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

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

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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 regionsand 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 ∼+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~~0.00±0.54	1980 – 1999	~~0~~0.00±0.41	1980 – 1999	~~0~~0.00±0.57	1980 – 1999
∼+1 °C	~~1~~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

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 ∼+1 °C, ∼+1.5 °C and ∼+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 ∼+1 °C, ∼+1.5 °C and ∼+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.

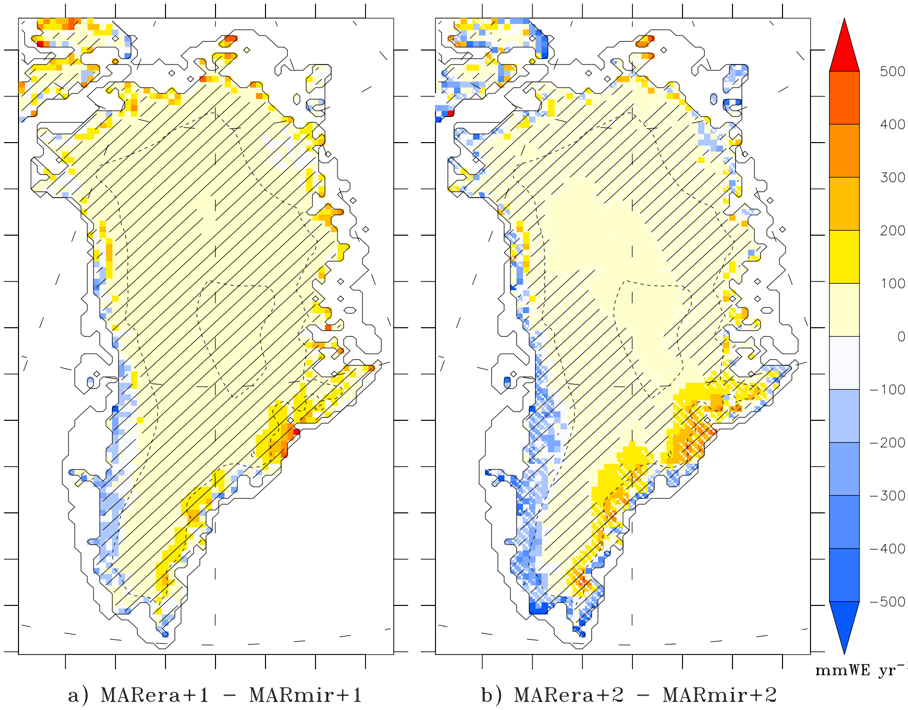

Figure 1. Differences of mean anomalies of annual SMB (in mmWE y^{-1}) between a) MARera+1 and MARmir+1 and b) MARera+2 and MARmir+2. Areas where anomaly differences are smaller than the inter-annual variability (i.e. the standard deviation) of the simulation of MAR forced by unaltered ERA-Interim over 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

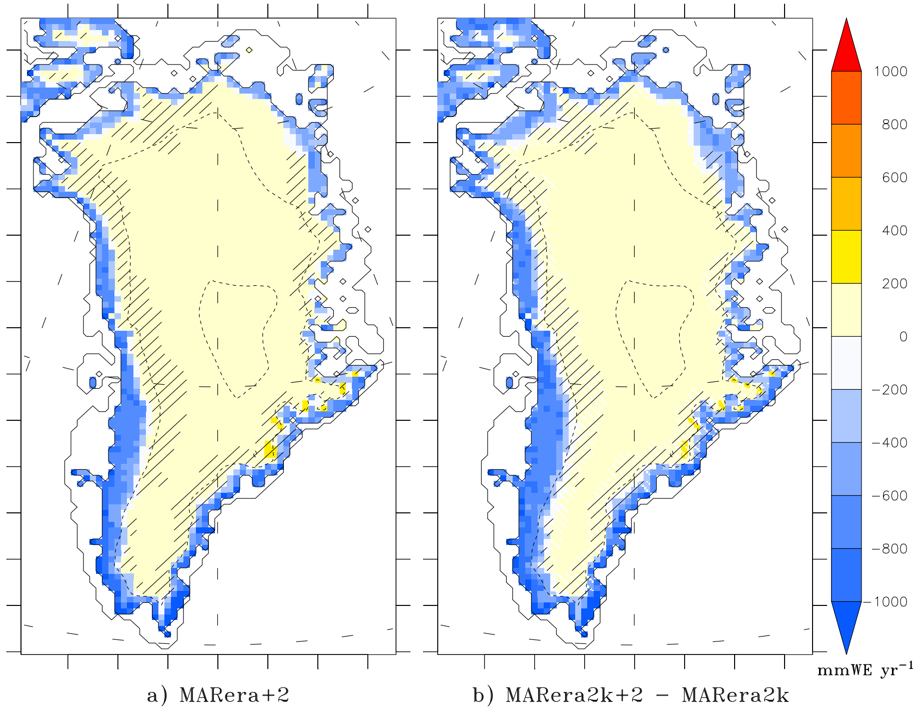

Figure 2. a) Mean anomalies of annual SMB (mmWE y^{-1}) of MAR forced ~~with~~ by warmer ERA-Interim warmer of +2 °C compared to MAR forced ~~with~~ by unaltered ERA-Interim over 1980 – 1999. b) Differences between mean anomalies of annual SMB (mmWE y^{-1}): MARera2k+2 - MARera2k. Areas where anomaly 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 m~~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 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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