cp-2018-12 (author) - final response

Dear Editor,

I would like thanks referees for theirs judicious review which improved significantly the manuscript. I would like to assure you that almost/all of their requests were integrated in the manuscript.

The Title of our paper has modified to “**Link between the North Atlantic Oscillation and the Surface Mass Balance components of the Greenland Ice Sheet under preindustrial and last interglacial climates: a study with a Coupled Global Circulation Model**”. Accordingly, the content of our paper now focuses on the components of the Surface Mass Balance.

Please find in this document the first version of the manuscript.

Yours sincerely,

Silvana Ramos Buarque, Ph.D.
David Salas y Melia, Ph. D.

cp-2018-12 - Author's response

Anonymous Referee #1

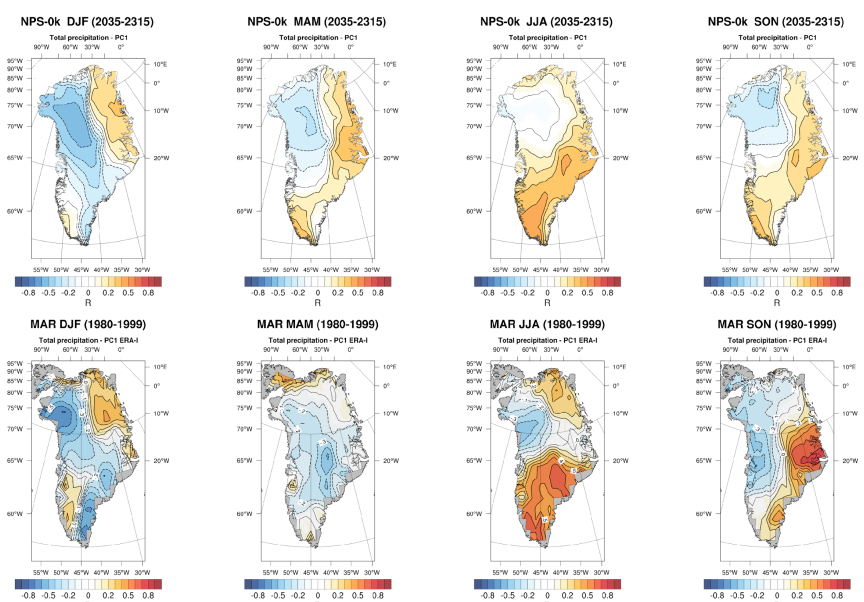
Received and published: 2 May 2018

This paper shows that the link between NAO and SMB over Greenland has been changed through the centuries by using the CNRM-CM5.2 global model. *The paper is interesting to read and deserves to be published in CP*. However, some (major) improvements are still needed before publication.

Major:

1. In Fettweis (2007), seasonal 2D correlations with NAO was shown (see Fig 15 and Fig16). Such similar figures should be shown with the MAR data used here and the CNRM based present climate reconstruction to check if CNRM is able to simulate the current pattern of NAO impacts on SMB. The validation by using the R value (correlation) shown in Fig 5 and Fig 6 is not enough for me. A 2D validation is needed here as the paper discusses 2D changes in the correlation with NAO.

In the new version of the paper, Fig 5 and Fig 6 have been removed. We agree that the added-value of these plots was low and decided to provide the correlation coefficients only in the text of the paper. Instead, we have inserted figures showing the seasonal spatial correlation of accumulation, ablation and surface mass balance with the NAO index. By contrast with the paper by Fettweis (2007), we chose not to display correlations for the intermediate seasons (MAM and SON), in order to focus on DJF and JJA, like in the rest of the paper. In this answer, you will find hereafter (FYI) the correlation between precipitation and the NAO index for all seasons.



2. The ERA forced 1979-2012 period is used here as validation for pre-industrial climate but since the end of the 1990's, we have observed a switch of NAO toward negative value in summer as remembered in this manuscript. This issue should be discussed or the period 1980-1999 should be used as validation. This reference period 1980-1999 was selected in Fettweis et al (2013b) for this reason because surface melt GrIS records were observed over the 2007-2012 period (included in the reference period used here) which is not representative of the present or pre-industrial climate.

In the new version of the paper, we now systematically use the 1980-1999 time-span for validation, instead of 1979-2012 previously, to be more consistent with preindustrial conditions. Among other results, this change in validation period affects the correlation we provide between SMB and NAO indices for MAR.

Minor:

1. Fig1: What is the interest of showing the whole globe while only the North Atlantic area is discussed here ? A zoom over the area of interest will be more useful.

We wanted to show the whole globe for a general, view of model biases. Following the reviewer's recommendation, we changed the domain of Fig. 1 to represent only the Arctic and the North Atlantic. However, since our model is a global one, we chose not to restrict the figure to Greenland, in order to place the biases over the GrIS in a wider, still not global context.

2. Fig2: as only positive values are shown, the legend could be adapted.

We adapted the legend to follow this recommendation.

3. As said earlier, what is the interest of showing Fig 5, fig 6 and Fig 11. Only the statistics listed here are useful for me and can be put in a table.

We agree with these comments, and removed Fig. 5, 6 and 11. The table hereafter shows correlations between the NAO index and the GrIS-averaged accumulation, melting and SMB for MAR and NPS under all climates. However, we have chosen not to integrate it into the paper since we now focus more on the 2D-correlations.

	Accumulation		Melting		SMB	
	DJF	JJA	DJF	JJA	DJF	JJA
MAR	**-0.21**	**0.54**	**-**	**0.37**	**-0.21**	**0.40**
NPS-0k	-0.22	0.48	-	0.51	-0.22	0.62
NPS-115k	-0.11	0.43	-	0.56	-0.11	0.62
NPS-130k	-0.04	0.48	-	0.43	-0.04	0.56

Seasonal (DJF and JJA) correlations between accumulation, melting and SMB averaged on GrIS and the NAO index.

Are there any trends in the CNRM based time series?

The trends are very small in the time series provided by CNRM-CM. However, we removed the trend for plotting the time series and computing the correlations, just as we did for MAR due to the large SMB trend over 1979-2012.

Over 1979-2012, the MAR based SMB should significantly decrease as well as the JJA NAO index.

The MAR based SMB and NAO time series were detrended, in order to correlate just interannual variations, not the trends over 1979-2012.

4. Why Fig 12 and Fig 13 are black and white and not in colour?

New figures were plotted with color shading.

Why only the correlation with accumulation is show over summer in Fig 12?

We added the correlation of winter accumulation with NAO+ and NAO- (new Fig 11). Note that for DJF, significant parts of the GrIS show negative correlations (unlike for JJA). Hence we adapted the range of plotted values accordingly for Figs. 11, 12 and 13. We adapted the text accordingly (see Sec. 4.2 and 4.3)

Over these figures, it is difficult to distinguish which is significant or not.

The dashed areas corresponding to significant correlations are now easier to see thanks to the colored background.

5. Section 4.3 : Fig 11 and Fig 12 are referenced in the text instead of Fig 12 and Fig 13 (ex: line 284).

Thanks for this comment, done.

cp-2018-12 - Author's response

Anonymous **Referee #2**

Received and published: 8 May 2018

The manuscript studies the connection between the NAO index and SMB of the Greenland ice sheet using a set of experiments with an AOGCM for different orbital configurations. The model uses a configuration of increased spatial resolution over the region of interest, which improves the representation of some atmospheric circulation features compared to the standard CMIP5 configuration. Correlation analysis reveals spatial and temporal patterns of correlation between the NAO and SMB. Despite improved resolution, the representation of surface melt is poorly represented in the model. With this, I feel there is limited confidence that the model is the right tool to study the NAO-*SMB* relationship.

We decided to focus the paper on the relationship between NAO and the components of the GrIS SMB, rather than on the relationship between NAO and SMB itself. The title of the paper was changed accordingly to "**Link between the North Atlantic Oscillation and the Surface Mass Balance components of the Greenland Ice Sheet under preindustrial and last interglacial climates: a study with a Coupled Global Circulation Model**"

I have made two suggestions in the general comments below how I see the study may be modified to circumvent this problem, both requiring a substantial reworking of the material, i.e. major revisions.

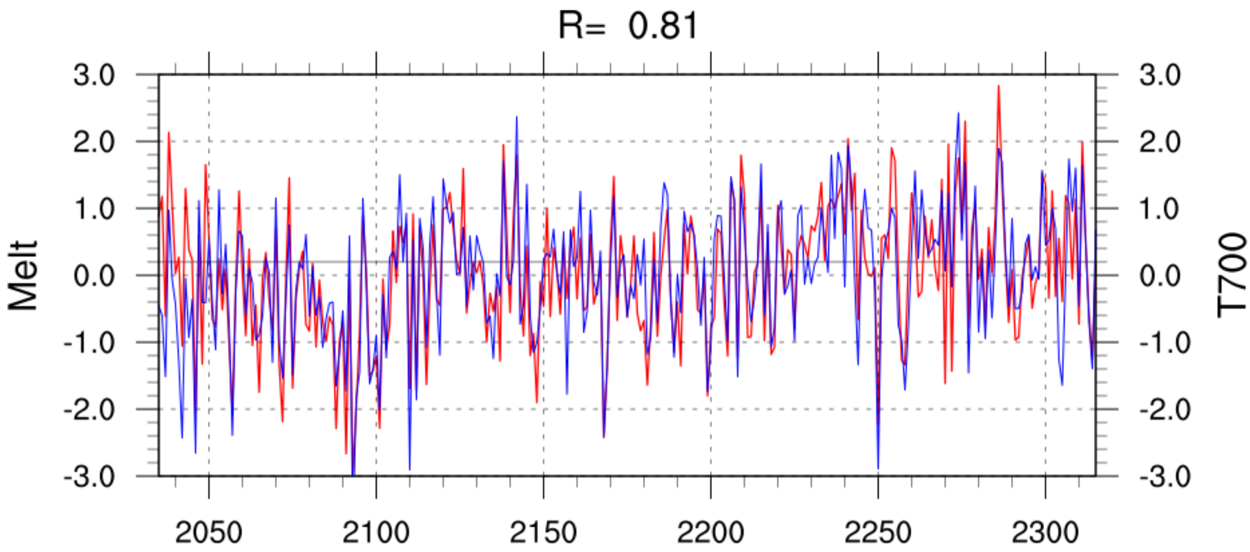
— General comments —

The model does not perform well in simulating surface melt and runoff, which is an important component to the surface mass balance at present, it will become more important in the future and likely was important during the Eemian warm period. This implies an important caveat for interpreting links between the NAO and SMB as put forward in the manuscript. As it stands now, the shortcomings of the model in terms of melting are also not well presented, with contradicting statements (see specific comments below). I was wondering if the authors could focus on precipitation changes (instead of SMB) and their relation to the NAO as a more robust feature of the model.

Thanks for this suggestion. Rather than focusing on precipitation changes, we focus on accumulation changes and their relation to the NAO, for a more direct link with SMB (except for Fig. 2)

Another possibility may be to look at a precursor of melt, like the 700 hPa temperature, which appears to be a good predictor for surface melt according to Fettweis et al. (2013a).

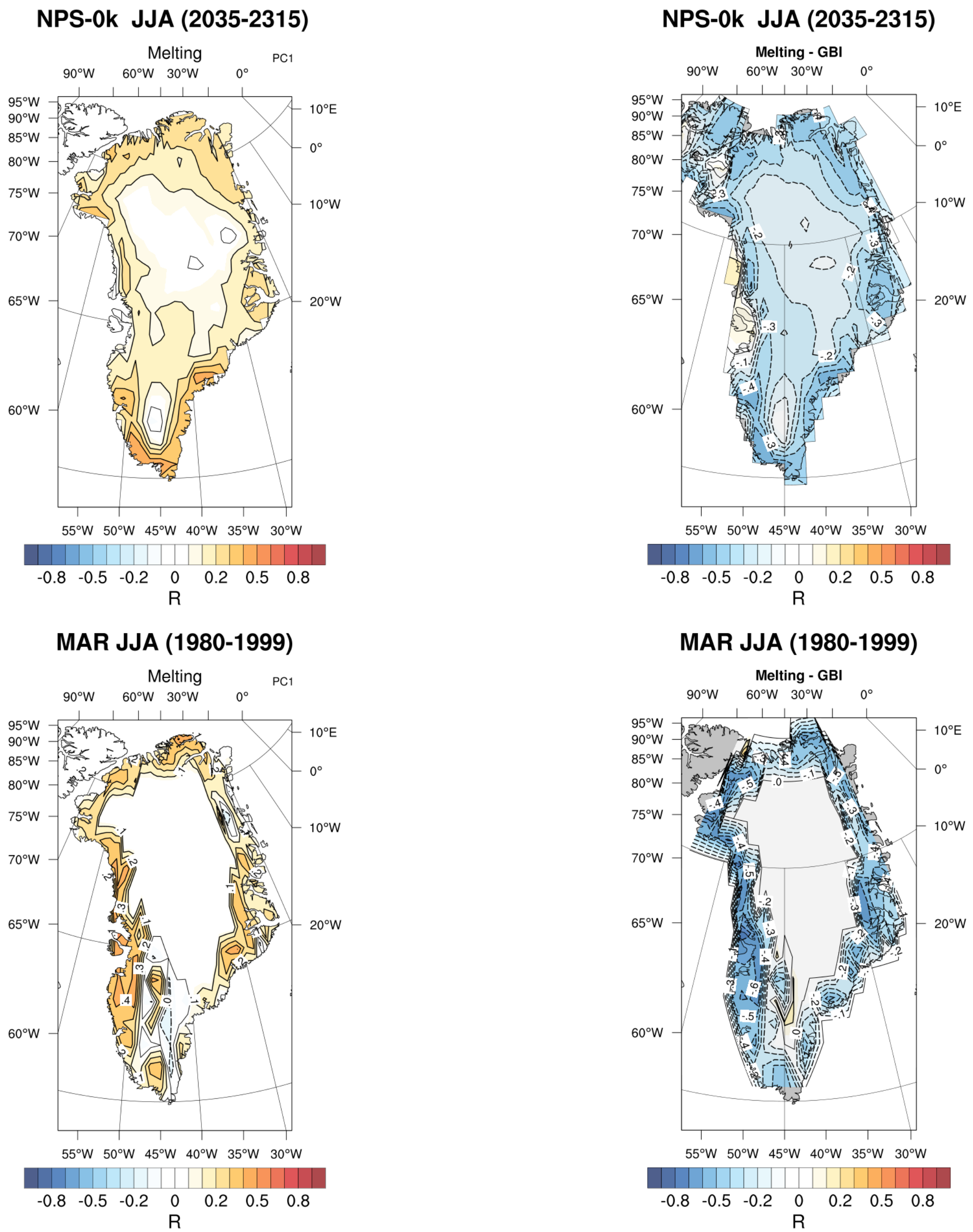
We computed the correlation of melt with the 700 hPa temperature on the same domain as Fettweis et al (2013a). Compared with the correlation (0.93) reported by Fettweis et al. (2013a), we found a slightly lower correlation (0.81) with CNRM-CM5.2 over 2035-2315 (see time-series hereafter). Based on this result, even if our simulated melt is clearly underestimated, this gives confidence in assessing the relation of melt with NAO, which we do in the revised version of the paper.



While it is recognised in the manuscript that earlier research has shown that "changes in atmospheric circulation" are responsible for a large part of the summer warming in Greenland (citing Fettweis et al., 2013), an important distinction put forward by Hanna et al. (2013) is not further discussed: they find that "Greenland coastal summer temperatures and Greenland Ice Sheet (GrIS) runoff since the 1970s are more strongly correlated with the Greenland Blocking Index (GBI) than with the NAO Index". In the context of the present paper concerned exactly with the relation between atmospheric circulation and GrIS SMB, it seems in place to also discuss the Greenland Blocking Index. Possibly the model in this study does not represent the GBI nor the relation to Greenland SMB very well. In that case, this should be clearly presented and discussed as another limitation of the model.

Indeed, the relation between atmospheric circulation indices with parameters playing a role in the SMB has been recently examined by Auger et al. (2017), who analyzed the influence of the NAO, the AMO, Icelandic Low, Azores High, regional blocking patterns, near-surface temperature and near-surface winds on precipitation in southwest Greenland. They found in particular that statistically significant correlations are higher between precipitation and near-surface winds (0.7) than correlations between precipitation and the NAO index (0.28). More over, the relationship between GBI and other climatic indices has been examined for the period 1852–2014 by Hanna et al. (2016) who found negative and significant GBI–NAO correlations in winter.

Figures hereafter show 2D correlations between melting and the NAO (left) as GBI (right) for NPS-0k (top) and MAR (bottom). The grid-point correlation map between melting / GBI is indeed very close to that of melting / NAO, however with opposite sign. That is why we have chosen not to extend the paper with discussing other atmospheric indicators.


NPS-0k JJA (2035-2315)
Melting
PC1
NPS-0k JJA (2035-2315)
Melting - GBI
MAR JJA (1980-1999)
Melting
PC1
MAR JJA (1980-1999)
Melting - GBI
90°W 60°W 30°W 0°
95°W 90°W 85°W 80°W 75°W 70°W 65°W 60°W
10°E 0° 10°W 20°W
55°W 50°W 45°W 40°W 35°W 30°W
-0.8 -0.5 -0.2 0 0.2 0.5 0.8
R

The correlation analysis is an important element of the manuscript and reveals important spatio temporal differences in the relationship between NOA and the Greenland SMB (or at least precipitation, see above). What I miss in the paper is a step beyond the correlation analysis to help the reader understand what this work really implies. Should we expect a stronger influence of the NAO on Greenland in the future or during the Eemian? What would that imply for a possible distribution of melt and precipitation changes? Does the seasonal difference in the relationship play an important role now and how will that change in the future?

We choose not to speculate on future climate, the best way would be to run adhoc simulations.

Indeed, the aim of this study is to identify the link of NAO phases with SMB and its components in a context of natural variability, e.g. to assess if the link under current climate is robust in past climates or not. Among the implications of our work, despite the underestimated melting, the northeastern part of the GrIS seems to be vulnerable to warming at 130 ka.

In the introduction, the study is fully motivated with a perspective on the future. Given the different forcing mechanism between the Eemian and the future (orbital vs. GHG), one could question if the chosen experiments (130 and 115 kyr BP orbital configuration) are really a good choice to learn something about future changes. In my opinion, the future perspective could be a much less important element in this paper and more focus be placed on understanding the Eemian climate itself. While the idea to learn something about the future by looking at the past is one of the well established and accepted motivations in paleo research, the opposite perspective can also be rewarding and should probably be added for a more balanced view. The fate of the GrIS during the Eemian e.g. remains a scientific problem of high relevance, which could be mentioned and discussed.

We agree with you. Indeed, the aim of this study is to show the link of both NAO phases with mean state of accumulation, melting and SMB on interglacial and preindustrial climates. These results about past climates could serve to interpret results for future climate, but this beyond the scope of our paper.

— Specific comments —

L22: Distinguish between Fettweis et al., 2013a and 2013b in the manuscript.

Modified.

L42: Could you please clarify the term "surface temperature feedback". Often a feedback is named mentioning two components that have mutual dependencies like SMB-surface elevation feedback or surface temperature - albedo feedback.

Done. We concisely explained this feedback and added a reference.

L61: "Better the link between NAO *variations* and …"

Modified

L62: The terminology "warm and cool phase of the Eemian" may not be correct. I would refer to the studied time slices as "the warm climate of the Eemian" and "the cold climate of the penultimate glacial inception" or similar.

Mysak (2008) defines a glacial inception as 'the transition from an interglacial to a glacial period. (…) the last glacial inception (LGI) at around 116 kyr BP'. Other studies, like Roche et al. (2010), define the last glacial inception as a period spanning 128-115 ka. To dismiss this ambiguity, we now refer to 115 ka as the 'late Eemian' (the definition of the end of the Eemian itself varies from 116 to 114 ka), or the cool phase of the Eemian.

L67: The MAR model could be introduced much earlier, e.g. when discussing results of Fettweis et 2013 (L35).

The statement from this paper, that we cited is the following 'analogous atmospheric circulations in the past shows that ~ 70 % of the 1993–2012 warming at 700 hPa over Greenland has been driven by changes in the atmospheric flow frequencies.' This statement appears only in the abstract and is not related to MAR, only to reanalyses. More over, we use this result in the introduction of the paper, and, even if it was derived from a MAR simulation, we think it is too early to describe the model there.

L78-81: This is a confusing description. As long as there is no coupling to an ice sheet model, it is standard for an AOGCM to operate with a fixed surface topography over land. As far as I can see it, this has nothing to do with technical requirements of the snow pack model as described here. It would be interesting to describe instead if and how the snow-pack model differs from other GCMs and from the MAR model, which I suspect has a full physical solution to the problems you are describing.

The snow model used in MAR is much more sophisticated than ours, but MAR has the same issue due to the lack of ice-sheet dynamics. We don't provide a compared description of both snowpack models since this would not help interpreting our results.

In the ablation zone of the GrIS (where the annual SMB is negative), all the snow that falls during the cold season melts during summer, and some of the underlying ice also melts, which is compensated by approximately the same amount of advected ice (if the ice sheet is in quasi-equilibrium). To represent the negative SMB in MAR, a reservoir of ice (20 m thick) has been introduced in the model in the ablation zone (Lefebre et al, 2005), and this ice partly melts during the simulation. In CNRM-CM5, we use a similar approach, except that our reservoir consists of snow rather than ice (same latent heat of fusion as snow per kg, and only the changes in the mass of snow matter, not the snow depth). Since we run very long simulations with CNRM-CM5, our snow reservoir needs to be “huge”, to make sure that is not entirely depleted even after 1000 years of simulation. Our method also ensures that the amount of water (liquid + frozen) in our climate model system is conserved.

L81-83: Since there is no ice-dynamical process in this model at all, it seems strange to evoke the idea of a calving flux.

It's actually a pseudo-calving flux, it corresponds to the calving flux from the GrIS that would be simulated if the dynamics of the ice-sheet were represented.

I think it would be far simpler to say that all precipitation over ice-covered land is equally distributed over the ocean north of 60N, while the snow pack evolution is calculated diagnostically, without contribution to the mass budget. It should be clarified that the instantaneous relocation of this mass (freshwater?) as an additional forcing does not have any influence on the ocean response.

The correction is applied on the snow reservoir, not precipitation, and the description of that process has to be consistent with what is really done in the paper. Hence the statement in the paper is maintained “To avoid unrealistic snow accumulation on the GrIS and an associated decrease in the modelled sea level, a pseudo-calving flux is computed at every time step from the spatially integrated snow reservoir excess over the GrIS and is distributed over the ocean north of 60°N.”

L86: A resolution of 40-50 km is still relatively low compared to the resolution of state-of-the-art regional climate models (MAR at 15km, RACMO at 11km). This should mentioned here.

We choose not be mention this here, but later in the paper (lines 186-188), where we suggest that the still relatively coarse resolution of the model may hamper the simulation of the spatial variability of surface melting, which meets your point.

L120: If model bias and climate change signal are combined, how do we tell them apart? Is there maybe another experiment that could separate these two factors?

In the case of global forced atmospheric simulations (with SST), it is, to some extent, possible to disentangle model biases from climate change signals. However, even in this idealized context, the phases of the large variability structures (NAO, PDO, etc.) can differ from observations (this would be the case even if the global model was 'perfect'). This aspect impacts estimates of climate change signals. In the case of a free global coupled ocean-atmosphere model like CNRM-CM5-2, it is even more difficult to separate model biases from climate change signals, since the ocean can produce very low frequency variability (centennial), of the order of the climate change signal itself. In observations, it is however possible, especially in high-variability areas to disentangle long term climate change from e.g. multi-decadal variability (detection).

L124: Is this discussion really important for the GrIS? Consider discussing the biases for Greenland in more detail instead.

Figure 1 has been redone with a focus on the Arctic. The analysis of biases in our global simulation has thus been removed.

L169: Is it elevation or surface slope that has an important impact on precipitation amounts? Clarify.

Our statement oversimplifies the underlying processes of accumulation, which depends on elevation, slope and the characteristics of the atmospheric flow. More over it could not be supported by the figures, since we do not provide elevation. Hence we just mentioned that the simulated patterns of accumulation are similar in MAR and NPS-0k.

L178: Clarify if this masking includes ice caps and glaciers in the periphery of the Greenland ice sheet.

The high spatial resolution Greenland mask from GADM does not include ice caps and glaciers.

L185: You attribute most of the underestimation of melt to the albedo limit. Why is that limit in place?

We use a global model, and some tuning parameters reflect a compromise to globally limit model biases in its representation of the snowpack (especially seasonal).

Are there other shortcomings of the snowpack model worth mentioning? How does the snowpack model compare in complexity and included processes to the one in MAR?

In the §2.1 we indicated that the snowpack is represented by the one-layer snow scheme of Douville et al. (1995). This model has been much used at Météo-France in climate modelling and numerical weather prediction until a recent transition (for CMIP6) to the new ISBA-ES model (no reference available yet). We added more information about this snow scheme and that of MAR (SISVAT) in the paper.

If resolution is an important limitation, how does the model compare to low resolution versions of MAR (Franco et al., 2012).

Even if our model resolution on Greenland is close to that of Franco et al (2012), another big difference between our global model and their model is the lateral constraint !

L194: Could add a few references after "Greenland" as a reminder.

We actually removed this sentence, which is quite a general statement out of place in this part of the paper.

L191: I strongly disagree with this statement. The model is clearly not reproducing the melting well and therefore shows considerable shortcomings to represent the SMB. The statement is in clear contradiction to the description L184 and L312.

Indeed we underlined the underestimation of the melting, however note that the simulated equilibrium line, which separates the accumulation zone from the ablation zone, is rather realistic compared to MAR (Fig. 4k-l) and the correlations between the NAO index and the GrIS-averaged melting as SMB are consistent with MAR (Table hereafter).

	Accumulation		Melting		SMB	
	DJF	JJA	DJF	JJA	DJF	JJA
MAR	**-0.21**	**0.54**	**-**	**0.37**	**-0.21**	**0.40**
NPS-0k	-0.22	0.48	-	0.51	-0.22	0.62
NPS-115k	-0.11	0.43	-	0.56	-0.11	0.62
NPS-130k	-0.04	0.48	-	0.43	-0.04	0.56

Seasonal (DJF and JJA) correlations between accumulation, melting and SMB averaged on GrIS and the NAO index.

L195: Could you please clarify if the NAO index is here calculated based on the normalised PC as described at line L156? In other words, is the NAO index definition the same for the ERA-based correlation with MAR SMB as the CNRM-CM5.2 correlation with CNRM-CM5.2 SMB?

The NAO index was calculated in the same way for NPS and ERA-Interim, namely from the normalized first PC of the detrended sea level pressure.

L215: Are "changes in precession" meant compared to pre-industrial or to other times during the Eemian?

Theses changes are meant wrt preindustrial, as now stated in the paper.

L246: Could you find a better word instead of "node"? This is the first time this term is used. Maybe 'region'?

This is standard in the community to refer to both centers of action of NAO (Islandic Low and Azores High).

L310: Again, I think this statement may be true for accumulation, but clearly not for melting.

Already answered previously.

L317: There is "another hand" missing in this sentence or somewhere in the following.

Done. This sentence has been moved to §3.3.

L331: Not sure what "nibbled" means, please revise. Interesting to speculate on the impact of the Greenland ice sheet during the Eemian, extend if possible.

There is little literature about this. Ideally, an ice sheet model should be used to investigate this aspect more in depth.

L344: This final statement may raise the suspicion that the findings in this paper are not yet established to be robust and may be subject to change. Maybe just a question of formulation. Revise.

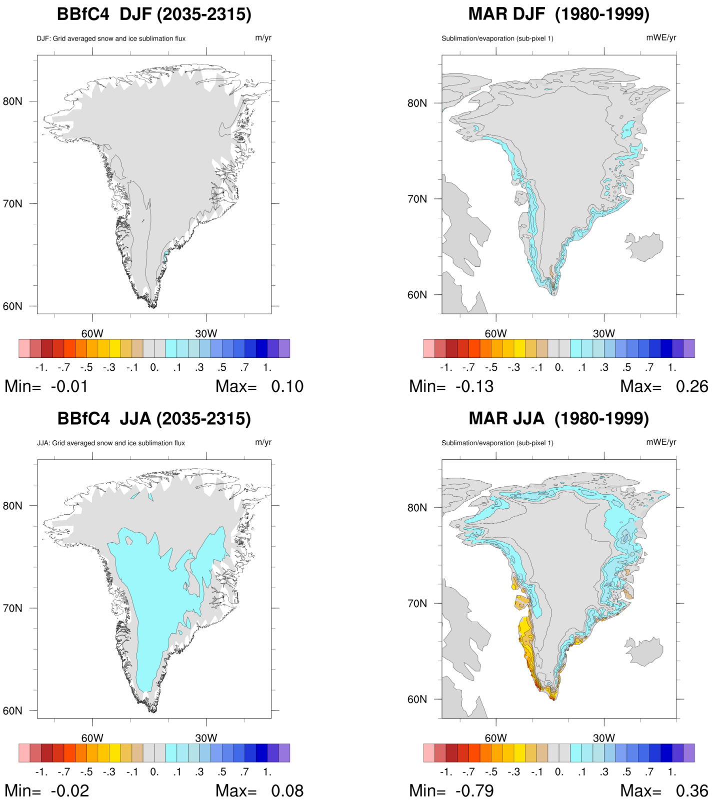
Thanks for this suggestion. Done.

Figure 2 Precipitation is defined positive. Maybe adjust the colour scale accordingly?

We adjusted the colour scale to follow this recommendation.

Figure 4 This figure clearly shows that ablation and SMB are very poorly represented in NPS-0k. Can you show the sublimation E subtracted from P to get accumulation C in the top panel (maybe as a supplement)? It seems to have a large impact on the resulting C. It also seems to have large spatial variability. Is that expected?

According to your suggestion we have evoluted the paper taking account SMB components rather the SMB itself. Now Figure 4, shows seasonal (DJF and JJA) means of accumulation, melting and SMB over Greenland from NPS-0k and MAR. Inside Greenland, the SMB of NPS-0k are, like for annual averages, a little noisy. The figure hereafter show for NPS-0k and MAR, the direct sublimation that are removed from precipitation. Inside Greenland, the accumulation of NPS-0k is underestimated (Table 2) due to strong direct sublimation however this does not vary much in space.



— References —

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Link between the Surface Mass Balance of the Greenland Ice Sheet and the North Atlantic Oscillation under preindustrial and last interglacial climates: a study with a Coupled Global Circulation Model

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Abstract. The relationship between the Surface Mass Balance (SMB) of the Greenland Ice Sheet (GrIS) and the North Atlantic Oscillation (NAO) is examined from numerical simulations performed with a new atmospheric stretched grid configuration of the Centre National de Recherches Météorologiques - Coupled Model (CNRM-CM) version 5.2 under three periods : preindustrial climate, a warm phase (early Eemian, 130ka BP) and a cool phase (glacial inception, 115 ka BP) of the last interglacial. The horizontal grid of the atmospheric component of CNRM-CM5.2 is stretched from the tilted pole on the Baffin Bay (72°N, 65°W) in order to obtain a higher spatial resolution on Greenland. The correlation between simulated SMB anomalies averaged over Greenland and the NAO index is weak in winter and significant in summer (about 0.6 for the three periods). In summer, spatial correlations between the NAO index and SMB display different patterns from one period to another. These differences are analysed in terms of the respective influence of the positive and negative phases of the NAO on accumulation and melting. Accumulation in South Greenland is significantly correlated with the positive (negative) phase of the NAO in a warm (cold) climate. Under preindustrial and 115 ka climates, melting along the margins is more correlated with the positive phase of the NAO than with its negative phase, whereas at 130 ka it is more correlated with the negative phase of the NAO in North and North-East Greenland.

1 Introduction

The recently observed acceleration of mass loss from the Greenland ice sheet (Hanna et al., 2013; Fettweis et al., 2013; Gillet-Chaulet et al., 2012 and references there in) is a concern due to its possible contribution to future sea-level rise. For example, Yan et al. (2014) estimated the GrIS contribution to global sea-level rise by 2100 by means of ice-sheet model simulations (including dynamics) forced with output from 20 CMIP5 (Coupled Model Intercomparison Project phase 5) to range from 0 to 16 (0 to 27) cm under the Representative Concentration Pathways (RCP) 4.5 (RCP8.5). For a given RCP, this uncertainty is mainly due to the large spread among CMIP5 model simulations. Furthermore, Fürst et al. (2015) found that the largest source of uncertainty in projections of the GrIS contribution to sea-level rise arises from the SMB rather than from the dynamics of the ice sheet.

The SMB of the GrIS has shown a downward trend since the early 1990s (Ettema et al., 2009). This downward trend is due to increased surface melting (Sasgen et al., 2012; Vernon et al., 2013). For example, during 12-15 July 2012, surface melting affected over 97% of the GrIS (Nghiem et al. 2012; Dahl-Jensen et al., 2013), in the context of a negative phase of the North Atlantic Oscillation (NAO). Typically, this weather regime is associated with an anticyclonic circulation centered over Greenland that induces warmer and drier summers than normal and southerly warm air advection along the western Greenland coast at the surface and at 500 hPa. In recent years, changes in atmospheric circulation explain about 70% of the summertime warming in Greenland (Fettweis et al., 2013). Over the last 30 years, changes in the NAO index were found in winter and summer but not in spring and autumn (Hanna et al., 2013). In winter, the year-to-year climate variability of the North Atlantic region is well captured by the NAO index because the atmospheric circulation is active and well organized. By contrast, in summer, the NAO explains a smaller fraction of the circulation variability in this region (Folland et al., 2008). On top of NAO changes, Arctic amplification plays a role in the recent SMB trend. Pithan and Mauritsen (2014) quantified the contributions of various feedbacks to Arctic temperature amplification from CMIP5 models and found that the largest contribution is due to a surface temperature feedback, because of the smaller increase in surface outgoing longwave radiation per °C of warming at cold surface temperatures than at higher temperatures prevailing at lower latitudes.

In this paper, we focus on the link between NAO and SMB and its components (accumulation and melting) and its stability under different climates. In particular, the early and late periods of the last interglacial state (Eemian) respectively correspond to a warm and a cold climate, which can, to some extent, serve as analogs to interpret recent and future climate changes. Mechanisms of such changes can be studied by using Coupled Global Circulation Models (CGCMs). However, current CGCMs, that couple atmosphere-land surface and ocean-sea ice models are increasingly comprehensive, but their typical horizontal resolution is currently around 100 km, which is too coarse to correctly represent local circulation in Greenland and surface moisture flux convergence. For example, snow sublimation is generally underestimated in CGCMs because the realism of this process highly depends on a good representation of the wind and especially on its maxima which increase with resolution (Lenaerts et al., 2012). Ettema et al. (2009) have quantified SMB on the GrIS by using high-resolution (about 11 km) limited-area regional climate model simulations and found that considerably more mass accumulates than previously thought, revising upwards earlier estimates by as much as 63%. This result points out the need to use high resolution models for estimating SMB. High resolution is also a necessary condition to well capture the spatial variability of the snow melt on margins of the GrIS especially where snow melt gradients are strong. This ability becomes all the more important as the expected trend of SMB in a warming climate is an enhanced melting along the GrIS margins. Hence, in order to locally increase horizontal resolution at a reasonable computational cost, in this study we use a stretched grid configuration (with enhanced resolution over Greenland) of the atmospheric component ARPEGE-Climat of CNRM-CM.

The questions addressed in this paper are: **i)** What is the link between NAO and the variability of the GrIS SMB under preindustrial climate ? **ii)** How robust is this link under the warm and cool phases of the Eemian ? **iii)** What are the regions where SMB is most influenced by the NAO and to what extent ? This paper is structured as follows. Section 2 describes the stretched grid configuration of CNRM-CM and the experimental design for this study. The preindustrial control simulation performed with CNRM-CM is analysed in section 3 and compared with the ECMWF Reanalysis ERA-Interim (Dee et al., 2011) and a previous CMIP5 simulation. The SMB and its link with NAO as simulated by CNRM-CM are compared with a simulation performed with MAR (Modèle Atmosphérique Régional). Section 4 is devoted to assessing the response of Greenland climate to large scale changes under the warm (130 ka) and the cool (115 ka) phases of the Eemian, with a focus on summer.

2 Features of the climate modelling simulations

2.1 Modelling tool

This study uses the CGCM CNRM-CM5.2 developed jointly by CNRM (Centre National de Recherches Météorologiques) and CERFACS (Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique) as described by Voldoire et al. (2013). The components of CNRM-CM5.2 are the atmospheric model ARPEGE-Climat (Deque et al., 1994), the surface platform SURFEX (Le Moigne et al., 2009), the river routing TRIP (Oki and Sud, 1998), the ocean model NEMO (Madec, 2008) and the sea ice model GELATO (Salas y Mélia, 2002). The components of CNRM-CM5.2 are coupled by means of the OASIS coupler (Valcke, 2006).

The ice mass transport due to the dynamics of the GrIS is not explicitely represented within CNRM-CM5.2. To circumvent this, the GrIS is represented by an initially prescribed huge amount of snow that evolves according to the balance between the snowfall rate, the direct sublimation and the snow melt, but without any modification of the topography of Greenland, the snowpack being represented by the one-layer snow scheme of Douville et al. (1995). To avoid unrealistic snow accumulation on the GrIS and an associated decrease in the modelled sea level, a pseudo-calving flux is computed at every time step from the spatially integrated snow reservoir excess over the GrIS and is distributed over the ocean north of 60°N.

The atmospheric component ARPEGE-Climat is used in a ‘‘low-top’’ configuration with 31 vertical levels (the highest level is set at 10 hPa). The horizontal grid is defined by a T127 spectral triangular truncation (a global mean spatial resolution of about 150 km). In this study, however, we chose to increase horizontal resolution to 40-50 km over Greenland in order to improve the spatial representation of SMB, in particular near the GrIS margins. To do so, the north pole of the ARPEGE-Climat horizontal grid was displaced to the Baffin Bay (72°N, 65°W) and the grid was stretched by a factor of 2.5 following the spherical harmonic-based functions on a transformed sphere (Courtier and Geleyn, 1988). In the rest of this study, this configuration of CNRM-CM5.2 will be referred to as NPS (North Pole Stretched). Different previous studies have used this functionality of increasing the horizontal resolution in a region of interest while decreasing it in other regions without any additional computational cost compared to a globally uniform resolution (e.g. Lorant and Royer, 2001 ; Doblas-Reyes, 2002 ; Chauvin et al., 2006). The physics and the calculations of the non-linear terms require spectral transforms onto a reduced Gaussian grid (Hortal and Simmons, 1991).

The ocean component is deployed on the horizontal quasi-isotropic tripolar grid ORCA1 (Hewitt et al. 2011) with 42 vertical levels and a horizontal resolution of about 1°. This grid has a latitudinal grid refinement of 1/3° at the Equator, andn the North Pole singularity is replaced by two poles located in Canada and Siberia.

2.2 Experimental Set-up

Three 280-year simulations were performed with NPS : preindustrial (NPS-0k), early Eemian climate (130 ka BP, denoted as NPS-130k) and glacial inception (115 ka BP, denoted as NPS-115k). These simulations differ only by the astronomical parameters (orbital eccentricity, axial tilt or precession and obliquity) that drive incoming insolation changes (Berger, 1988). In this study, we defined these parameters following Berger (1978) [see Table 1] . In all the simulations, the concentrations of tropospheric aerosols (organic and black carbon, sea salt, sulphate and sand dust) are estimates from the LMDz-INCA chemistry-climate model (Szopa et al., 2013) for years 1850-1860, considered as representative of preindustrial conditions. The atmospheric concentrations of well-mixed greenhouse gases (carbon dioxide, methane, nitrous oxide, ozone and CFCs) are yearly means for 1850. The 3D stratospheric ozone concentration is averaged from years 160-259 of the CMIP5 preindustrial control experiment run with CNRM-CM5.1. The solar constant is equal to 1365.6537 W/m2 for all the experiments, and the concentration of stratospheric aerosols produced by volcanic eruptions is a monthly zonal mean climatology derived from Ammann et al. (2003).

Atmospheric state variables (temperature, pressure, humidity and wind fields) were initialized from a previous forced integration of ARPEGE-Climat simulation. The initial states of NEMO and GELATO correspond to the first year of the CMIP5 preindustrial control experiment run with CNRM-CM5.1.

3 Evaluation of the preindustrial control integration

The NPS-0k simulation was integrated for 280 years without discarding the spin-up since the model reaches a steady state soon after initialization. This is probably due to the fact that NPS-0k and CMIP5 preindustrial simulations essentially differ by their atmospheric horizontal grids. In the rest of this study, all the analyses of NPS will be based on the entire simulation.

3.1 Model evaluation

Differences between the simulated time-mean 2m air temperature in the preindustrial experiments NPS-0k and CMIP5 (years 1-280) and the ERA-Interim reanalysis for winter (DJF) and summer (JJA) over the 1979-2012 period are plotted in Fig. 1. Note that these differences do not only depict model biases but also include the climate change signal since the preindustrial era.

The near surface warm biases along the eastern boundary currents of Peru and Benguela seen in the preindustrial CMIP5 simulation are more pronounced for NPS-0k. These well-known biases are due to the poor representation of coastal ocean upwelling and strato-cumulus, leading to an overestimated surface downwelling short-wave (Voldoire et al., 2013). A weak (CMIP5) to moderate (NPS-0k) warm bias can be seen in DJF in the Southern Ocean. This bias is probably due to several coupled processes. A rough representation of turbulent surface heat and momentum fluxes and vertical turbulent mixing in the ocean and atmospheric boundary layers, particularly in their entrainment zones, could be the causes, among others, of such biases. Biased kinetic energy transfers at the air-sea interface is also a potential source of oceanic biases because this coupled ocean-atmosphere process is particularly active in regions of strong currents (Giordani et al., 2013). Previous simulations performed with a low horizontal resolution configuration of CNRM-CM suggest that these biases are probably amplified by the much coarser horizontal resolution of the stretched model in this region (around 300 km) than in Baffin Bay.

The North Atlantic cold bias (off Newfoundland) is common to all coupled climate models using NEMO in its ORCA-1° configuration. For NPS-0k, the bias is similar in DJF and JJA whereas for CMIP5 it is more pronounced in DJF than in JJA. The Arctic is also dominated by a cold bias that is more pronounced in CMIP5 than NPS-0k in winter. The cold winter bias in the Barents Sea already existed in CNRM-CM3 and remains in CNRM-CM5.2. Even if the geographical distribution of Arctic sea ice is generally well simulated by CNRM-CM5.2, particularly in winter, the ice edge in the Greenland and Barents seas does not match observations well.

In order to evaluate accumulation on the GrIS, the annual mean and monthly mean (January and July) precipitation simulated for NPS-0k, CMIP5 and ERA-Interim are plotted in Fig. 2. The simulated solid precipitation strongly depends on the model resolution, especially along the southeastern Greenland coast where the topography varies sharply over short distances and acts as a barrier for the atmospheric flow. The seasonal variations of precipitation over South and North Greenland are out of phase, with annual maximum values occurring respectively in January and July. In January, the mean precipitation in NPS-0k along the southeastern and southwestern Greenland coasts is similar to ERA-Interim. The improvement due to the higher horizontal resolution of NPS-0k compared with CMIP5 is clear for the representation of the highest annual precipitation (higher than 0.8 mWE /yr) and of the distribution of precipitation along the coast. In July, the simulated precipitation in NPS-0k over South Greenland and along the western margin of the GrIS is very similar to ERA-Interim. Note that the most important contribution to the annual total precipitation is from July precipitation.

The NAO index can be defined as the difference in sea-level atmospheric pressure between Lisbon (Portugal) or Ponta Delgada (Azores) and Stykkisholmur or Reykjavik (Iceland) (Hurrel, 1995). The drawback of this proxy is that it does not account for the fluctuations of the locations of the Icelandic low and the Azores high. This implies that the NAO station-based index does not completely capture the seasonal, interannual and multidecadal spatial variability of the North Atlantic pressure patterns (Hanna et al., 2013). The NAO index can also be defined is as the leading Principal Component (PC) of atmospheric pressures usually at sea level, 850hPa or 500hPa. The associated empirically-determined orthogonal function (EOF) provides the spatial structure of NAO (Bjornsson and Venegas, 1997).

In this work, the NAO index is defined as the normalized PC associated with the first EOF (EOF1) of the detrended monthly sea-level pressure (SLP) anomalies in the North Atlantic (20°N–70°N; 90°W–40°E). Fig. 3 shows the EOF1 for NPS-0k and

ERA-Interim (1979-2016) in winter (DJF) and summer (JJA). In DJF, the positions of the simulated centers of action of NPS-0k are similar to those of ERA-Interim. In JJA, only the southern center of action in NPS-0k reveals a slight southwestward shift compared to ERA-Interim. The EOF1 of NPS-0k and ERA-Interim explain respectively 35.9% and 50.3% of the total variance of SLP in DJF and 30.3% and 36.2% in JJA.

3.2 Simulated SMB mean-states

The SMB can be written as:

$$SMB = P - E - M \quad , \tag{1}$$

where P, E and M (all positive) respectively represent snowfall, the sublimation of the snowpack and surface melting. Fig. 4 compares accumulation C=P-E, melting M and SMB diagnosed from NPS-0k with their counterparts simulated by MAR for the period 1979-2012, which serves as a reference. The latter simulation was performed with MAR version 3.2 (Fettweis et al., 2013) at a horizontal resolution of 25 km and was driven by ERA-Interim at its lateral boundary conditions.

NPS-0k and MAR accumulations compare well and show that surface elevation strongly influences accumulation. Three regions of accumulation were identified in these simulations. A “dry” region in central and North-East Greenland, where C is less than 0.2 m/yr, a “wet” region along the southeastern and southwestern margins of the GrIS where C is greater than 1 m/yr and the rest of Greenland where accumulation is intermediate. NPS-0k reproduces quite well the “wet” zone simulated by MAR thanks to its relatively high resolution. The “dry” zone is also well simulated, even if in the central part of South Greenland the net accumulation is less in NPS-0k than in MAR. In central Greenland, the lower annual mean accumulation in NPS-0k compared to MAR is due to the greater summertime sublimation in NPS-0k than in MAR.

GrIS-averaged seasonal accumulation, melting and SMB for NPS-0k and MAR are presented in Table 2. These spatial integrations were computed after interpolating output from both models on an rectilinear grid and masked over the same exogenous Greenland mask obtained from the Global Database of Administrative areas (GADM, http://www.gadm.org/country). In DJF, the mean accumulation averaged on the GrIS in NPS-0k is in close agreement with MAR (0.31 and 0.32 mWE/yr respectively), whereas in JJA, it is lower in NPS-0k than in MAR (0.29 and 0.34 mWE/yr respectively to NPS-0k and MAR).

Regarding melting, there is less agreement between NPS-0k and MAR. In NPS-0k, the simulated melting rates are underestimated along the margins, especially in the southwestern part of the GrIS, south of the Jakobshavn region, and along the northeastern part of the GrIS. MAR displays much higher melting rates along the margins. Melting is underestimated in NPS-0k mainly because in CNRM-CM5.2 the minimum albedo of permanent ice is set to 0.8, which hampers the feedback between albedo, solar radiation absorption and melting. Moreover, even at a horizontal resolution of 50 km, the relatively steep topography of the GrIS near the margins cannot be correctly represented, which probably contributes to the biased simulated surface melting in this area.

Melting exceeds accumulation near the margins of the GrIS. This feature is typical of a warm climate but is not simulated by NPS-0k. In the "dry" region, NPS-0k and MAR display slightly positive SMBs (<0.2 mWE/yr). All in all, the SMB is reasonably represented in the NPS-0k simulation compared to the reference MAR, even if the surface melting of the snowpack is strongly underestimated near the margins of the GrIS.

3.3 Relationship between the interannual variability of GrIS SMB and NAO

The NAO index explains much of the weather and climate variability over the North Atlantic and Greenland, hence in this section we examine its link with the variability of GrIS SMB. We compute the NAO index from ERA-Interim since this reanalysis is the lateral boundary condition of the MAR regional simulation that we used as a reference to validate SMB and its components. Fig. 5 shows the GrIS-averaged SMB simulated by MAR (1979-2012) and the NAO index from ERA-Interim. These reconstructions for the 1979-2012 period will serve as a basis for comparison with our model simulations. The correlation between the two time-detrended variables is -0.11 in wintertime and 0.41 in summertime. Fig. 6 shows the simulated GrIS-averaged SMB and the NAO index for NPS-0k in winter and summer. Like in MAR, in winter, the correlation coefficient is slightly negative (-0.22), meaning that a positive NAO index is preferably (but not systematically) associated with SMBs lower than average on Greenland (or net accumulation, since there is virtually no melting in winter, see Table 2). In summer, SMB anomalies are more strongly correlated with the NAO index (0.62) than in the MAR simulation. Note however that the correlation estimate from MAR and ERA-Interim is probably not robust due to the short time series used (34 years). In order to test the stability of this correlation, we splitted up the NAO index and SMB time series simulated by NPS-0k into 8 consecutive chunks of 34 years and found that the correlation coefficients for these 34-year time-spans ranged from 0.42 to 0.71, which is compatible with the result obtained from MAR and ERA-Interim.

4 Greenland climate, NAO and GrIS SMB during the 130 ka, 115 ka and preindustrial periods

4.1 Changes in solar radiation and climate response

The orbital eccentricity, precession and obliquity modulate the solar flux at the top of the Earth's atmosphere. The eccentricity is the deviation of the orbit from a perfect circle and is the only orbital parameter that can modify the global year-mean solar irradiance per unit surface area. The precession is the change in the orientation of the Earth's rotational axis and the obliquity is the angle between the Earth's rotational axis and its orbital axis. Both parameters alter the repartition of solar energy by latitude bands. The eccentricity and precession parameters mainly modulate the Earth-Sun distance, whereas obliquity mainly determines the latitude with largest solar irradiance. During Eemian, changes in precession led to significant insolation changes due to the high eccentricity. On top of that, high (low) obliquity is associated with less (more) insolation at middle and high latitudes. Hence, since the obliquity increases with time from the beginning (130 ka) to the end (115 ka) of the interglacial period, high latitudes received less irradiation at 115 ka than at 130 ka.

Zonal averages of monthly and annual insolation anomalies between the Eemian and the preindustrial periods are shown in Fig. 7. The 130 ka is characterized by positive annual anomalies at high latitudes with very different seasonal cycles between the Northern Hemisphere (NH) and the Southern Hemisphere (SH). Strong positive anomalies (>50 W/m2) prevail north of 20°N during approximately two months (April-May) whereas in the South Hemisphere positive anomalies only appear south of 60°S during approximately one month. In tropical regions, anomalies are negative for six consecutive months and the annual mean insolation anomaly is close to zero. At 115 ka, insolation anomalies are broadly with opposite sign compared to those of 130 ka. More (less) solar energy reaches tropical (polar) regions for 115 ka than for 130 ka. The monthly gradient of insolation anomaly during spring and autumn decreases between 130 ka and 115 ka. The Earth's orbital parameters lead to zonal annual changes of insolation from the preindustrial period that depend on the seasonality of solar radiation. In the Arctic, the annual increase (decrease) of insolation anomalies at 130 ka (115 ka) compared to the preindustrial results in a warmer (cooler) climate from March to June (April to July). In order to document the near-surface response to the changes in insolation, the simulated NPS-130k and NPS-115k 2m-temperature summertime anomalies (with reference to NPS-0k simulation) are plotted in Fig. 8. The three NPS experiments only differ by the orbital parameters and therefore changes in mean states and variabilty can be attributed to differences in solar forcing. In NPS-130k, the largest positive 2m-temperature anomalies, as high as 4 °C, appear in the central part of the GrIS (Fig. 8a), where the high elevation leads to cold and dry conditions. This anomaly suggests that in this region the ice sheet and atmosphere interact through a thermodynamic balance. In this region, the mean circulation is mostly controlled by local processes. Conversely, in NPS-115ka, the largest cooling anomalies do not correspond with the highest elevations, suggesting that even in the central part of the GrIS, the mean climate is mainly determined by atmospheric dynamics rather than local processes. The largest negative temperature anomalies occur in the northern part of central Greenland (Fig. 8b), which are influenced by cold northerly winds blowing from the ice-covered Arctic Ocean to Greenland, cooling the near-surface atmosphere.

We finally examine changes in the seasonal (DJF and JJA) means of accumulation, melting and SMB averaged over the Greenland mask for interglacial and preindustrial climates (Table 2). Under all climates, there is more accumulation in summertime than in wintertime and, as expected since accumulation increases with temperature, the accumulation is stronger at 130 ka for both seasons. Even if simulated melting rates are underestimated, since the same model is used for all experiments, we compare them in terms of relative values. As a consequence of obliquity changes, melting is much larger at 130 ka than for preindustrial and 115 ka.

The spatial structure of the JJA NAO patterns does not depend much on the considered period, as shown in Fig. 9. The southern positive node extends farther west and south during 130 ka, and the extension of the northern negative node is smaller at 130 ka than at 115 ka and preindustrial. The total variance of SLP explained by the EOF1 does not depend much either on the period, and is equal to 30.3 % , 33.0 % and 29.8 % respectively in NPS-0k, NPS-115k and NPS-130k.

4.2 The link between NAO and SMB

Correlation maps between SMB and the NAO index for preindustrial and both interglacial climates are plotted in Fig. 10. In winter (Figs. 10a-c), the overall similarity in the patterns of SMB shows that even if the representation of the GrIS orography in CNRM-CM is rather coarse, the model reasonably simulates the rising of moisture in the atmosphere over the steepest parts of the GrIS. Also, we note that variations in zonal annual insolation do not significantly modulate accumulation. The correlation maps show that the link between the NAO index and SMB is relatively strong under all climates in the northwestern (negative correlations) and northeastern (positive correlations) parts of the central GrIS. No melting occurs in winter and the SMB reduces to net accumulation. The strongest negative correlations in the northwestern part of central Greenland are due to the lower snow precipitation during the negative phase of the NAO, contrasting with strong westerly advection of moisture in South Greenland.

In summer (Figs. 10d-f), patterns of SMB are different for each climate and correlation coefficients are positive, increasing from northeastern central Greenland (dry zone) towards the coast. At 130 ka (Fig. 10f), the large mid-to-high latitude warming explains the relatively wide area with negative SMB along the GrIS margins. In particular, strong snow melting occurs in the northeastern part of the GrIS, suggesting this area to be a vulnerable part of the GrIS under a warm climate since melting is not compensated by accumulation. Similarly, Born and Nisancioglu (2012) concluded that at 126 ka, the strongly negative annual mean SMB in the northeastern part of the GrIS leads to a significant thinning of the ice-sheet, which is amplified by the ice elevation feedback. At 115 ka (Fig. 10e), in the southern part of the GrIS, positive and negative SMB are strongly correlated with NAO. On the margins the cold summer climate inhibits melting, whereas at higher elevations, the SMB becomes positive as a response to increased accumulation due to atmospheric moisture transport. Note that at 130 ka, the northeastern part of the GrIS shows slightly negative SMB not correlated to the NAO index. The preindustrial SMB patterns (Fig. 10d) are intermediate between 115 ka (Fig. 10e) and 130 ka (Fig. 10f). In North-West (South) Greenland, they are rather similar to those of 130 ka (115 ka). Over most of Greenland the preindustrial patterns of correlation are rather similar to 130 ka despite lower values in particular along coastal areas. In the northeastern part of the GrIS (up to 70°N), preindustrial SMB is less correlated to the NAO index than at 130 ka. Under preindustrial climate, the strongest correlations are confined to the southern margins, as well as at 115 ka, reflecting reduced snow precipitation at lower elevations during the negative phase of the NAO, when the atmospheric flow is less pronounced. More inland, the strong correlations are due to the barrier effect of the GrIS that forces the rise of atmospheric moisture and subsequent snow precipitation (Bromwich et al., 1999; Folland et al., 2009; Fettweis et al., 2011; Auger et al., 2017).

To better understand these summertime differences in SMB and NAO correlations for the contrasted climates of the Eemian, the analysis now focuses on the influence of NAO phases on accumulation and melting.

4.3 Impact of the summertime phases of the NAO on SMB and its components

As was done for NPS-0k (Fig. 6), the correlation between the GrIS-averaged summertime SMB anomalies and the NAO index was plotted for both interglacial climates (Fig. 11). The correlation coefficients for NPS-0k, NPS-115k and NPS-130k are respectively equal to 0.61, 0.62. and 0.56. In order to go further in the analysis, we sampled positive and negative phases of the NAO and computed grid-point correlation maps with accumulation (Fig. 11) and melting (Fig. 12). Summers with an absolute value of the NAO index less than one standard deviation were excluded. The statistical significance of correlation coefficients is estimated at the 99% confidence level.

In the eastern part of the GrIS, significant correlations between accumulation and NAO only occur for positive NAO phases. In North Greenland, significant correlations are only seen under 130 ka climate for positive NAO phases. The link between accumulation and NAO is rather strong in South Greenland with correlations greater than 0.25. The positive phase of the NAO favours accumulation in most of South Greenland in preindustrial (Fig. 12a) and 130 ka (Fig. 12c), i.e. under warm climates, whereas under the colder 115 ka climate, the negative phase of the NAO favours accumulation (Fig. 12e). The accumulated precipitation primarily arises from oceanic evaporation and atmospheric transport towards South Greenland. Oceanic evaporation is related to surface atmospheric forcing and SST anomalies which can be generated by NAO phases. For example, the negative phase of the NAO is associated with negative SST anomalies from Baffin Bay to the Greenland Sea and positive SST anomalies in the central North Atlantic (Pinto and Raible, 2012 and references there in). More over, at 115 ka, the latitudinal insolation gradient (Fig. 7, bottom) induces a larger northward atmospheric moisture transport from the warmer tropical ocean, supplying higher latitudes with moisture (Ramstein et al., 2005). Finally, central Greenland sees less precipitation, since moist air masses tend to generate precipitation, hence getting drier on their way towards inland Greenland. More over, the presence of the anticyclone over the GrIS induced by downdraft air masses over the cold northern ice sheet also prevents the penetration of moist air masses into the interior of Greenland (Merz et al., 2014 and references there in).

For the positive phase of the NAO, the correlation of melting with the NAO index is greater than 0.25 mainly along the steepest margins of the GrIS except along the eastern coast north of 70 °N for all climates (Figs. 13a-c). For the negative phase of the NAO, melting tends to be correlated with the NAO index only for 130 ka, along the eastern coast north of 70 °N (Figs. 13d-f). Note that the preindustrial displays no significant link between the negative phase of the NAO and melting.

Conclusions and perspectives

In this paper we examined the link between the Surface Mass Balance of the Greenland Ice Sheet and the North Atlantic Oscillation (NAO) for the last interglacial and preindustrial climates. For this study we developed a configuration of CNRM-CM5.2 with enhanced atmospheric horizontal resolution on Greenland (40 to 55 km), which is reasonably suited for simulating the spatial variability of accumulation and surface melting. On the basis of a comparison with a regional simulation performed with MAR for 1979-2012, we showed that the simulated accumulation in our preindustrial simulation is realistic, whereas surface melting is much underestimated due to the too high minimum albedo (0.8) used in CNRM-CM5.2.

For all climates, the anomalies of the averaged SMB over all of Greenland and the NAO index (normalized leading PC of detrended SLP anomalies) are weakly correlated in wintertime (around -0.2) and strongly correlated in summertime (around 0.6). These correlations are in broad agreement with those between SMB simulated by MAR and the NAO index computed from ERA-Interim for the period 1979-2012. Note that, on the one hand, our estimate of the summer correlation computed from MAR and ERA-Interim is probably not robust due to the relatively short sampling time (34 years). In summer, the underestimation of surface melt does not seem to affect much the correlation between the SMB averaged over all of Greenland and the NAO index because it remains consistent with results of Fettweis et al. (2013) highlighting the link between surface melting over the GrIS and the negative phase of the NAO.

This study also emphasized the spatial pattern of the link between SMB and the NAO index. In winter, this spatial pattern is similar for all mean states, with negative (positive) correlations in the western (eastern) part of central Greenland. Both regions are characterized by relatively dry conditions in contrast with South Greenland. More over, the similarity between regional patterns of the SMB as well as its correlation with the NAO index under all climates indicate that the variability of insolation has a weak influence on the patterns of accumulation in winter. In summer, the spatial patterns of SMB and its correlation with the NAO index depend on the climate. The link between NAO and SMB is all the stronger as the climate is warm (e.g. stronger at 130 ka than at 115 ka) and gets stronger from the northwestern part of central Greenland to the margins. Even if our model strongly underestimates melting compared to MAR, strong negative SMB appears, especially in the northeastern part of Greenland under warm climates (preindustrial and 130 ka). This result shows that in a warm climate, the northern and northeastern parts of the GrIS could be nibbled. In South Greenland, very strong SMB gradients confined to the margins are associated with strong correlations with NAO under preindustrial and 115 ka climates. More inland, the SMB is positive because the southwesterly and southeasterly flows strongly interact with the topography. In South Greenland, the simulated preindustrial SMB is similar to SMB at 115 ka, whereas in North Greenland it can be viewed as intermediate between 115 ka and 130 ka patterns.

The last part of this work highlights the influence of both positive and negative phases of the NAO on accumulation and melting. Accumulation in South Greenland varies preferentially with the positive (negative) phase of the NAO in a warm (cold) climate. Under warm climates, the positive phase of the NAO favours the large scale advection of moisture in South-West Greenland and subsequent precipitation. At 115 ka, the accumulation tends to be controled by the negative phase of the NAO. In summertime, the negative phase of the NAO is significantly correlated to melting only in North-East Greenland at 130 ka, whereas its positive phase promotes melting along the margins of the GrIS under all climates. The representation of the spatial structures of accumulation and melting and their links with NAO are both significantly improved due to the enhancement of horizontal resolution on Greenland in the NPS configuration compared with the CNRM-CM5 configuration used for CMIP5. Future work will investigate the critical influence of sea-ice and SST to establish the robustness of the simulated links between SMB and its components with both phases of the NAO.

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465 **Table 1. Astronomical forcing for all simulations after Berger (1978) in degrees.**

*** The precession is the longitude of the perihelion relative to the moving vernal equinox minus 180°.**

simulation	Period	Eccentricity	Precession*	Obliquity
NPS-0k	preindustrial	0.01672	102.0	23.446
NPS-115k	115 ka BP	0.04142	110.9	22.405
NPS-130k	130 ka BP	0.03821	228.3	24.242

Table 2. Winter (DJF), summer (JJA) and annual mean accumulation, melting and SMB averaged on the GrIS for the MAR (1979-2012) simulation and for the NPS simulations at preindustrial, 115 ka and 130 ka (years 1-280). Units are in m/yr WE.

Period	**Accumulation**		**Melting**		**SMB**	
	DJF	JJA	DJF	JJA	DJF	JJA
MAR	0.319	0.343	0.000	-1.683	0.318	-1.343
PI	0.238	0.241	0.000	-0.349	0.238	-0.108
115 ka BP	0.225	0.235	0.000	-0.206	0.225	0.029
130 ka BP	0.241	0.276	0.000	-0.901	0.241	-0.626

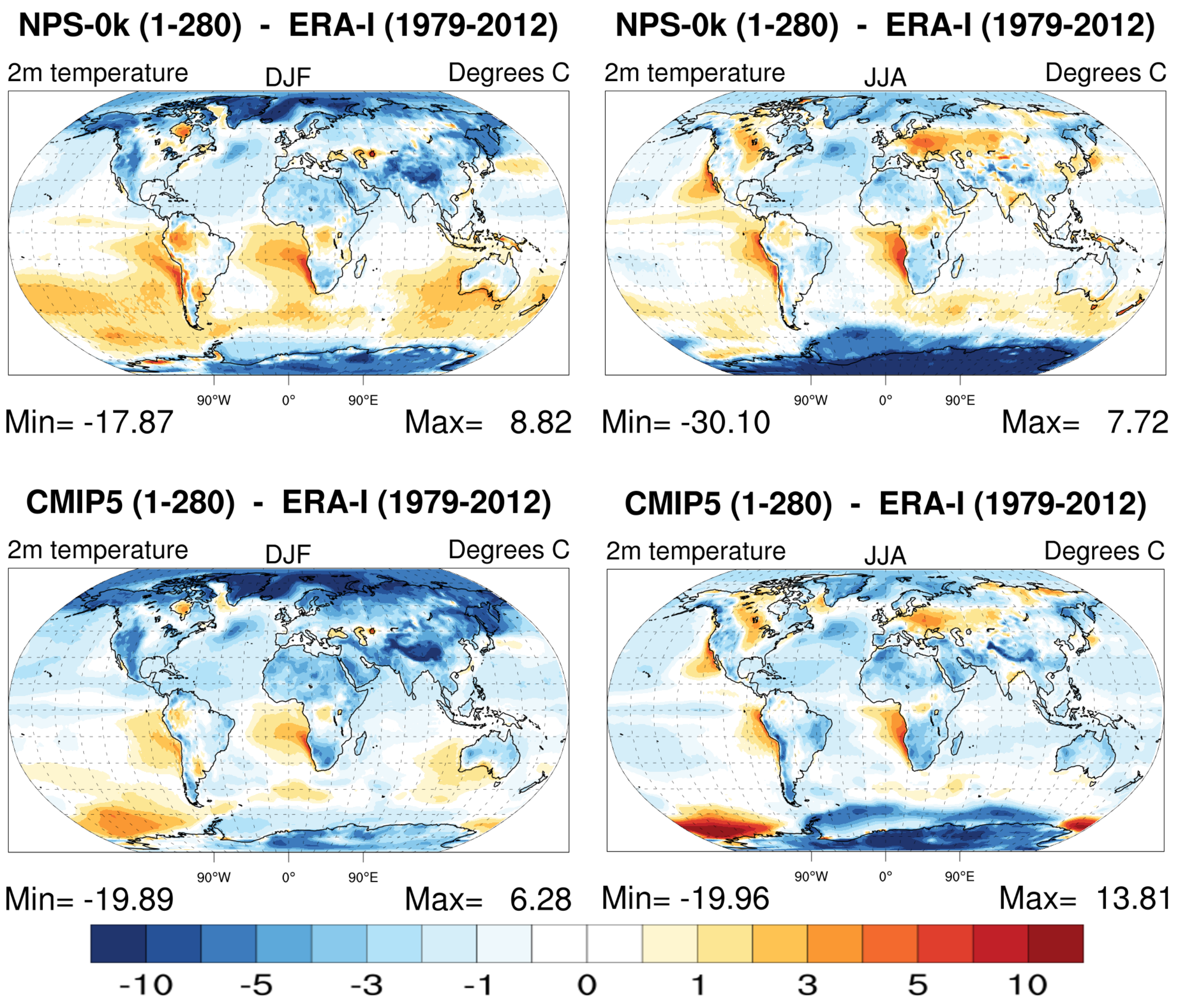

Figure 1: 2m temperature biases between the mean states from both preindustrial simulations (top) NPS-0k and (bottom) CMIP5 relative to the ECMWF reanalysis ERA-Interim (years 1979-2012) in (left) boreal winter (DJF) and (right) summer (JJA).

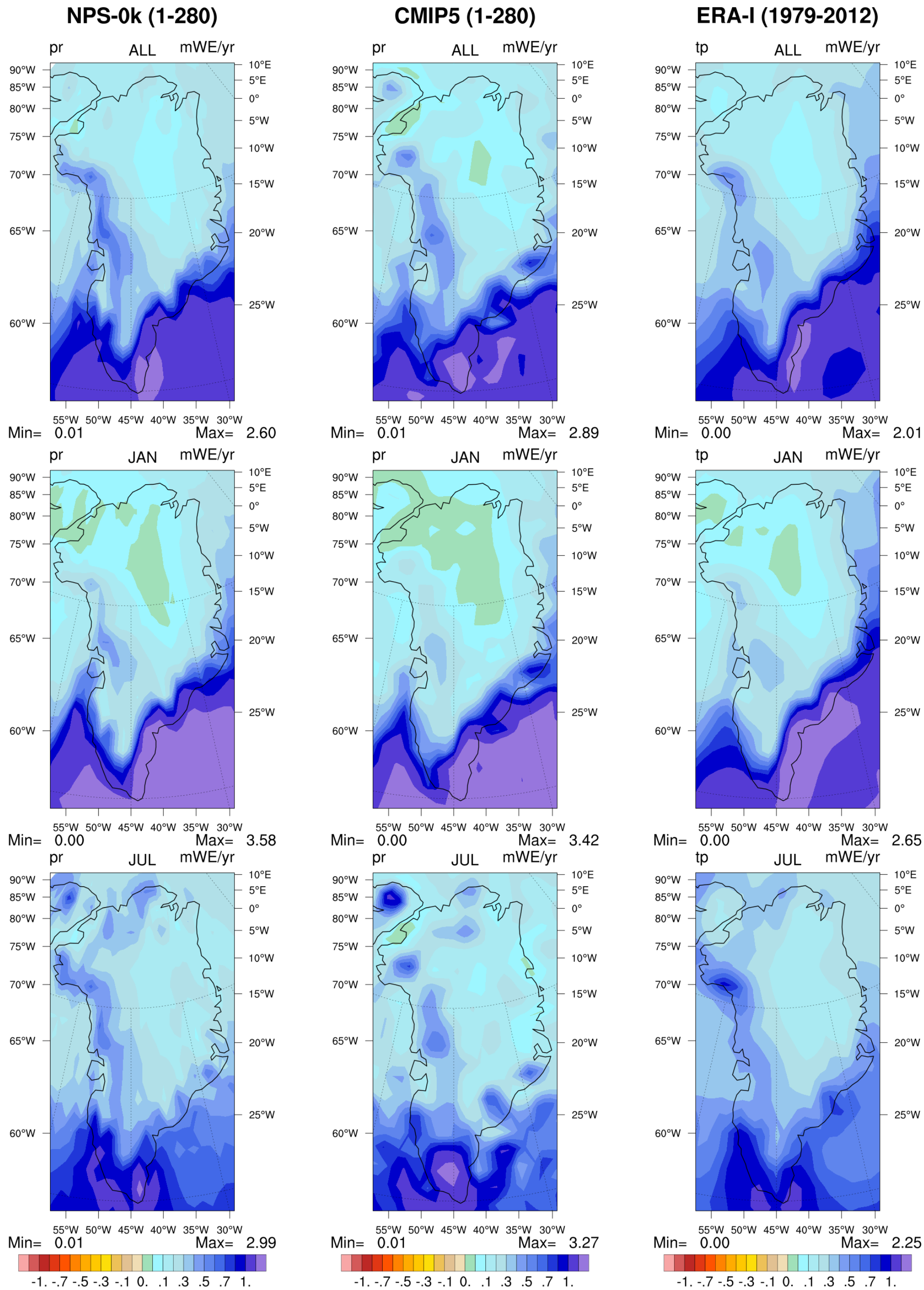

Figure 2: Annual mean precipitation (top) and monthly mean precipitation for January (middle) and July (bottom) in the preindustrial simulations (years 1-280) NPS-0k (left) and CMIP5 (middle) and ERA-Interim (1979-2012) (right).

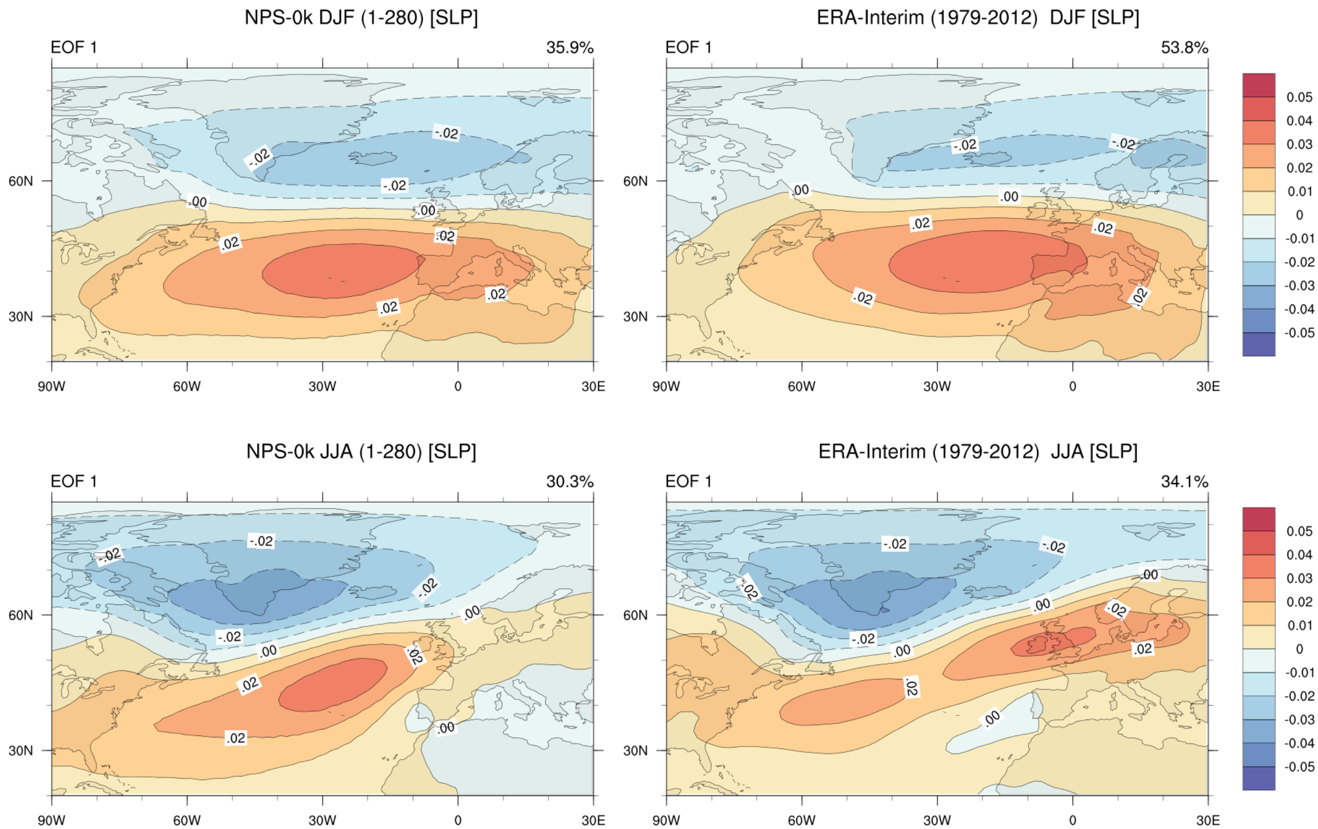

Figure 3: Leading EOF of SLP for (left) NPS-0k (years 1-280) and (right) ERA-Interim (years 1979-2012) in winter (DJF, top row) and in summer (JJA, bottom row).

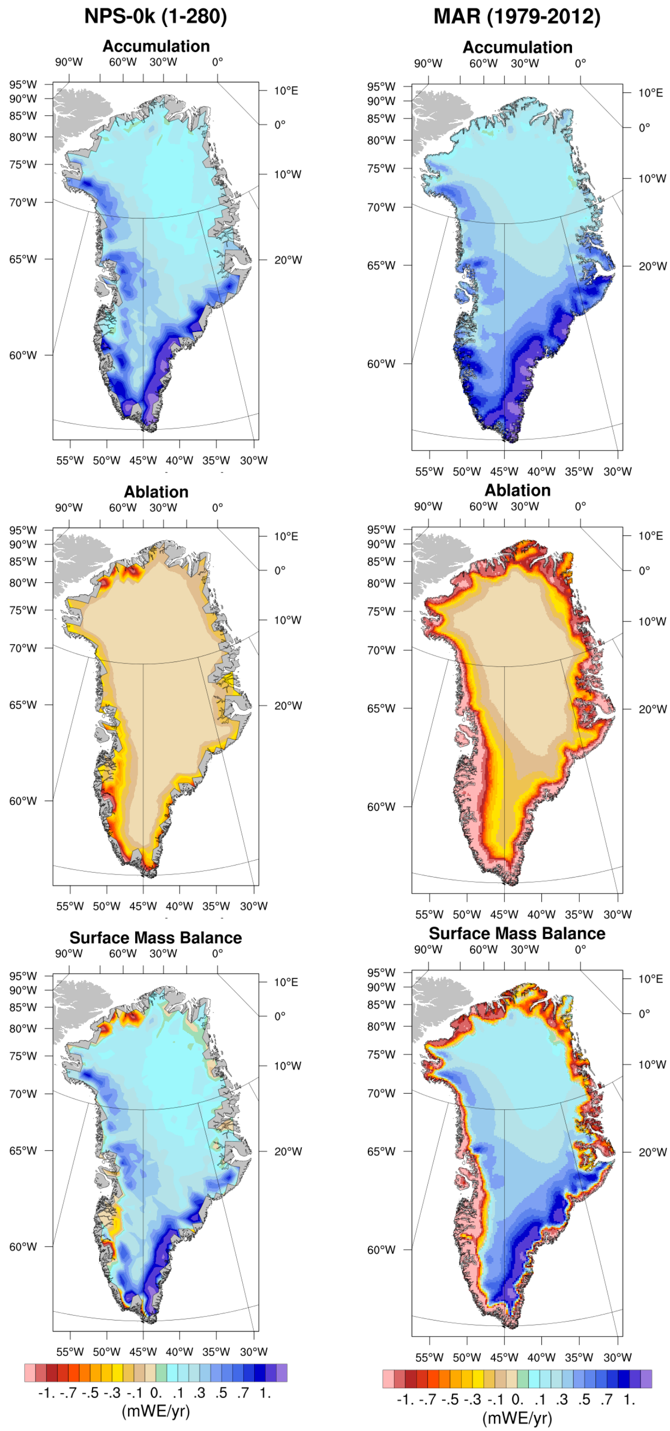

Figure 4: Annual mean accumulation (top), ablation (middle) and SMB (bottom) over Greenland from NPS-0k (left) and MAR (right) .

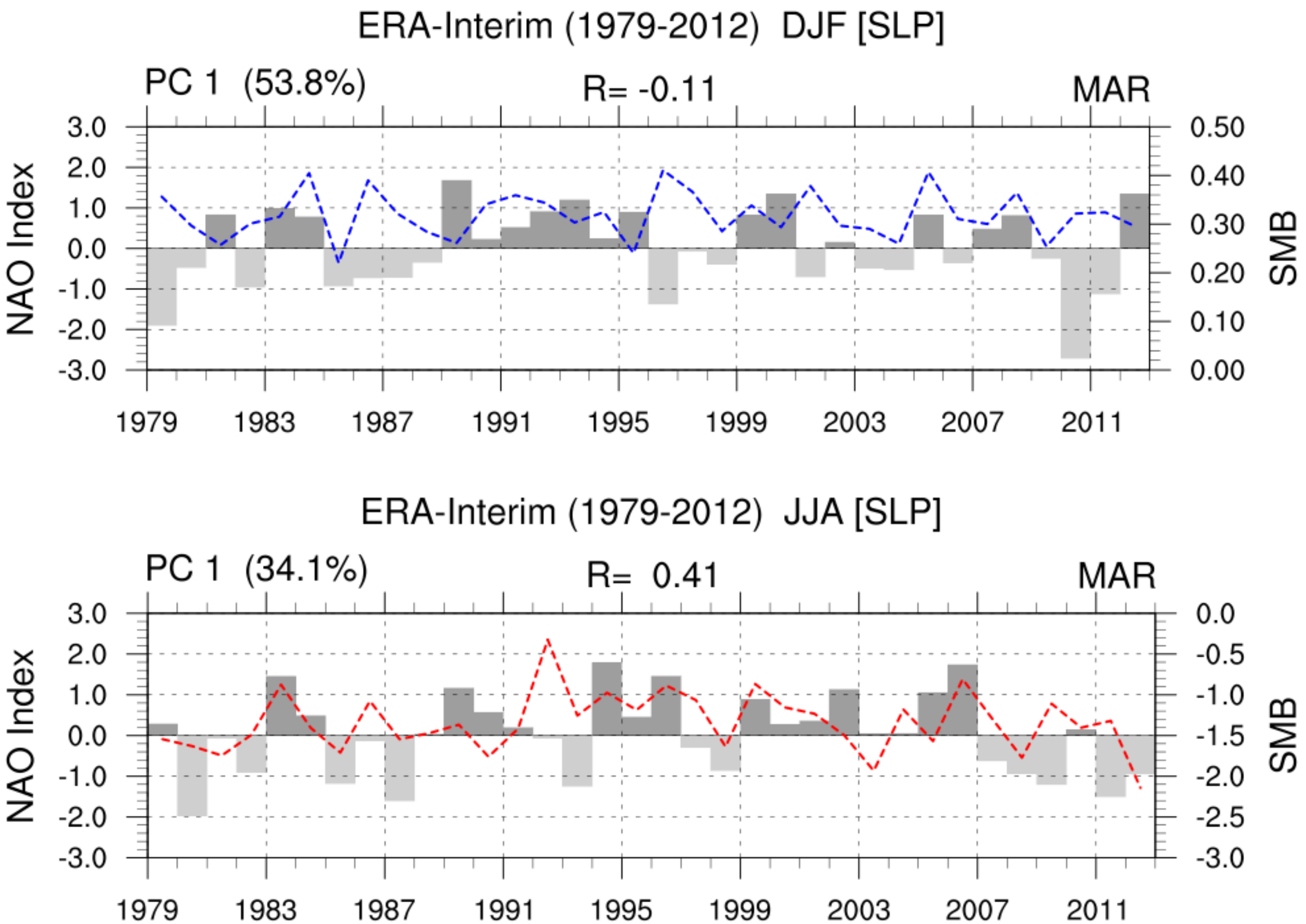

Figure 5: (grey bars) Time series of normalized leading PC derived from an EOF analysis of ERA-Interim SLP over the extra-tropical North Atlantic (20N-70N;90W-40E) and (dashed lines) average SMB over Greenland simulated by MAR for winter (DJF, top) and summer (JJA, bottom).

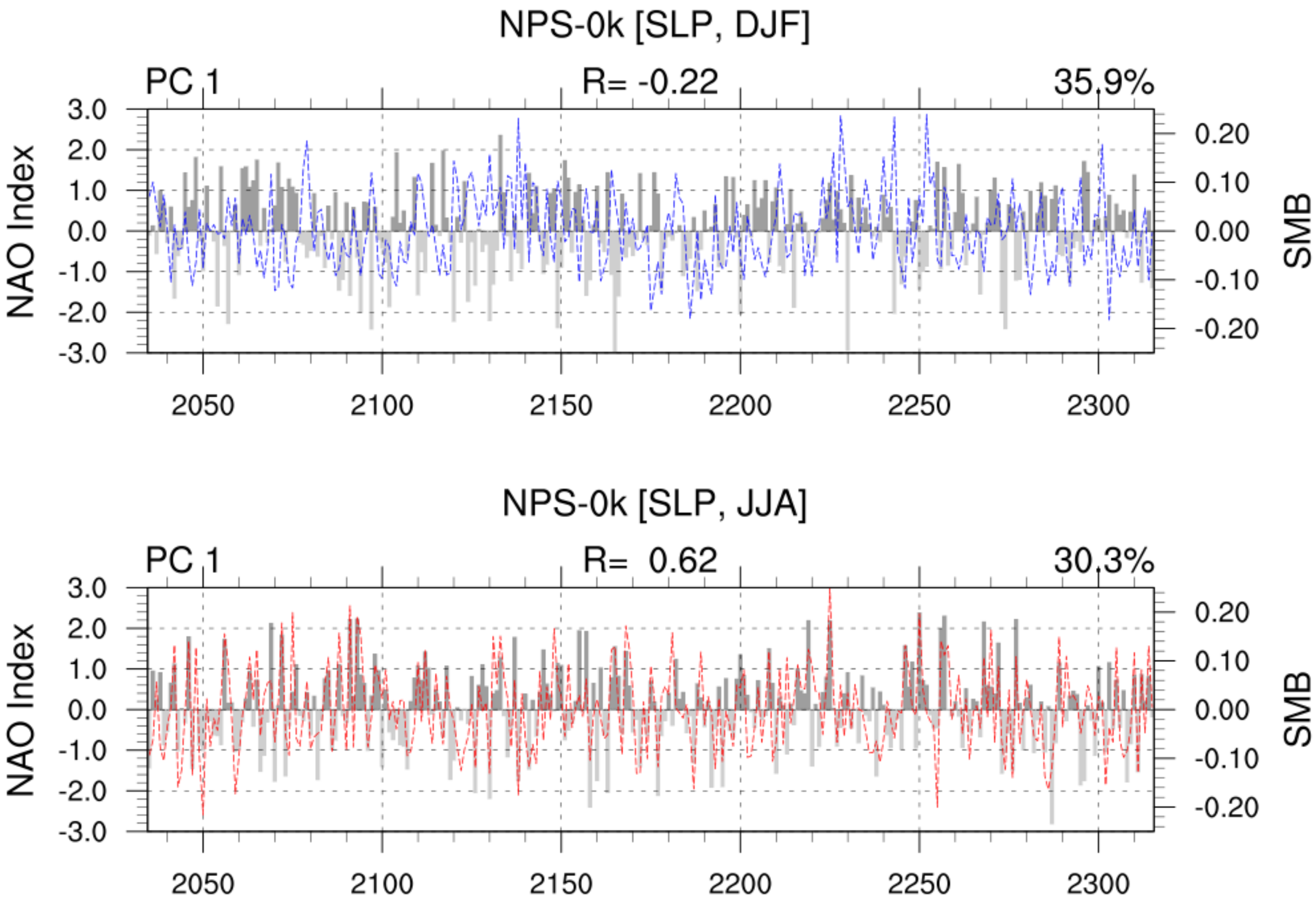

Figure 6: (grey bars) Time series of normalized leading PC derived from an EOF analysis of SLP over the extra-tropical North Atlantic and (dashed lines) average SMB over Greenland in NPS-0k for winter (DJF, top) and summer (JJA, bottom).

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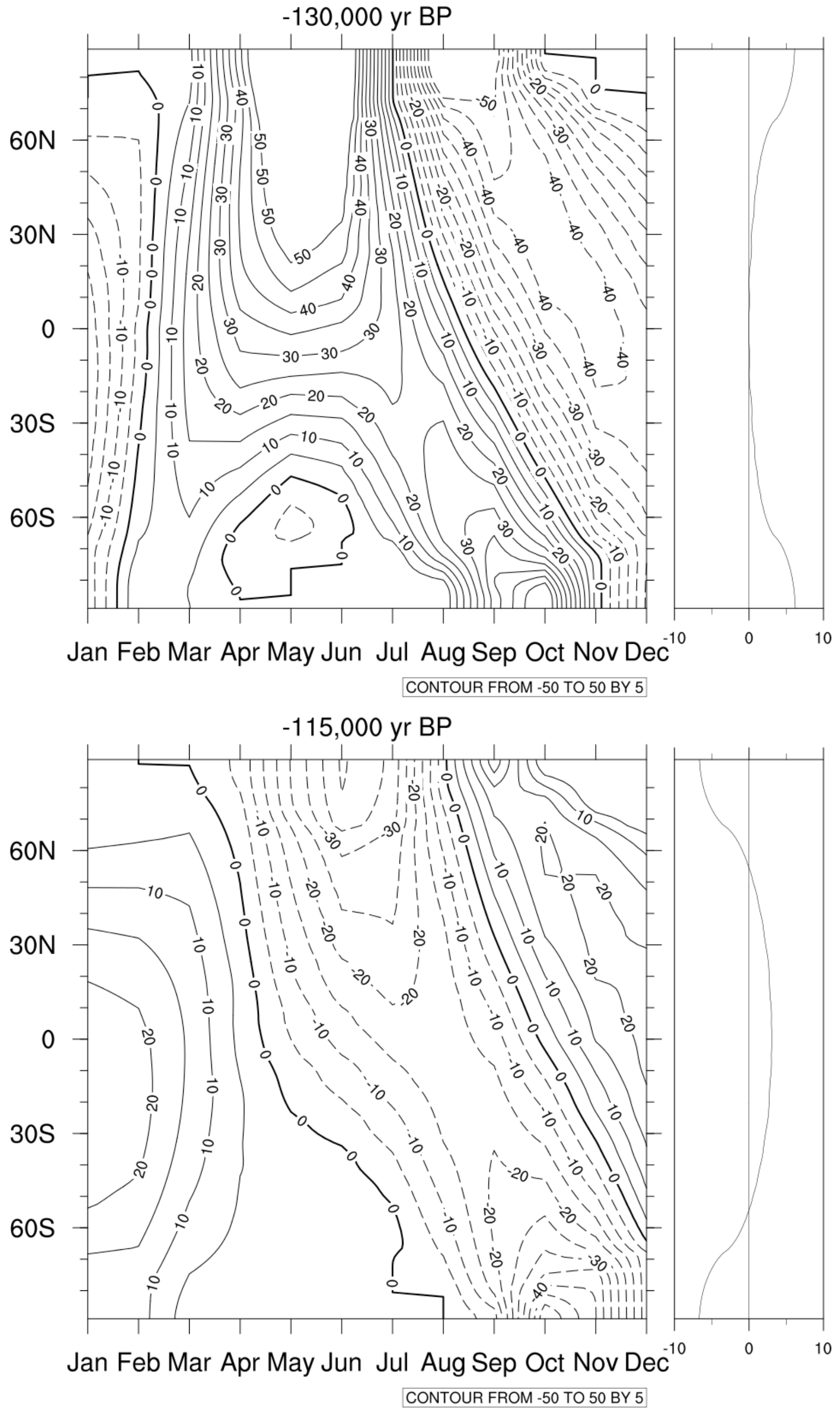

Figure 7: Zonal mean departures of (left) monthly and (right) annual insolation from preindustrial conditions for (top) 130 ka and (bottom) 115 ka BP. On the left panels, contours are drawn every 5 W m-2 from -50 to 50 W m-2. Full lines are for positive deviations (Eemian values larger than preindustrial) .

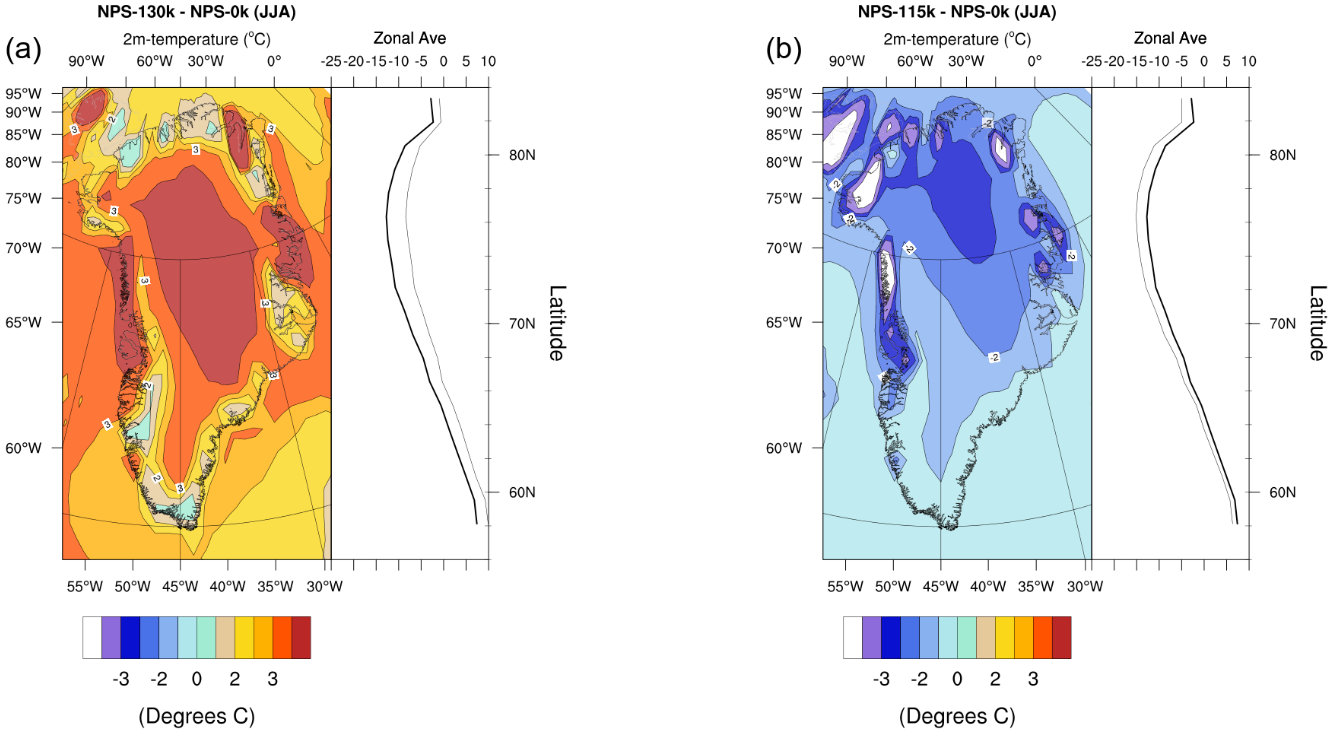

Figure 8: Summer (JJA) 2m temperature anomalies for 130 ka (left) and 115 ka (right) from preindustrial conditions. In both plots, the left and right subplots respectively represent the spatial pattern of anomalies and their zonal average.

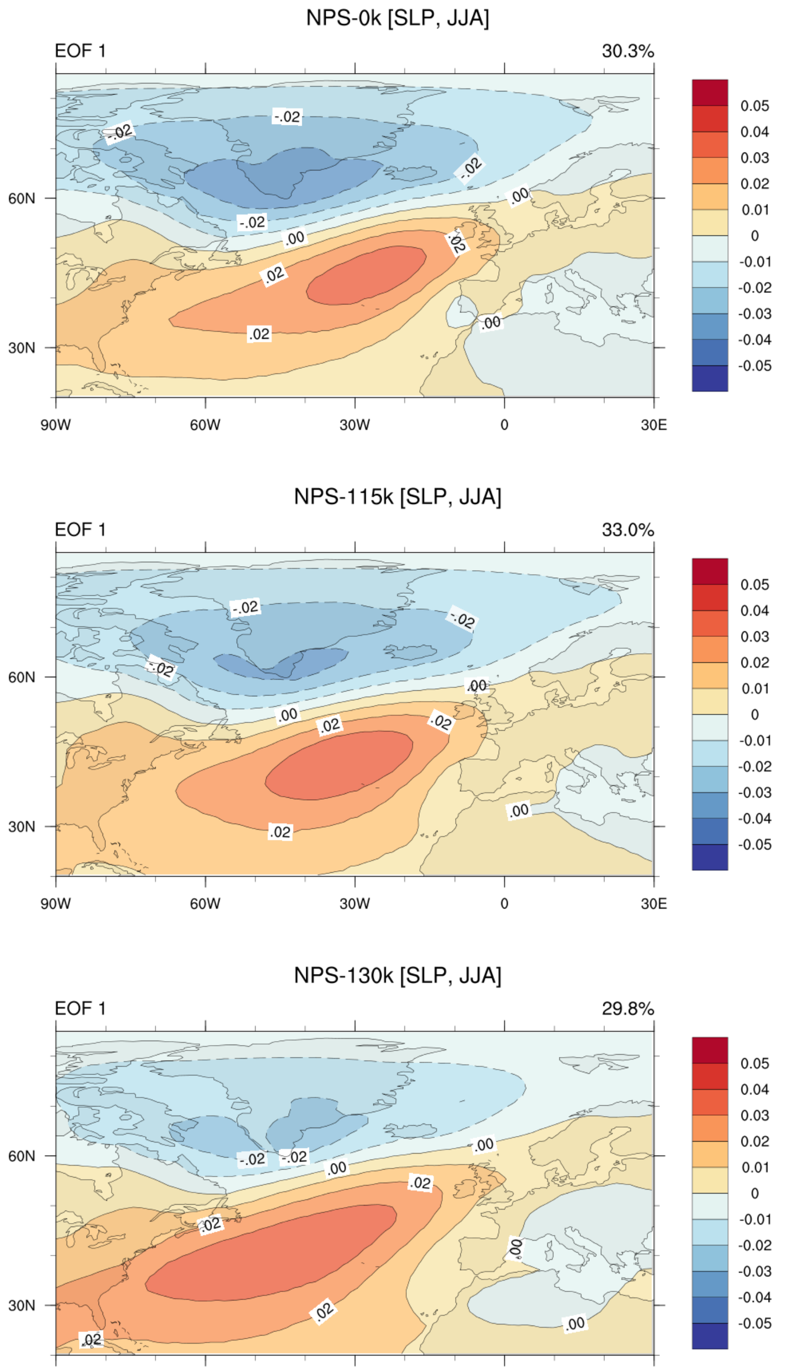

Figure 9: Summertime (JJA) leading EOF of SLP for (top) NPS-0k, (middle) NPS-115k and (bottom) NPS-130k (years 1-280).

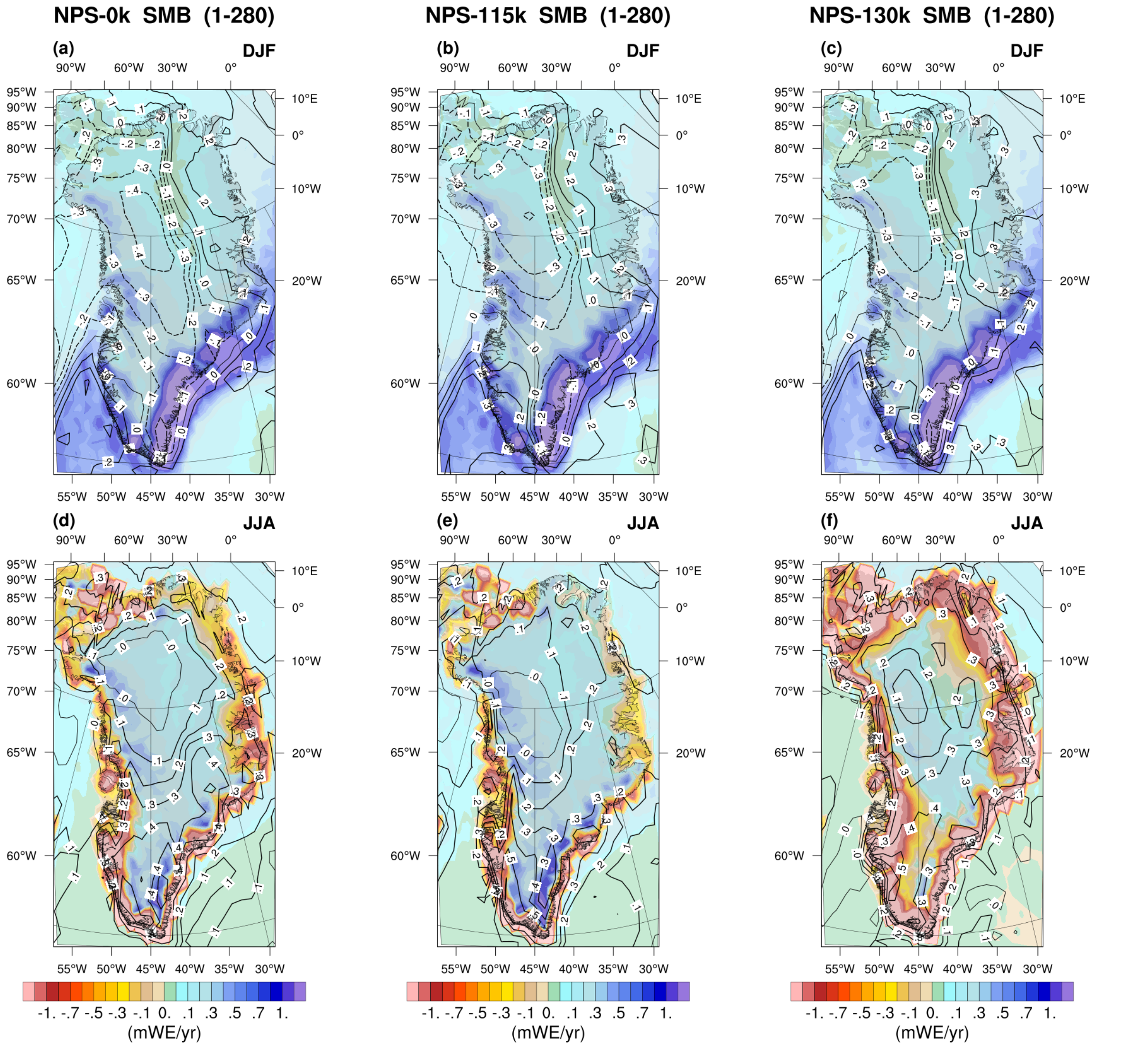

Figure 10: SMB (in m WE/yr) and (superimposed) the correlation between SMB and the NAO index for (left) preindustrial, (middle) 130 ka and (right) 115 ka in (top) winter and (bottom) summer.

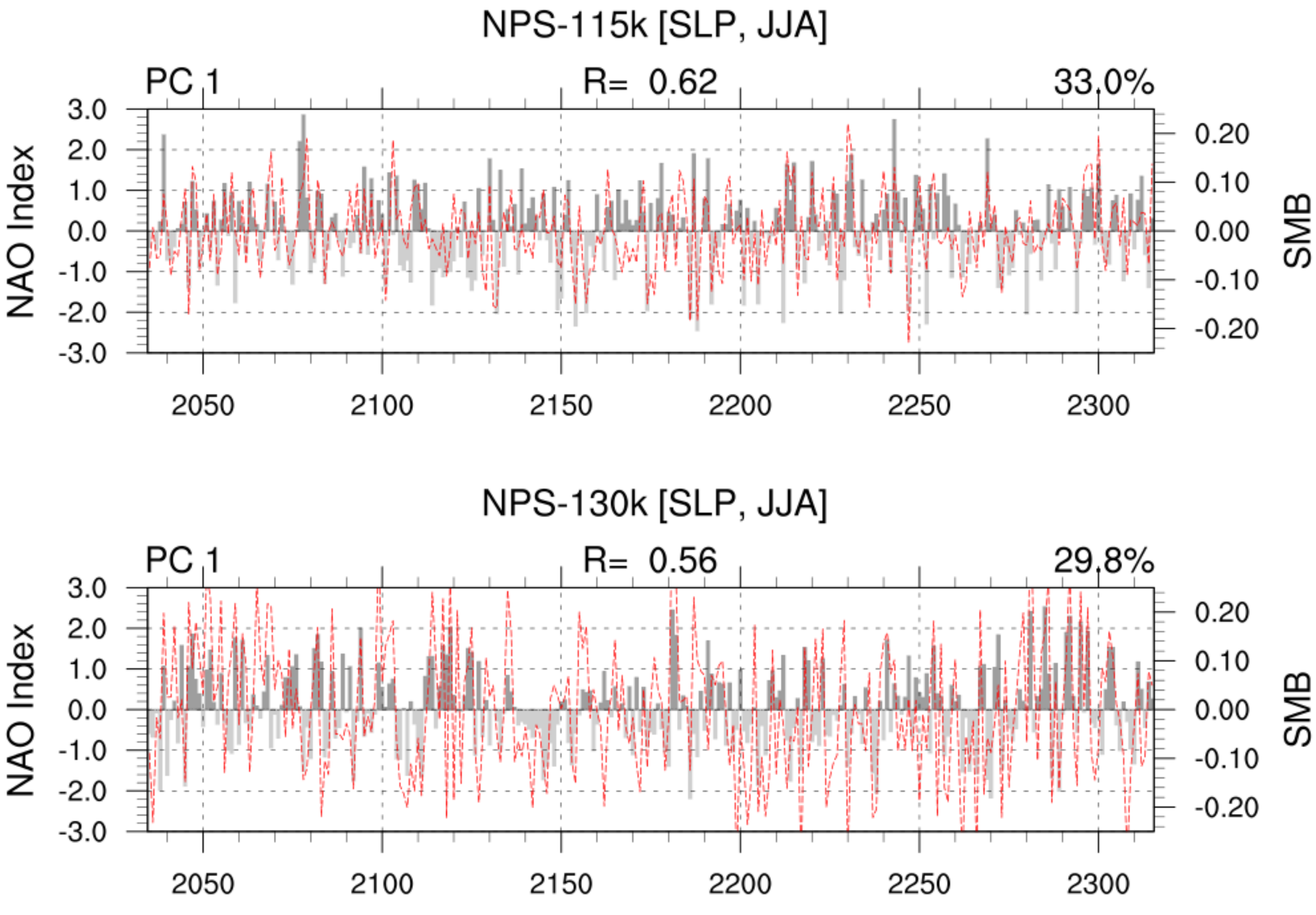

Figure 11: (grey bars) Time series of normalized leading PC derived from an EOF analysis of SLP over the extra-tropical North Atlantic and (dashed lines) average SMB over Greenland in NPS-115k (top) and NPS-130k (bottom) for summer (JJA).

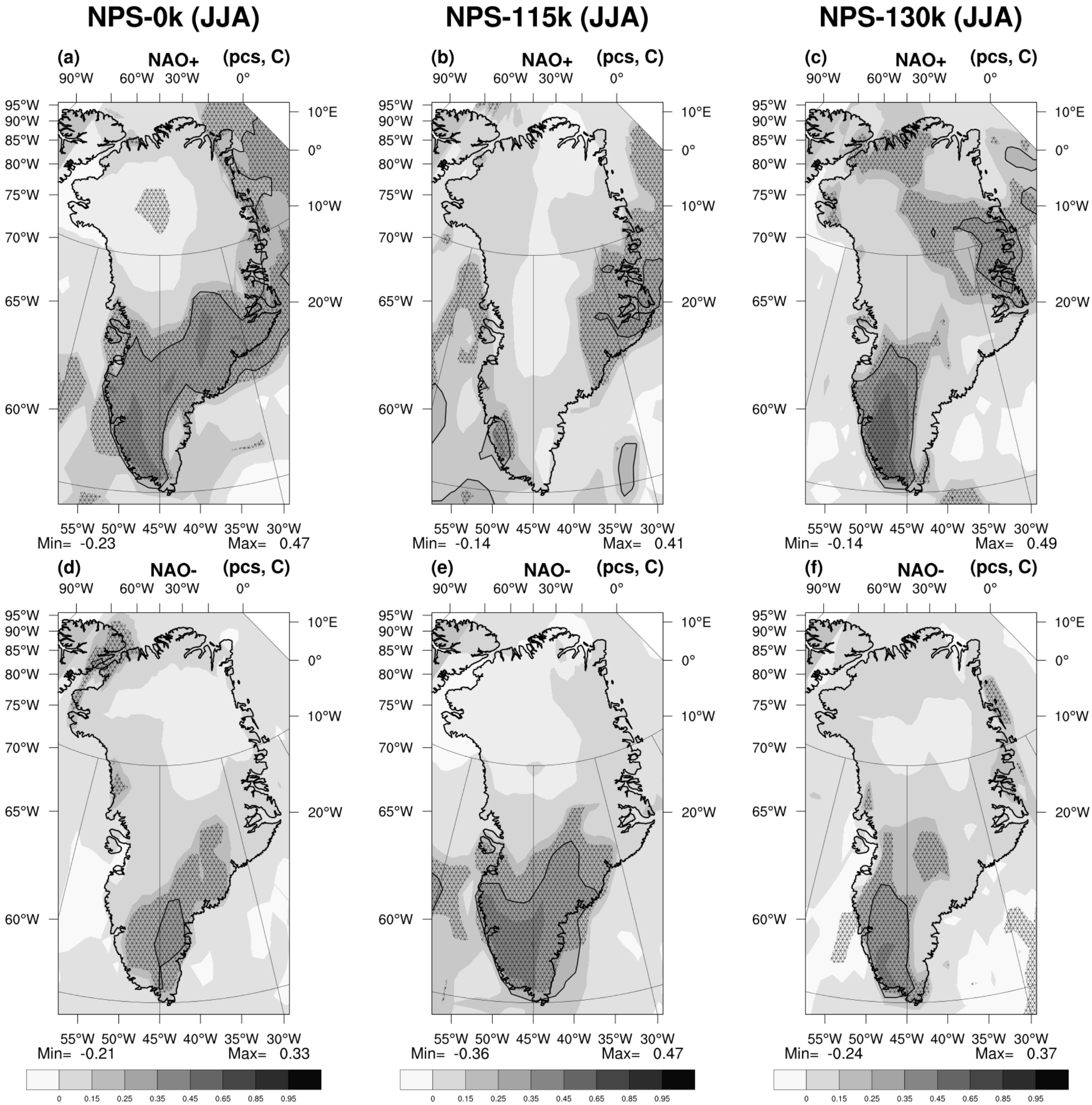

Figure 12: Spatial correlation between accumulation and the NAO index for (left) preindustrial, (middle) 115 ka and (right) 130 ka. Top (bottom) row: positive (negative) NAO situations (sampled for NAO indices with absolute value higher than one stantard deviation). Dotted areas represent correlations significant at the 99% level.

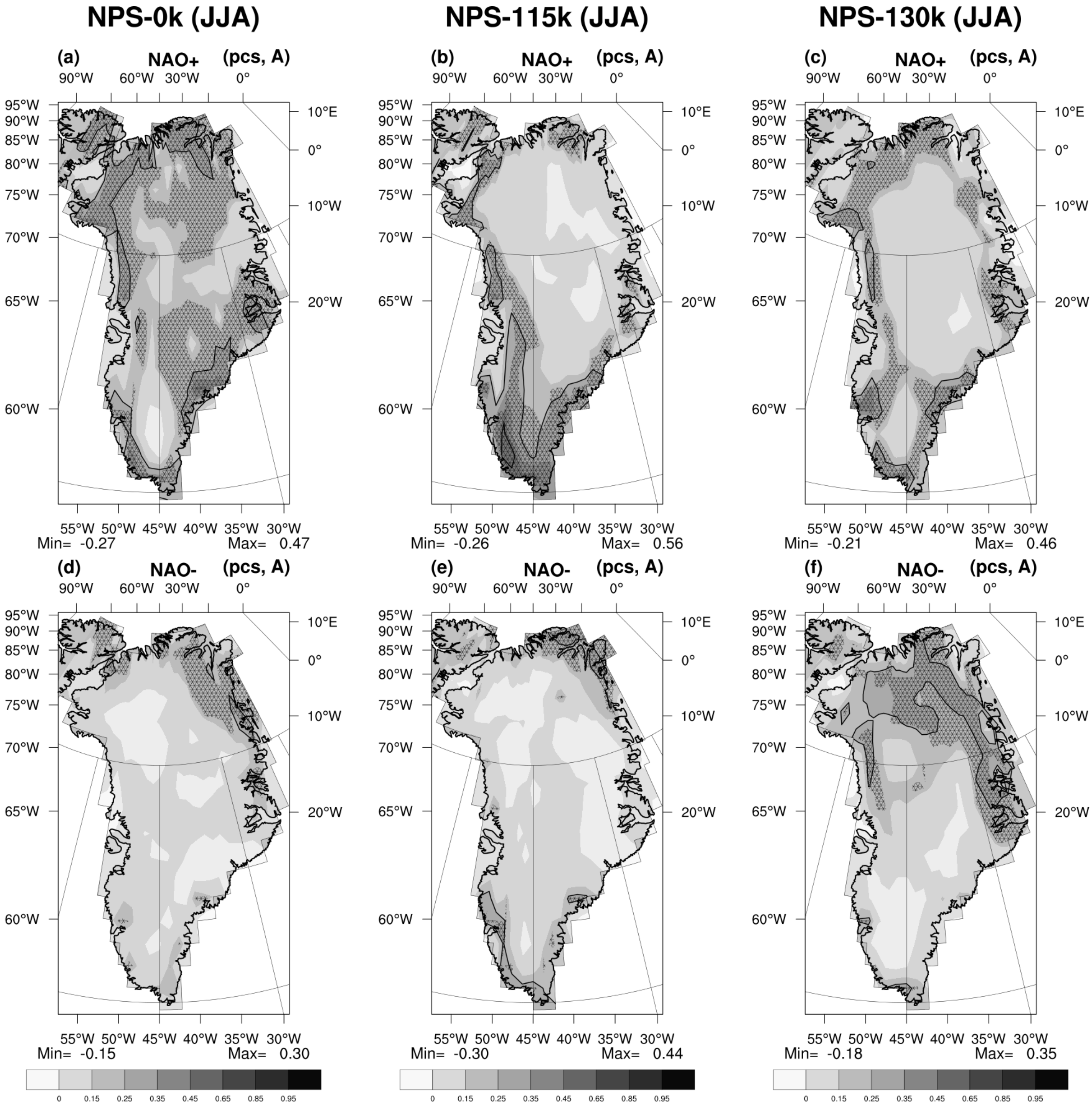

Figure 13: Same as Fig. 12, but for spatial correlation between melting and the NAO index.