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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

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Abstract. Since the 2000's, a change in the atmospheric circulation over North Atlantic 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 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 projections of the GrIS surface mass balance (SMB). We compare GrIS SMB estimates from the regional climate model MAR forced by warmer 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 GrIS SMB from MAR simulations forced with three GCMs over a future period 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 reanalysis over the climatologically stable period 1980 – 1999 is similar to those produced with MAR forced with GCMs over future periods characterized by a similar warming over Greenland. However, over the two last decades (2000 – 2016) when a circulation change has been observed in summer, MAR forced with warmer 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, melting records have been observed over the GrIS (Tedesco et al., 2013; Hanna et al., 2014; Fettweis et al., 2017) and 70% of this melt increase have been 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 in summer over Greenland which heigthen 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 (Tedesco et al., 2016); (2) an increase in incoming solar radiations resulting in more surface heating (Hofer et al., 2017); and (3) a decrease in snowfall rates in summer (Noël et al., 2015).

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 future 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). This rises the question of how future projections of the GrIS SMB could be 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 the next decades?

To address this issue, we have used the regional atmospheric climate model MAR (Modèle Atmosphérique Régional) especially developed for polar regions and performed 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 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 an increase of the cloud life time, partly correcting the underestimation of downward longwave radiations and the overestimation of inland precipitations found in Fettweis et al. (2017).

2.2 Forcing experiments

MAR requires prescription of atmospheric fields (temperature, relative 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 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 over Greenland, before a circulation shift occurred 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 to this reference period. We performed two sets of sensitivity experiments according to the large-scale forcing used, as described below.

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

2.2.1 Forcing with the ERA-Interim reanalysis

MAR was first forced with 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). 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). 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 anomalies averaged over 2000 – 2016 (Appendix A, Table A1). Note that 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.

2.2.2 Forcing with CMIP5 GCMs

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 and the future RCP4.5 scenario (Moss et al., 2010) over 2006 – 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 (as represented by the GCM) of 1980 – 1999 were considered (Table 1). 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) 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) temperature at 700 hPa over Greenland 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, the SMB obtained with warmer 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 anomalies of these GCMs-forced future projections during the 20-yr 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 for the sensitivity experiments using the ERA-Interim reanalysis as forcing, the mean SMB anomalies relative to 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 respectively +1 °C, +1.5 °C and +2 °C (Appendix A, Table A2). The main difference with the ERA-Interim forced experiments is that no correction has been applied at the MAR lateral boundaries and the SSC used are those 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 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 climate needs to be evaluated. In Figure 1, we compare two different anomalies (here using MIROC5 as forcing):

- SMB anomaly MARera+1 (resp. +2);
- SMB anomaly MARmir+1 (resp. +2)

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 reanalysis. GCM-forced simulations also predict a higher precipitation increase along the south-east of the ice sheet. 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. While GCMs fail to represent the circulation change observed in summer over Greenland since 2000's, MAR forced by warmer reanalysis over 1980 – 1999 simulates similar SMB anomalies than MAR forced by GCMs over the corresponding warmer future periods. Therefore, evaluating MAR forced by warmer reanalysis over 2000 – 2016 allows us to evaluate the likely impact of a warmer climate induced by a circulation change on the GrIS SMB.

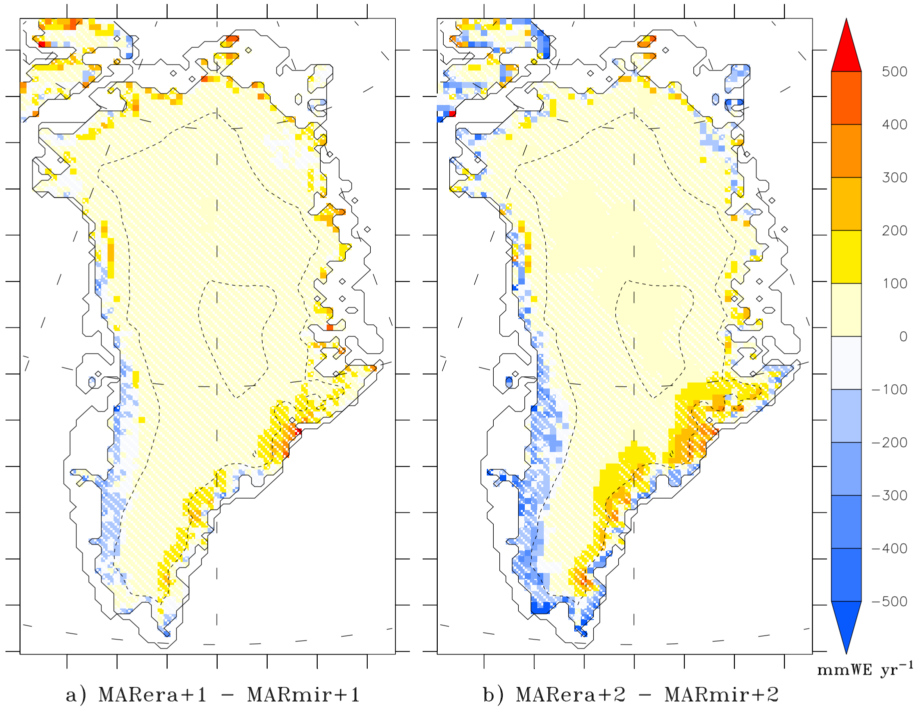

Figure 1. Differences of mean anomalies of annual SMB (in mmWE y^{-1}) between a) MARera+1 and MARmir+1 and b) MARera+2 and MARmir+2. Areas where anomaly differences are smaller than the inter-annual variability (i.e. the standard deviation) of the simulation of MAR forced by unaltered ERA-Interim over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

3.2 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 anomaly MARera2k+1 (resp. MARera2k+1.5) is significantly more negative than warmer reanalysis and GCM-forced future experiments relative to a climate warmer by +1.5 °C (resp. +2 °C) (Table 2). This means that the recent circulation change associated with warmer reanalysis enhances the decrease in SMB 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) 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 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

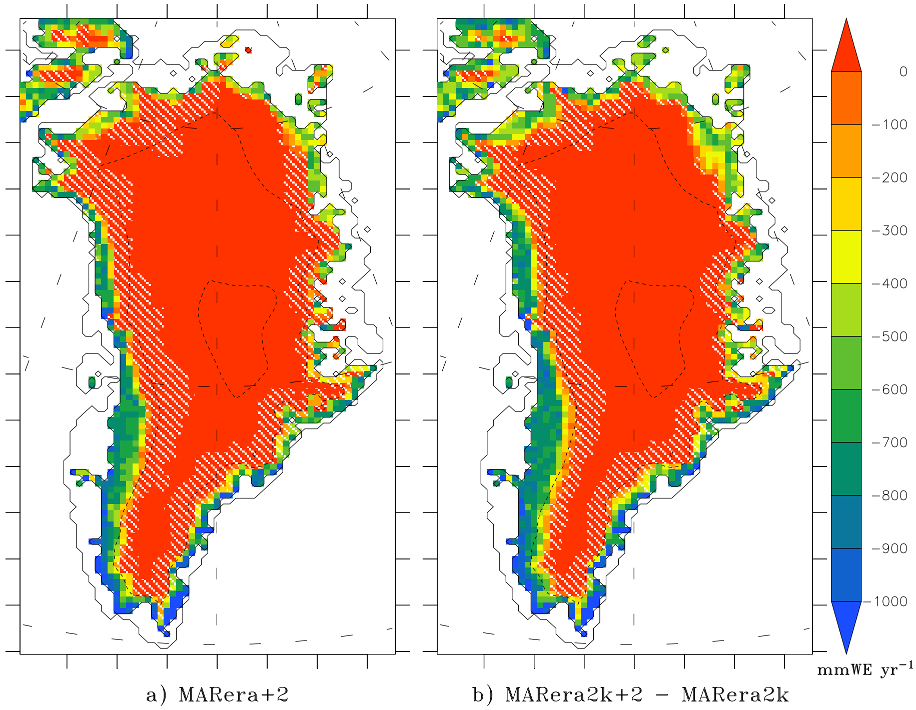

Figure 2. a) Mean anomalies of annual SMB (mmWE y^{-1}) of MAR forced with warmer ERA-Interim warmer of +2 °C compared to MAR forced with unaltered ERA-Interim over 1980 – 1999. b) Differences between mean anomalies of annual SMB (mmWE y^{-1}): MARera2k+2 - MARera2k. Areas where anomaly differences are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

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.

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 3 W m^{-2} higher over the 2000 – 2016 period than over the reference period (Table 2). 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). This effect combined with a higher free atmosphere temperature explains then the increase in downward longwave radiation (LWD) in a warmer climate (Hofer et al., 2017).

The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-65
Manuscript under review for journal The Cryosphere
Discussion started: 17 April 2018

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 melt which further decreases the albedo, potentially reaccelerating melting. 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.

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 2). With a circulation change, the increase in T2m is higher and no more uniform as a result of enhanced warm air advection along West GrIS (see Fig. S1 in supplementary material). Such more frequent anticyclonic conditions 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 atmospheric circulation change observed in summer over Greenland since the 2000's on 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.

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 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 of ∼+1 °C, ∼+1.5 °C and ∼+2 °C is predicted by these GCMs.

The comparison between SMB anomalies relative to warmer reanalysis and GCM future experiments revealed that the results are similar 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 reanalysis over 2000 – 2016 with GCM-forced future SMB anomalies. This comparison suggests that SMB anomalies are, this time, 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 west coast, both promoting a decrease in albedo. As a result, the melt increase is enhanced and is responsible for the higher decrease in SMB.

The results of this study suggests that previous estimates of future GrIS SMB projections produced using CMIP5 data as forcing (e.g., Rae et al., 2012; Fettweis et al., 2013a) could be significantly overestimated 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 GCMs predict circulation changes in the next decades and, if so, of evaluating their potential influence on future projections of the GrIS SMB.

The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-65
Manuscript under review for journal The Cryosphere
Discussion started: 17 April 2018

Table 2. Mean GrIS integrated anomalies of annual SMB (Gt y^{-1}), runoff (RU), snowfall (SF), 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.

Anomaly	Temp. increase (°C)	Forcing: ERA-Interim 1980 – 1999	Forcing: ERA-Interim 2000 – 2016	Forcing: Mean of the 3 GCMs
Annual mean SMB (Gt yr^{-1})	+0	0	**-205**	0
	+1	-84	**-326**	-118
	+1,5	-146	**-408**	-164
	+2	**-206**	**-492**	**-197**
Annual mean RU (Gt yr^{-1})	+0	0	**-211**	0
	+1	**142**	**393**	**141**
	+1,5	**236**	**508**	**215**
	+2	**328**	**626**	**283**
Annual mean SF (Gt yr^{-1})	+0	0	-8	0
	+1	37	28	13
	+1,5	56	46	29
	+2	**75**	**63**	51
JJA mean SWD (W m^2)	+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 (W m^2)	+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 (W m^2)	+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	0,0	**1,24**	0,0
	+1	**0,97**	**2,20**	**1,07**
	+1,5	**1,45**	**2,68**	**1,62**
	+2	**1,93**	**3,15**	**2,01**

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

The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-65
Manuscript under review for journal The Cryosphere
Discussion started: 17 April 2018

Table A2. Abbreviation description of GCM sensitivity experiments

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

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

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The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-65
Manuscript under review for journal The Cryosphere
Discussion started: 17 April 2018

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