 Introduction

Starting in the late 1990's, the surface mass balance (SMB, i.e. the difference between mass sources and sinks at the surface) of the Greenland Ice Sheet (GrIS) has been decreasing through a rise in surface meltwater runoff (Fettweis et al., 2013a; van den Broeke et al., 2016). Since the 2000's, multiple melting records have been broken over the GrIS (Tedesco et al., 2013; Hanna et al., 2014; Fettweis et al., 2017) and 70% of this melt increase can be attributed to an atmospheric circulation change gauged through a shift of the summer North Atlantic Oscillation (NAO) index to negative values (Fettweis et al., 2013b). These changes have favoured anticyclonic conditions (i.e. more frequent blocking events) in summer over Greenland which enhance the melt-albedo feedback through three main ways (Box et al., 2012): (1) an increase in advection of warm air along the western coast of the ice sheet enhancing the surface sensible heat flux, thus strengthening snow grain metamorphism and further decreasing surface albedo (Tedesco et al., 2016); (2) a decrease in snowfall rates in summer leading to longer exposure of bare ice at the GrIS margins (Noël et al., 2015) ; and (3) an increase in incoming radiation resulting in more surface heating. For this last feature, the debate about the contribution of shortwave and longwave radiations is still ongoing as the role of clouds is opposite between the ablation zone (more sensitive to shortwave anomalies) and the accumulation zone (more sensitive to longwave anomalies). Hofer et al. (2017) points out the importance of increasing incoming solar radiation while other studies allocate the increase in surface heating and melting to longwave radiation notably due to the transport of water vapor (Neff et al., 2014; Bonne et al., 2015) and liquid low-level clouds (Bennartz et al., 2013). These processes reduce meltwater refreezing and then enhance meltwater runoff (Van Tricht et al., 2016).

Such an amplification in surface melt is well represented by Regional Climate Models (RCMs) forced by climate reanalysis which capture the current circulation change (Ettema et al., 2009; Fettweis et al., 2011, 2017; Noël et al., 2015, 2018). However, as General Circulation Models (GCMs) do not presently predict any future circulation change (Belleflamme et al., 2012; Fettweis et al., 2013b; Hanna et al., in review, 2018), the melt increase currently observed is underestimated when RCMs are forced by GCM scenarios starting from 2000's (e.g., Fettweis et al., 2011, 2013b; Rae et al., 2012). This raises the question of how RCM-based projections of future GrIS SMB are affected by the GCM forcing if the recent shift to negative NAO phases in summer persists through the next decades?

To address this issue, we use the Modèle Atmosphérique Régional (MAR), especially developed for polar regions, to perform a sensitivity study based on the analysis of MAR-derived GrIS SMB anomalies resulting from various forcing experiments with ERA-Interim reanalysis and three GCMs from the CMIP5 database (The 5th phase of the Climate Model Intercomparison Project; Taylor et al., 2012).

2 Data and methodology

2.1 The regional climate model MAR

The model MAR is a RCM specifically developed for simulating polar climate specificities (e.g., Amory et al., 2015; Gallée et al., 2015; Lang et al., 2015), furthermore abundantly evaluated over the Greenland ice sheet (e.g., Fettweis et al., 2011, 2017). In this study, we use the version 3.8 of MAR, and refer to Fettweis et al. (2017) for a more detailed description of MAR. Relative to the version 3.5 used in Fettweis et al. (2017) and in addition to usual bug fixes and improved computation efficiency, the main improvement of MAR v3.8 consists of an increase of the cloud life time, partly correcting the underestimation of downward longwave radiation and the overestimation of inland precipitation described in Fettweis et al. (2017).

MAR requires prescription of atmospheric fields (temperature, specific humidity, wind speed, pressure) at its lateral boundaries as well as sea surface conditions (SSC, defined as sea ice concentration and sea surface temperature) from climate reanalysis or GCM outputs. Using ERA-Interim reanalysis (Dee et al., 2011) to force MAR, Fettweis et al. (2013a) have shown that the period 1980 – 1999 is characterized by a stable climate and general circulation over Greenland, before a circulation shift

Table 1. 20-yr periods corresponding to an increase in temperature of ∼+1 °C, ∼+1.5 °C and ∼+2 °C for the three selected GCMs (MIROC5, NorESM1 and CanESM2). The exact increase in temperature and the standard deviation for these periods compared with 1980 – 1999 are shown.

	MIROC5		NorESM1		Can ESM2	
	Temp. increase (°C)	Period	Temp. increase (°C)	Period	Temp. increase (°C)	Period
∼+0 °C	0.00±0.54	1980 – 1999	0.00±0.41	1980 – 1999	0.00±0.57	1980 – 1999
∼+1 °C	1.00±0.39	2007 – 2027	0.99±0.52	2014 – 2034	1.00±0.41	1997 – 2017
∼+1.5 °C	1.52±0.52	2019 – 2039	1.51±0.57	2023 – 2043	1.49±0.60	2006 – 2026
∼+2 °C	1.97±0.64	2029 – 2049	2.00±0.55	2033 – 2053	1.99±0.49	2016 – 2036

occurred in summer at the end of the 1990's. In this study, we thus consider the period 1980 – 1999 as a reference (Fettweis et al., 2013a), and discuss mean GrIS annual SMB anomalies with respect to this reference period.

2.2 Forcing experiments

We performed two sets of sensitivity experiments according to the large-scale forcing used, as described below.

2.2.1 ERA-Interim forcing

MAR was first forced by the ERA-Interim reanalysis every 6 hours at a spatial resolution of 25 km over 1979 – 2016. Two distinct periods are considered: the reference period 1980 – 1999, and the period 2000 – 2016 for which a different atmospheric circulation has been observed in summer on average by comparison with the reference period (Fettweis et al., 2013b, 2017; Hanna et al., in review, 2018). Then, we performed sensitivity experiments in which ERA-Interim atmospheric temperatures were increased by respectively +1 °C, +1.5 °C and +2 °C at each of the 24 vertical sigma levels of the MAR atmospheric lateral boundaries (hereafter referred to as perturbed reanalysis). The mean SMB anomalies of these sensitivity experiments are referred to as MARera+1, MARera+1.5 and MARera+2 respectively for anomalies averaged over 1980 – 1999, and MARera2k, MARera2k+1, MARera2k+1.5 and MARera2k+2 for corresponding anomalies averaged over 2000 – 2016 (Appendix A, Table A1). Note that the relative humidity at the lateral boundaries was conserved by modifying the specific humidity according to temperature changes in order to obtain precipitation fields consistent with warmer ERA-Interim atmospheric temperatures. However, SSC from ERA-Interim reanalysis remained unchanged in the sensitivity experiments.

2.2.2 GCM forcing

We performed three additional experiments in which MAR was forced over 1980 – 2060 with three GCMs from the CMIP5 database, using the Historical scenario over 1980 – 2005 and the future RCP4.5 scenario (Moss et al., 2010) over 2005 – 2060. Then, for each GCM, three 20-yr periods (different for each GCM) characterized by a climate of about ∼+1 °C, ∼+1.5 °C and ∼+2 °C warmer on average than the climate over the reference period (as represented by the GCM) of 1980 – 1999 were considered (Table 1). The differences between the GCM periods are only due to the timing required to reach each relative warming. Note that each warming was computed as the mean JJA (June-July-August) temperature anomaly compared to 1980 – 1999 over the computation domain (100°W- 0°W, 55°N-85°N) at four vertical levels in the free atmosphere (850 hPa, 700 hPa, 600 hPa and 500 hPa).

The three GCMs used are CanESM2, NorESM1 and MIROC5, identified in Fettweis et al. (2013b) as the CMIP5 GCMs best representing the general circulation at 500 hPa (influencing the precipitation amount and pattern simulated by MAR) and the JJA temperature at 700 hPa over Greenland (influencing the melt amount simulated by MAR) compared to ERA-Interim over 1980 – 1999. However, some discrepancies remain between MAR forced by these GCMs and MAR forced by ERA-Interim over 1980 – 1999. For instance, MAR underestimates runoff and overestimates snowfall when forced by NorESM1 compared to MAR forced by ERA-Interim (Fettweis et al., 2013a). This is also confirmed by a recent study comparing melt energy budgets from MAR forced by ERA-Interim, MIROC5, NorESM1 and CanESM2 (Leeson et al., 2018). This is why the SMB obtained with perturbed reanalysis cannot be directly compared to the SMB obtained with GCM forcing data because of these divergences over the reference period.

Therefore we compare anomalies of these GCM-forced projections during the 20-yr future periods of ∼+1 °C, ∼+1.5 °C and ∼+2 °C to the corresponding GCM-forced MAR climate over the reference period (1980 – 1999) and not directly to MAR forced by ERA-Interim over 1980 – 1999. As for the sensitivity experiments using the ERA-Interim reanalysis as forcing, the mean SMB anomalies associated with these GCMs experiments are respectively referred to as MARcan+x for CanESM2, MARmir+x for MIROC5 and MARnor+x for NorESM1 where x equals 1, 1.5 or 2 corresponds to a warming of respectively +1 °C, +1.5 °C and +2 °C (Appendix A, Table A2). Contrary to ERA-Interim forced experiments, no humidity correction has been applied at the MAR lateral boundaries and the SSC are directly prescribed from the RCP4.5 scenario projected by the respective GCM.

3 Results

3.1 Analysis of warming experiments without circulation change

Before assessing the impact of the current circulation change on SMB projections, we evaluate analogies between MAR forced by perturbed reanalysis and by GCM scenarios over future periods experiencing a similar warmer climate. Figure 1 shows difference in SMB anomalies between MARera+1 (resp. +2) and MARmir+1 (resp. +2, using MIROC5 as forcing) over 1980 – 1999 when the mean general circulation in summer is similar in both ERA-Interim and GCMs.

Even if the differences are mainly not statistically significant (i.e. lower than the inter-annual variability of the simulation of MAR forced by unaltered ERA-Interim over 1980 – 1999), the runoff anomalies are generally higher if MAR is forced by GCMs rather than by corresponding perturbed reanalysis. GCM-forced simulations also predict a higher precipitation increase along the south-east of the ice sheet. These weak differences are caused by the SSC which were not modified in experiments based on perturbed reanalysis while the GCM-forced simulations use future SSC. Anomalies at the ice sheet margins (Fig. 1)

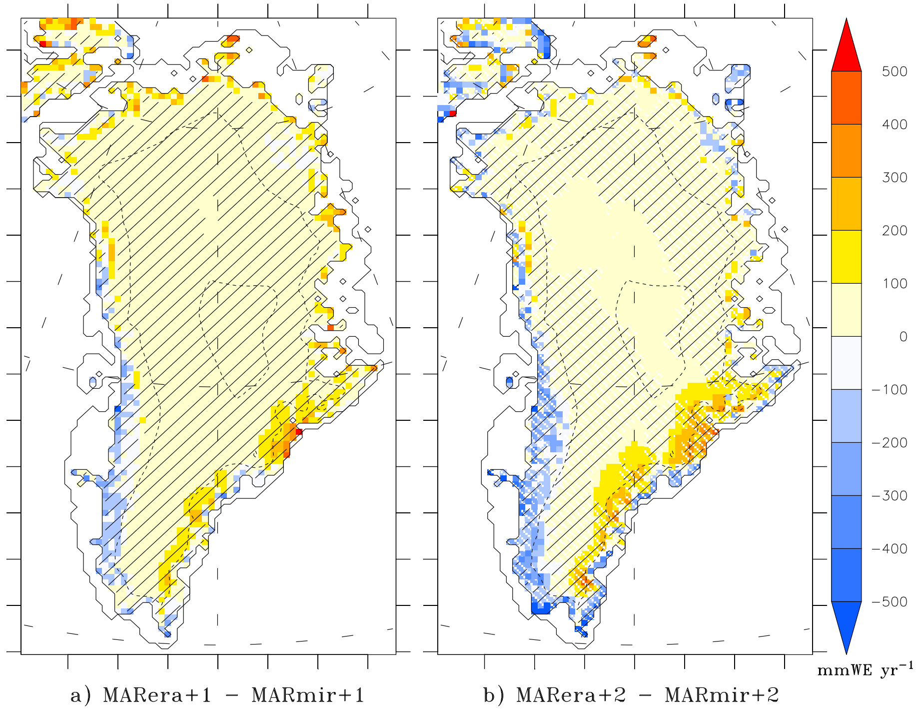

Figure 1. Differences of mean anomalies of annual SMB (in mmWE y^{-1}) between a) MARera+1 and MARmir+1 and b) MARera+2 and MARmir+2. Areas where anomaly differences are smaller than the inter-annual variability (i.e. the standard deviation) of the simulation of MAR forced by unaltered ERA-Interim over 1980 – 1999 are hatched. Dashed lines are equal altitude lines of 2000 m and 3000 m. See Appendix A Table A1 and Table A2 for abbreviations.

are similar to the SMB anomalies found by Noël et al. (2014) who evaluated the (insignificant) impacts of SSC on the SMB of the Greenland ice sheet. We therefore assume that anomalies between MARera+x and MARmir (or MARnor or MARcan) result from the SSC unchanged in MARera+x. Because GCMs fail to represent the circulation change observed in summer over Greenland since 2000's, MAR forced by perturbed reanalysis over 1980 – 1999 simulates similar SMB anomalies as MAR forced by GCMs over the corresponding future warmer periods. Therefore, evaluating MAR forced by perturbed reanalysis over 2000 – 2016 allows us to evaluate the likely impact of a warmer climate induced by an increase of blocking events (as currently observed) on the projected GrIS SMB.

3.2 Influence of a potential future circulation change

Over 2000 – 2016, the JJA temperature in the ERA-Interim reanalysis has increased by 0.7 °C in the free atmosphere (mean 850-500 hPa temperature integrated over the computation domain) compared to 1980 – 1999. This offset in temperature has thus to be taken into account when comparing the anomalies of the different warming experiments. The SMB anomaly MAR-era2k+1 (resp. MARera2k+1.5) is significantly more negative (up to a factor of two) than perturbed-reanalysis experiments

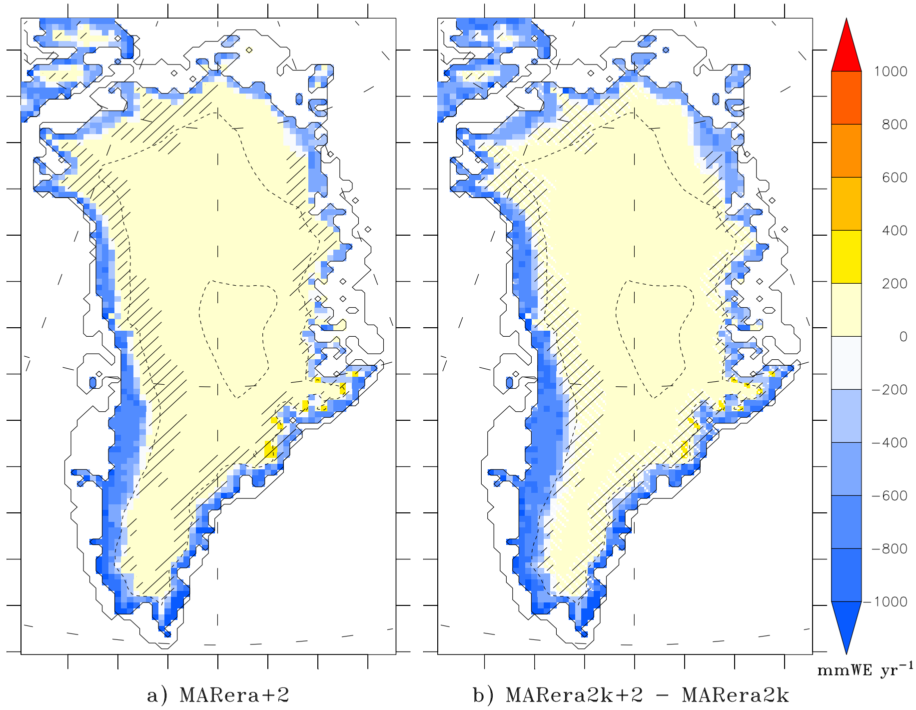

Figure 2. a) Mean anomalies of annual SMB (mmWE y^{-1}) of MAR forced by warmer ERA-Interim warmer of +2 °C compared to MAR forced by unaltered ERA-Interim over 1980 – 1999. b) Differences between mean anomalies of annual SMB (mmWE y^{-1}): MARera2k+2 - MARera2k. Areas where anomaly differences are smaller than the inter-annual variability (i.e. the standard deviation) of the simulation of MAR forced by unaltered ERA-Interim over 1980 – 1999 are hatched. Dashed lines are equal altitude lines of 2000 m and 3000 m. See Appendix A Table A1 and Table A2 for abbreviations.

and GCM-forced future experiments relative to a climate warmer by +1.5 °C (resp. +2 °C) (Table 2). This suggests that capturing the recent circulation change simulated by perturbed-reanalysis experiments would enhance the projected SMB decrease compared to the decrease projected for a warmer climate without any circulation change. This is illustrated in Figure 2 where the decrease in SMB is amplified for an equal increase in temperature of +2 °C over 2000 – 2016 (Fig. 2b), i.e. including the recent circulation change, compared to the decrease for the reference circulation over 1980 – 1999 (Fig. 2a). Additional 2D-representations of these differences for GCM experiments are available in supplementary materials.

As runoff (RU) and snowfall (SF) mainly drive the GrIS SMB (Box et al., 2004), we mainly discuss in the following the anomalies relative to these two components. As for SMB anomalies, RU and SF anomalies are computed as differences between the corresponding mean value for a given experiment and the mean value for the reference period using the unaltered large-scale forcing (Table 2). Even though non-significant, an increase in SF is observed for all experiments associated with a rise in temperature in response to a higher air capacity for holding water vapor (Fettweis et al., 2013a). Moreover, mean RU anomalies increase with the temperature rise in all warming experiments, most significantly for the experiments using perturbed reanalysis

Table 2. Mean GrIS integrated anomalies of annual SMB (Gt y^{-1}), runoff (RU), snowfall (SF) and melt (ME) compared to 1980 – 1999. Anomalies from GCM-forced simulations are given as averaged. Anomalies greater than the 1980 – 1999 standard deviation (i.e. greater than the inter-annual variability) of the simulation of MAR forced by unaltered ERA-Interim are shown in bold.

		Forcing		
	Temperature increase (°C)	ERA-Interim 1980 – 1999 (MARera)	ERA-Interim 2000 – 2016 (MARera2k)	Mean of the 3 GCMs
	+0	0	**-205**	0
Annual mean	+1	-84	**-326**	-118
SMB ($Gtyr^{-1}$)	+1.5	-146	**-408**	-164
	+2	**-206**	**-492**	**-197**
	+0	0	**-211**	0
Annual mean	+1	**142**	**393**	**141**
RU ($Gtyr^{-1}$)	+1.5	**236**	**508**	**215**
	+2	**328**	**626**	**283**
	+0	0	-8	0
Annual mean	+1	37	28	13
SF ($Gtyr^{-1}$)	+1.5	56	46	29
	+2	**75**	**63**	51
	+0	0	**195**	0
Annual mean	+1	**133**	**352**	**135**
ME ($Gtyr^{-1}$)	+1.5	**210**	**440**	**203**
	+2	**291**	**534**	**261**

over 2000 – 2016 when the circulation change has occurred. It can thus be concluded that runoff is mainly responsible for the SMB discrepancies between the different sensitivity experiments in a warmer climate. As for RU, melt (ME) anomalies are also amplified with the circulation change (Table 2). However, RU anomalies are systematically higher than ME anomalies. This can be explained by two factors (Machguth et al., 2016): (1) there is less pore place available for meltwater storage in warmer and then more saturated firn and, (2) the bare ice area (in the ablation zone) is larger in warmer climate reducing the potential surface for meltwater storage which also amplifies the meltwater runoff increase. The future decrease of the ice sheet meltwater retention capacity has notably been discussed by Van Angelen et al. (2013).

On average over the ice sheet, downward shortwave radiation (SWD) and downward longwave radiation (LWD) are respectively almost 4 Wm^{-2} and 3 Wm^{-2} higher over the 2000 – 2016 period than over the reference period (Table 3). This concords with Hofer et al. (2017)'s conclusions which argue that the current observed melt increase since the 2000's is a combination

Table 3. Mean GrIS integrated anomalies of summer energy fluxes ($W.m^{-2}$) and summer surface 2-m temperature (°C) compared to 1980 – 1999. Anomalies from GCM-forced simulations are given as averaged. Anomalies greater than the 1980 – 1999 standard deviation (i.e. greater than the inter-annual variability) of the simulation of MAR forced by unaltered ERA-Interim are shown in bold.

		Forcing		
	Temperature increase (°C)	ERA-Interim 1980 – 1999 (MARera)	ERA-Interim 2000 – 2016 (MARera2k)	Mean of the 3 GCMs
JJA mean SWD (Wm^2)	+0	0.0	**3.7**	0.0
	+1	-2.7	0.9	-0.7
	+1.5	**-4.2**	-0.6	-2.4
	+2	**-5.8**	-2.2	-3.9
JJA mean LWD (Wm^2)	+0	0.0	**3.2**	0.0
	+1	**4.8**	**8.1**	**4.5**
	+1.5	**7.2**	**10.6**	**7.3**
	+2	**9.7**	**13.2**	**9.4**
JJA mean absorbed SWD (Wm^2)	+0	0.0	**5.4**	0.0
	+1	1.9	**7.5**	2.0
	+1.5	**3.0**	**8.8**	2.8
	+2	**4.0**	**10.0**	**3.9**
JJA mean T2m (°C)	+0	0.00	**1.24**	0.00
	+1	**0.97**	**2.20**	**1.07**
	+1.5	**1.45**	**2.68**	**1.62**
	+2	**1.93**	**3.15**	**2.01**

of the increase in SWD and LWD. However both simulations forced by perturbed reanalysis as well as in GCM-forced simulations with a warmer climate suggest a strong SWD decrease as a result of an increasing cloud cover, as already discussed in Franco et al. (2013). This effect combined with a higher free atmosphere temperature explains then the increase in LWD in a warmer climate (Hofer et al., 2017).

Due to the enhanced positive melt-albedo feedback since the 2000's, SWD absorbed by the surface is more than two times higher in simulations with perturbed reanalysis over 2000 – 2016 than over the reference period. Due to a lower albedo (in particular in the ablation zone), the surface absorbs more energy, amplifying the melt increase which further decreases the albedo, potentially reaccelerating melting in addition to a decrease of the ice sheet capacity to refreeze meltwater. This positive feedback triggered by more frequent anticyclonic summer situations over Greenland causes a runoff increase nearly two times higher in simulations over 2000 – 2016 than in the simulations over the reference period.

In the absence of a circulation change, the increase in near-surface temperature (T2m) is only due to the temperature increase prescribed at the MAR lateral boundaries (Table 3). With a circulation change, the increase in T2m is higher and no more uniform as a result of enhanced warm air advection along the West GrIS (see Fig. S1 in supplementary material). Such more frequent anticyclonic conditions, resulting from more frequent blocking events (Hanna et al., in review, 2018), explain the increase in cloud cover at the north of the ice sheet and the associated LWD increase shown in Hofer et al. (2017) in this area, while sunnier conditions dominate in the southern part.

4 Conclusions

The goal of this study is to assess the impact of unresolved recent atmospheric circulation change in GCMs on RCM-based projections of future GrIS SMB. For this purpose, we used the RCM MAR and performed forcing sensitivity experiments with the ERA-Interim reanalysis and large-scale fields from 3 selected GCMs of the CMIP5 database to investigate the influence of a warmer atmosphere in the context of a circulation change inducing more frequent blocking events.

We used the annual SMB produced with each original forcing over the climatologically stable period of 1980 – 1999 as a reference, to compute mean annual SMB anomalies relative to each forcing experiment.

The first experiments consisted of increasing the atmospheric temperature in the ERA-Interim reanalysis by +1 °C, +1.5 °C and + 2 °C at the MAR lateral boundaries over two distinct periods, i.e. 1980 – 1999 and 2000 – 2016, respectively before and after the shift in the summer NAO index. Additional forcing experiments were then performed using the three selected GCMs to force MAR over the reference period and over 20-yr future periods for which a similar temperature increase of ∼+1 °C, ∼+1.5 °C and ∼+2 °C is predicted by these GCMs in the free atmosphere.

The comparison between SMB anomalies relative to perturbed reanalysis and GCM future experiments revealed similar results for each corresponding warming experiment, since for each GCM the atmospheric circulation remains unchanged over time. This allowed us to evaluate the likely impact of a warmer climate induced by a circulation change on the GrIS SMB by comparing SMB anomalies relative to perturbed reanalysis over 2000 – 2016 with GCM-forced future SMB anomalies. This comparison suggests that capturing the circulation change leads to SMB anomalies two times higher on average with a circulation change than without for a similar atmospheric warming. These higher anomalies are explained by more frequent summer anticyclonic situations over GrIS leading to an increase in SWD and warm air advection along the west coast, both promoting a decrease in albedo. As a result, the runoff increase is enhanced and is responsible for the higher decrease in SMB.

The results of this study suggest that previous estimates of GrIS melt projections produced using CMIP5 data as forcing (e.g., Rae et al., 2012; Fettweis et al., 2013a) could be significantly underestimated if the current summer atmospheric circulation pattern over Greenland persists. In the context of the forthcoming 6th phase of the Coupled Model Intercomparison Project, our conclusions highlight the importance of examining whether GCMs predict circulation changes in the next decades and, if so, of evaluating their potential influence on projections of the future GrIS SMB. Another remaining scientific challenge of particular interest for GrIS SMB projections is to establish if the increasing frequency of blocking events could be linked to global climate change.

Appendix A: Description of the abbreviations used in this study

Table A1. Abbreviation description of reanalysis sensitivity experiments

MARera+1	Anomalies between MAR forced by the ERA-Interim reanalysis warmer of +1 °C over 1980 – 1999 and MAR forced by the unaltered ERA-Interim reanalysis over 1980 – 1999
MARera+1.5	Anomalies between MAR forced by the ERA-Interim reanalysis warmer of +1.5 °C over 1980 – 1999 and MAR forced by the unaltered ERA-Interim reanalysis over 1980 – 1999
MARera+2	Anomalies between MAR forced by the ERA-Interim reanalysis warmer of +2 °C over 1980 – 1999 and MAR forced by the unaltered ERA-Interim reanalysis over 1980 – 1999
MARera2k	Anomalies between MAR forced by the ERA-Interim over 2000 – 2016 and MAR forced by the unaltered ERA-Interim reanalysis over 1980 – 1999
MARera2k+1	Anomalies between MAR forced by the ERA-Interim reanalysis warmer of +1 °C over 2000 – 2016 and MAR forced by the unaltered ERA-Interim reanalysis over 1980 – 1999
MARera2k+1.5	Anomalies between MAR forced by the ERA-Interim reanalysis warmer of +1.5 °C over 2000 – 2016 and MAR forced by the unaltered ERA-Interim reanalysis over 1980 – 1999
MARera2k+2	Anomalies between MAR forced by the ERA-Interim reanalysis warmer of +2 °C over 2000 – 2016 and MAR forced by the unaltered ERA-Interim reanalysis over 1980 – 1999

Table A2. Abbreviation description of GCM sensitivity experiments

MARmir+1	Anomalies between MAR forced by MIROC5 over a warmer 20-yr period of +1 °C relatively to the reference period 1980 – 1999 and MAR forced by MIROC5 over the reference period
MARmir+1.5	Anomalies between MAR forced by MIROC5 over a warmer 20-yr period of +1.5 °C relatively to the reference period 1980 – 1999 and MAR forced by MIROC5 over the reference period
MARmir+2	Anomalies between MAR forced by MIROC5 over a warmer 20-yr period of +2 °C relatively to the reference period 1980 – 1999 and MAR forced by MIROC5 over the reference period
MARnor+1	Anomalies between MAR forced by NorESM1 over a warmer 20-yr period of +1 °C relatively to the reference period 1980 – 1999 and MAR forced by MIROC5 over the reference period
MARnor+1.5	Anomalies between MAR forced by NorESM1 over a warmer 20-yr period of +1.5 °C relatively to the reference period 1980 – 1999 and MAR forced by MIROC5 over the reference period
MARnor+2	Anomalies between MAR forced by NorESM1 over a warmer 20-yr period of +2 °C relatively to the reference period 1980 – 1999 and MAR forced by MIROC5 over the reference period
MARcan+1	Anomalies between MAR forced by CanESM2 over a warmer 20-yr period of +1 °C relatively to the reference period 1980 – 1999 and MAR forced by MIROC5 over the reference period
MARcan+1.5	Anomalies between MAR forced by CanESM2 over a warmer 20-yr period of +1.5 °C relatively to the reference period 1980 – 1999 and MAR forced by MIROC5 over the reference period
MARcan+2	Anomalies between MAR forced by CanESM2 over a warmer 20-yr period of +2 °C relatively to the reference period 1980 – 1999 and MAR forced by MIROC5 over the reference period

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

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