Answer to Referee #2

This manuscript by Merz et al. studies the climatic conditions in Greenland during the last interglacial period (the Eemian). The Eemian was a period with slightly higher global temperatures than present, and the GrIS was likely reduced, but to which extent is a subject of debate, as is its contribution to sea level. Orbital forced enhanced summertime solar radiation is the main driver of warmer conditions and resulted in a retreat of the GrIS, but feedbacks in this system are likely of large importance. Moreover, paleoclimatic reconstructions based on ice cores from Greenland give information on local climate conditions. However, these records are strongly affected by, for example, changes in local topography. Therefore, interpretation of these records can benefit from an improved understanding of feedbacks within the ice sheet – climate system. The manuscript describes a set of climate model simulations in which different topographies of the GrIS are used. In this way, the influence of a reduced GrIS topography on the interglacial climate is assessed. This work shows that the surface air temperature is strongly affected by changes in the local surface elevation, even when a first order correction using lapse rates is applied. Changes in the local energy balance are most important: in winter, the sensible heat flux is strongly increased due to changes in the slope, through the strength of the katabatic wind, while in summer the largest influence is exerted by changes in the albedo. This work is a valuable contribution in this subject. Nevertheless, I have three major issues that need more attention.

We kindly thank the referee for the very careful review and the constructive feedback which stimulated further valuable discussion of the results. The comments have all been addressed and answered below.

Major points:

1) My main point of concern is that, in my opinion, the followed approach results in an overestimation of Eemian surface air temperatures in Greenland. It is a misconception that Eemian optimum climate conditions coincide with the minimal ice sheet extent. During peak warming, ice sheet mass balance is minimal (strongly negative), and hence ice sheet retreating rate is large. The minimum ice sheet extent is a consequence of that, but occurs later, when changing climate conditions (cooling) lead to a positive mass balance, and thus a reversal from a retreating to an advancing ice sheet. The time between the maximum retreat rate an minimum extent is at least several millennia, assuming that summertime NH insolation is the dominant forcing for GrIS mass balance. The goal of this study is to reconstruct surface air temperature (SAT) during Eemian optimum conditions. However, four different ice sheet topographies are used that are reconstructions of minimum Eemian GrIS extent:

- EEMr1 minimum extent at 123.3 ky BP (Robinson et al., 2011)
- EEMr2 and EEMr3 minimum extent at 121.1 ky BP (Robinson et al., 2011)
- The timing of the EEMr4 minimum extent is not given in Born and Nisancioglu (2012), but as their result is obtained after a constant Eemian forcing over 6000 yr, this geometry has also most likely not been reached at 125 ky BP.

Hence, the topographies used in these sensitivity experiments are all underestimations of GrIS surface elevation during Eemian optimum conditions (125 ky BP). With this in mind, results on the influence of topography on SAT are still valuable as sensitivity experiments, but statements on absolute values of Eemian maximum SAT do not hold. Perhaps the results from experiment EEMr1 as the closest approximation to the GrIS configuration at time of maximum insolation, and as such Eemian optimum climate reconstructions can only be taken representative from experiment EEMr1.

We thank the review for taking up this point (i.e. the time lag between Eemian optimum temperatures and minimum GrIS extent), which is certainly of importance for the discussion of the results. We are aware of the fact that the GrIS needed several millennia for a substantial retreat. However, the Eemian optimum with respect to insolation already occurred much earlier than 125ka (see Fig. 1 in Cape, 2006) with 65°N summer peak insolation between 132ka and 126ka. As a consequence, NH polar summer temperatures likely peaked quite early (~127ka) whereas in winter the slight warming during the Eemian went on until ~121ka (Bakker et al., 2013). Hence, defining the timing of the Eemian optimum climate is not straightforward. The timing of the minimum in GrIS extent is quite uncertain, too. According to Kopp et al., 2009, a first maximum NH ice-sheet loss occurs around 125ka (Fig. 4 in their manuscript). However no statements could be made about the detailed contribution of the GrIS. On the other hand it is true that Robinson's GrIS topographies are reached around 123ka and 121ka, respectively. However, there are also several shortcomings in ice sheet models (e.g., the very simplified representation of the atmosphere) that complicate the timing of the minimum Eemian GrIS.

Taking into account these findings and uncertainties we still think our choice of setting the sensitivity simulations within 125ka climate conditions can be regarded as reasonable. Furthermore, the key process of warming associated with increased sensible heat flux (dominant during the winter season) would very likely be similar at later stages during the Eemian as it is independent of the amount of insolation (NH polar winters are anyway exempt of any insolation anomalies).

Nevertheless, we completely agree that the Greenland warming associated with the changes in the GrIS topography is an effect which occurs during later stages of the Eemian and cannot explain early peaks in Greenland temperatures. We, thus, include the following sentence to address this timing issue in the manuscript and to emphasize that GrIS topography related temperature anomalies are rather relevant for later stages during the Eemian.

Within revised Section 6.3 (Implications for Greenland temperature reconstructions)
“Besides, the warming associated with a reduction in the GrIS is likely an effect which occurs during later stages of the Eemian as a substantial ice sheet retreat requires several millennia of interglacial climate conditions (i.e., strong insolation forcing). Thus, the presented sensitivity effect cannot explain early peaks in Greenland temperature during the Eemian.”

As extensively discussed in the answer of 2) we further have weakened the arguments regarding the interpretation of absolute Eemian temperatures. Specifically, we omit the comparison with the NEEM δ^{18}O record but rather use the δ^{15}N temperature estimate instead. In contrast, to the 8°C Eemian warming based on δ^{18}O, which is representative for the condensation temperature, the δ^{15}N records provides information about the Eemian firn temperatures. The Eemian δ^{15}N temperature estimate of 5°C is averaged over 128.5-114 ka and indicates the Eemian warming in the long-term rather than showing a early peak as the δ^{18}O record does. Hence, the comparison of our simulations with δ^{15}N should be reasonable.

2) The comparison with the Greenland temperature reconstructions (section 6.3) also suffers from the above-mentioned issue, which needs revision. Apart from that, temperatures reconstructed from ice cores are essentially a measure for condensation temperature, due to the isotopic fractionation process occurring along the moisture pathway. Isotope records are nevertheless often corrected for that using lapse rate considerations, to translate the isotopic signal to a SAT record. This study shows that the modified GrIS geometry has an imprint on SAT (warming), due to a larger sensible heat flux from a strengthening of the katabatic wind. Although this is a very likely mechanism, this argument cannot be used to (partly) explain the isotope-derived temperature (+8K), as any warming of the surface as a result of an enhanced SHF induced by strengthening of the katabatic wind would not show up in an isotope-derived SAT record. Hence, the disagreement between SAT from this study and the NEEM SAT remains even larger, and as such this section needs to be revised.

This is again a very attentive and valid point. We fully agree with the referee that the process involving surface wind and sensible heat flux, unlikely shows up in the δ^{18}O record as the processes in the (stable) boundary layer do not translate in a corresponding condensation temperature signal. We clarify this point in the manuscript and compare the simulated SAT warming rather with the δ^{15}N estimate (5°C Eemian warming) which is a proxy for the firn temperature and thus related to changes in annual mean SAT.

Several paragraphs of Section 6.3 (“Implications for Greenland temperature reconstructions) and Section 7 (Summary and conclusions) have been revised in order to efface the invalid comparison of our SAT results with the (8°C) NEEM δ^{18}O warming.

P6711, L1
“The simulated pNEEM warming is compared to the Eemian δ^{15}N signal from the NEEM ice core which indicates that the annual mean Eemian firn temperatures between 128.5-114 ka were on average 5°C warmer than present (NEEM community members, 2013, supplementary material). Hence, neither of the simulations can reproduce the full magnitude of the Eemian warming observed in the NEEM core (Fig. 11c). Besides, the warming associated with a reduction in the GrIS is likely an effect which occurs during later stages of the Eemian as a substantial ice sheet retreat requires several millennia of interglacial climate conditions (i.e., strong insolation forcing). Thus, the presented sensitivity effect cannot explain early peaks in Greenland temperatures during the Eemian, such as the 8 ± 4°C warming at 126 ka suggested by the NEEM δ^{18}O record. Moreover, one has to keep in mind that δ^{18}O is a measure for condensation temperature determined by the isotopic fractionation process occurring along the moisture pathway. Hence, the presented winter mechanism comprising wind and energy flux processes in the stable boundary layer is unlikely recorded by δ^{18}O. Consequently, the remarkable δ^{18}O peak found at NEEM needs to be explained by other processes.”

P6713, L7 (Revised conclusions)
"The results of this study further are relevant for the interpretation of Eemian climate reconstructions based on Greenland proxy archives such as the NEEM ice core. Changing the GrIS topography acts as a local forcing for Greenland's climate, whereas the effect on the climate outside of Greenland is small and mostly negligible. Concerning the Eemian temperature at pNEEM we find that a smaller GrIS can account for up to 3.2°C of the Eemian-PI warming. In view of the local nature of the climate effect in our model, the strong Eemian warming found in NEEM ice (NEEM community members, 2013) has at least partly to be regarded as a local effect rather than interpreting the full magnitude as a large-scale climate signal.

The simulated temperature response to changes in the GrIS topography shows particularly local characteristics during the winter season, when the shape of the GrIS determines which areas are (relatively) warmed by the SHF in the katabatic wind zones in contrast to areas which experience little turbulence and, thus, a strong cooling. However, these results strongly depend on processes within the stable boundary layer, and there is some uncertainty concerning the amplitude of these SAT anomalies as they are sensitive to the details of the boundary layer formulation (Holtslag et al., 2013). In contrast, the Eemian temperature anomalies during the summer months are mostly independent of boundary layer processes. In all simulations, we find a widespread (lapse rate corrected) summer warming of 4-5°C over Greenland being in agreement with proxy estimates (CAPE Last Interglacial Project Members, 2006) and conforming with observed melt layers in the NEEM ice core (NEEM community members, 2013). Thereby, enhanced summer insolation due to the Eemian orbital parameters is the primary forcing independent of the implemented GrIS. However, the GrIS extent determines which areas become ice-free, thus, encountering intensified warming through the albedo feedback. However, the resulting temperature change is likely underestimated, as the CCSM4 model simulates too low summer albedo values above Greenland's snow and ice surfaces assuming a present-day GrIS (Vizcaino et al., 2013). Consequently, the potential albedo change through surface melt is diminished by this model bias (e.g., simulated albedo change of 0.03 instead of a more likely increase of 0.15). Nevertheless, our results show that the spatial pattern of Eemian warming over Greenland has likely been very diverse and in order to gain a complete understanding of Greenland's Eemian climate additional climate reconstructions are needed.

Although, this sensitivity study includes some scenarios with a strongly melted GrIS, none of the simulations can fully explain for the observed Eemian warming reconstructed from the NEEM ice core. Moreover, to experience the strongest warming at pNEEM associated with this process (i.e. the maximum SAT response to a reduction in GrIS volume), the pNEEM site needs to be located in the slope area as depicted in Fig. 9, enhancing the winter mechanism in our model. This corresponds to our EEMr2/EEMr3 experiment or a scenario where pNEEM is located even closer to the ice sheet margin, suggesting a much smaller GrIS and a much lower altitude of the pNEEM site contrary to the reconstruction by NEEM community members (2013). Clearly, more detailed ice sheet modeling studies and improved reconstructions of the altitude changes at pNEEM are required to solve this contradiction. Moreover, other processes such as a reduced NH sea ice cover or increased meridional heat transport by ocean currents are needed to fully explain the substantially stronger thermal response observed in the Arctic relative to the NH lower latitudes during the Eemian interglacial."

3) Greenland ice sheet surface air temperature changes are for a major part determined by the local surface energy balance, as also shown in this study. Therefore, it is of large importance that the climate model is able to realistically describe this surface energy balance over the GrIS. Not much information is given on the performance of the coupled atmosphere – land model scheme, merely references to Neale et al (2013), Evans et al (2013), and Merz et al (2013) where I did not find information on the performance of the surface energy balance scheme over ice sheets.
How reliable are the results obtained over GrIS?
How well does the present-day run represent the observed SAT distribution over Greenland?
As the katabatic wind is an important driver of the sensible heat flux, how well does this model represent the katabatic wind pattern, considering the limited resolution (100x50km)?
Have there been comparisons carried out with present-day measurements of the energy balance components?
As the summertime net solar radiation is a large component of the surface energy balance, the albedo parameterization strongly influences the results. More info on the albedo scheme is needed, e.g. aging effects; does the albedo depend on grain size/snow density/water content? The albedo values in Figure 9f (maximum 0.68) seem far too low for a realistic snow surface (albedo of 0.8-0.9).
What is the design of the snow scheme in CLM4? Multiple layers? Is there a transition from snow to ice? What happens with melt water? Does it run-off immediately of can it refreeze in the firn?
I suggest adding a section on this subject, for example in section 2 and section 5, add information on surface heat fluxes in the PI simulation (before dealing with the EEMpd run).

We agree with the referee that the model validation with respect to its performance of Greenland's surface climate was rather scarce and should be extended. Fortunately, a recent study (Vizcaino et al., 2013) analyzes the the fully-coupled CCSM4 with 0.9˚ x 1.25˚ horizontal resolution (called CESM therein) concerning its representation of Greenland's surface climate. This is done for present-day climate by a comparison with a corresponding simulation of the regional model RACMO2 (Ettema et al., 2010), which itself has been evaluated against in situ observations (Ettema et al., 2010a, van den Broeke et al., 2009). The model evaluation by Vizcaino et al. (2013) covers the Greenland surface energy balance and the resulting surface temperatures thus being of great value for this study.

Consequently, we make use of this valuable reference and add a paragraph within the model description (Section 2) which discusses the performance of the CCSM4 with respect to Greenland's surface climate.

P6688, L11
“A general model validation of the CCSM4 atmosphere-land-only setup is presented in (Evans et al., 2013), denoted as CAM-FV simulation therein. An evaluation of the atmosphere component (CAM4) is further provided in Neale et al. (2013). The fully-coupled CCSM4 with 0.9°x1.25° horizontal resolution (called CESM therein) has been specifically validated against the regional model RACMO2 (Ettema et al., 2010) concerning its representation of Greenland's climate (Vizcaino et al., 2013). It is shown that CCSM4 reasonably simulates surface air temperatures (SAT) as well as the components of the surface energy balance over Greenland. As Vizcaino et al. (2013) mainly focused on summer heat fluxes we repeated the model validation for the winter season also using RACMO2 (Ettema et al., 2010) as reference. Thereby we could confirm that CCSM4 represents well the components of the Greenland climate system that are of importance for this study, namely SAT, surface winds and the surface energy fluxes (not shown).”

The individual parts of your question are answered in detail below:

How reliable are the results obtained over GrIS?
How well does the present-day run represent the observed SAT distribution over Greenland?

As mentioned above, the CCSM4 is expected to produce reliable results regarding the Greenland climate as it compares well with the regional model RACMO2 for present-day climate conditions (Vizcaino et al., 2013). The spatial SAT pattern of CCSM4 matches the RACMO2 equivalent during both, the winter and summer season (see Fig. 2 in Vizcaino et al., 2013). The main differences are found over the North Dome and in interior northern Greenland where CCSM4 simulates higher SAT very likely due to smoothed topography.

As the katabatic wind is an important driver of the sensible heat flux, how well does this model represent the katabatic wind pattern, considering the limited resolution (100x50km)?

As shown in Fig. B1, the DJF and JJA surface winds as well as the annual wind directional constancy (which is a established measure for the katabatic winds (Bromwich, 1989)) show good agreement between CCSM4 and RACMO2, particularly over the ice sheet areas. Larger differences are observed over the ocean and in coastal areas where the CCSM4 model resolution is too coarse to resolve the complex topography and hence the winds are rather too strong as the surface is too smooth. However, all in all we have good confidence in the simulated winds over the GrIS itself. Note that the CCSM4 winds are generally stronger than the RACMO2 winds. This can be explained by the fact that RACMO2 provides 10 m surface winds whereas for CCSM4 we declare the winds on the lowest model level (approx. at 60 m height) as surface winds as the 10 m wind field is not an available output variable of CCSM4. Consequently, the CCSM4 surface winds are likely stronger as they are less affected by surface friction.

Have there been comparisons carried out with present-day measurements of the energy balance components?

Unfortunately, the number of surface energy flux measurements on the GrIS is very limited. For the validation of RACMO2 (Ettema et al., 2010a) four years of measurements of three station data has been used (van den Broeke et al., 2009). Moreover these three measurement stations are all located close to each other in the ablation zone of the western GrIS (van den Broeke et al., 2009). Hence the observations do not cover different areas of the GrIS. Nevertheless, the energy flux measurements (van den Broeke et al., 2009) and van den Broeke et al., 2005) show that the modeled seasonal cycle of surface energy fluxes (as shown for EEMpd in Fig. 8 in the manuscript) are reasonable. Moreover, energy flux measurements on Antarctica also confirm that sensible heat flux is most effective in the katabatic wind zones (van den Broeke et al., 2005), whereas it is considerably lower on plateau areas of the ice sheet. This increases our confidence that the simulated results regarding co-occurring changes in surface wind speed and sensible heat flux are valuable.

As the summertime net solar radiation is a large component of the surface energy balance, the albedo parameterization strongly influences the results. More info on the albedo scheme is needed, e.g. aging effects; does the albedo depend on grain size/snow density/water content? The albedo values in Figure 9f (maximum 0.68) seem far too low for a realistic snow surface (albedo of 0.8-0.9).

It is indeed the case that CCSM4 underestimates the summer albedo over snow and ice surfaces over large areas of the GrIS. This model bias has also been discussed by Vizcaino et al. (2013) who explain the discrepancy (compared to RACMO2) with too warm snow temperatures affecting the snow grain size. In addition, they state that CCSM4 simulates rainfall events in the interior of the ice sheet during summer which is rather unrealistic because of the low atmospheric temperatures there.

We add the following sentences to depict this model bias and the associated uncertainties for our results.

Within revised conclusions:
"Albedo-related warming is also simulated over glaciated areas (e.g., at pNEEM) that experience surface melting. However, the resulting temperature change is likely underestimated as the CCSM4 model simulates too low summer albedo values above Greenland's snow and ice surfaces assuming a present-day GrIS (Vizcaino et al., 2013). Consequently, the potential albedo change through melt water is diminished by this model bias (e.g., simulated albedo change of 0.03 instead of a more likely increase of 0.15)."

Detailed informations regarding the snow albedo scheme included in CLM4 are given in the model description by Oleson et al. (2010): Snow albedo and solar absorption are simulated within each snow layer using the Snow, Ice, and Aerosol Radiative Model (SNICAR) incorporating the two-stream radiative transfer solution by Toon et al. (1989). Albedo and vertical absorption profiles depend on various factors as the solar zenith angle, albedo of the substrate underlying snow, ice effective grain size and aerosol concentrations. The ice effective grain size is simulated with a snow aging routine (see Section 3.2.3 in Oleson et al. (2010) for further details on the snow aging routine).

What is the design of the snow scheme in CLM4? Multiple layers? Is there a transition from snow to ice? What happens with melt water? Does it run-off immediately of can it refreeze in the firn?

The technical description of the surface processes incorporated in the snow scheme is given in the CLM4 description paper by Oleson et al. (2010). The CLM4 snow scheme consists of five layers and a number of processes are included in the snow aging routine which affect the snow grain size. Thus, the net change in effective grain size occurring each time step is represented in each snow layer as a summation of changes caused by dry snow metamorphism, liquid water-induced metamorphism, refreezing of liquid water, and addition of freshly-fallen snow (Oleson et al., 2010). The model also simulates the ice and water content of the snow pack incorporating processes which cause phase-changes.

We have added a respective paragraph in the model description (Section 2), which provides additional information on the model's representation of the atmospheric boundary layer and snow-related processes.

P6688,L11:
"As this study focuses on Greenland's surface climate, processes occurring within the atmospheric boundary layer and concerning the (partially) snow-covered land surface are of importance. For the former, the atmospheric model (CAM4) uses the non-local atmospheric boundary layer parameterization by Holtslag and Boville (1993). A detailed description is given in Neale et al. (2010). The land model (CLM4) accounts for changes in surface characteristics emerging from snow-related processes. The corresponding snow scheme (Oleson et al., 2010) incorporates various processes such as snow aging through dry snow metamorphism, liquid water-induced metamorphism and refreezing of liquid water. The resulting changes in the ice effective grain size have important implications for the surface albedo (Oleson et al., 2010)."

Minor comments:

a) Abstract: Not clear what kind of climate model simulations are used to arrive at these conclusions

We have revised the first sentence of the abstract to clarify this issue.

P6684,L2: "The influence of a reduced Greenland ice sheet (GrIS) on Greenland's surface climate during the Eemian interglacial is studied using a set of simulations with different GrIS realizations performed with a comprehensive climate model."

b) Introduction P 6686, L9: The term “GrIS sensitivity” is poorly defined. Is it the sensitivity of the climate to a change in the topography of the Greenland ice sheet? Suggestion: use “sensitivity to GrIS topography”?

We have replaced the somewhat awkward term “GrIS sensitivity” with the suggested “sensitivity to GrIS topography” and further added a sentence in the introduction:

P6686, L9: “This response of the climate system to a change in the GrIS topography will be referred to as “sensitivity to GrIS topography" throughout this paper.”

c) Section 2.3 It would be interesting to compare these results (EEMpd) with the findings of Van de Berg et al 2011 (Nature Geosc.).

We appreciate the important findings by Van de Berg et al., 2011, however, we do not think that a respective reference would fit and improve Section 2.3. The results of Van de Berg et al., 2011 clearly focus on Greenland's surface mass balance which is not addressed here. Their description of the Eemian NH climate focuses on temperature and geopotential height at 500 hPa (Fig. 1B in their manuscript). As we do not discuss these two fields in our simulations, a comparison would be somewhat far-fetched.

d) The large variability in temperature (Fig. 1) is noteworthy; perhaps this can be put in perspective to Eemian proxy temperatures (CAPE Last Interglacial Project Members, 2006, Quat. Sci. Rev. 25, 1383-1400).

A respective sentence has been included in Section 2.3.

P6690, L10
“The distinct spatial variability in Eemian summer warming across the NH agrees with temperature reconstructions [Cape, 2006].”

e) Section 4.1 P6697,L2-4: A forcing due to a horizontal gradient in temperature deficit is a thermal wind forcing: make a distinction between the katabatic forcing and the thermal wind.

done

P6697,L2
“This air flow of cold air masses descending from the high elevated ice sheet are also known as katabatic winds. The katabatic force which is responsible for these downslope winds is driven by gravity. In addition, these winds are strengthened by the pressure gradient between the very cold ice dome and the relatively warmer regions located at the ice sheet margins, i.e. a thermal wind forcing.”

f) Section 5 To me it seems strange to average 3x3 grid points, especially when these include glaciated and non-glaciated points. Why not only show the nearest grid point?

From our experience, interpretation of single grid cells can be problematic and we, thus, prefer to average across a multiple grid cells to get a robust result. On the other hand, we understand the argument that it might be problematic to average across grid cells with different surface characteristics.
In this case, the heat fluxes at the nearest grid point to CC and pNEEM, respectively show almost identical heat fluxes as the 3x3 grid point averages shown in the manuscript. Furthermore, the pNEEM location is not known with certainty as it is just the best guess according to an ice-flow model (Huybrechts et al., 2007). Hence taking the average of 3x3 grid points, also somewhat accounts for this uncertainty in the exact position of the Eemian ice found in the NEEM core.

g) Section 6.2 P6709, L20-21: Figure 9f does not clearly show a decreased albedo for EEMr2 for pNEEM.

The slight albedo decrease is indeed hard to see in Figure 9f, so we rather give the numbers in the text.

P6709, L20
This surface melting process results in a slight decrease in local albedo, e.g., at pNEEM from 0.68 (EEMpd) to 0.65 (EEMr2) leading to in higher SW absorption as shown in Fig. 8.

h) Section 6.3 P6712, L4-7: This statement is not really supported. It seems not likely that surface wind have a great impact on moisture source pathways. Moreover, this should also ...

Unfortunately, part of your comment is missing. However, we agree with your point that the change in surface winds unlikely have a great impact on the moisture source pathways. It is rather the fact that pNEEM's relative locality (close to vs. far from ice sheet margin) and exposition (close to northwestern margin as in EEMr2/EEMr3 vs. closer to northeastern margin as in EEMr4) varies among the different sensitivity experiments. Hence though the large-scale atmospheric flow is found to be stable, the pNEEM location might be exposed to different moisture transport routes (as it will be investigated in a subsequent paper). However, as the according statement in the former manuscript seems to lead to misunderstandings, we have removed the corresponding sentence (P6712, L4-7)

I) Generally, the abbreviation for sensible heat flux is SHF, instead of SHFLX (and likewise for LHF).

This has been adapted in the manuscript including all figures.

Figures:

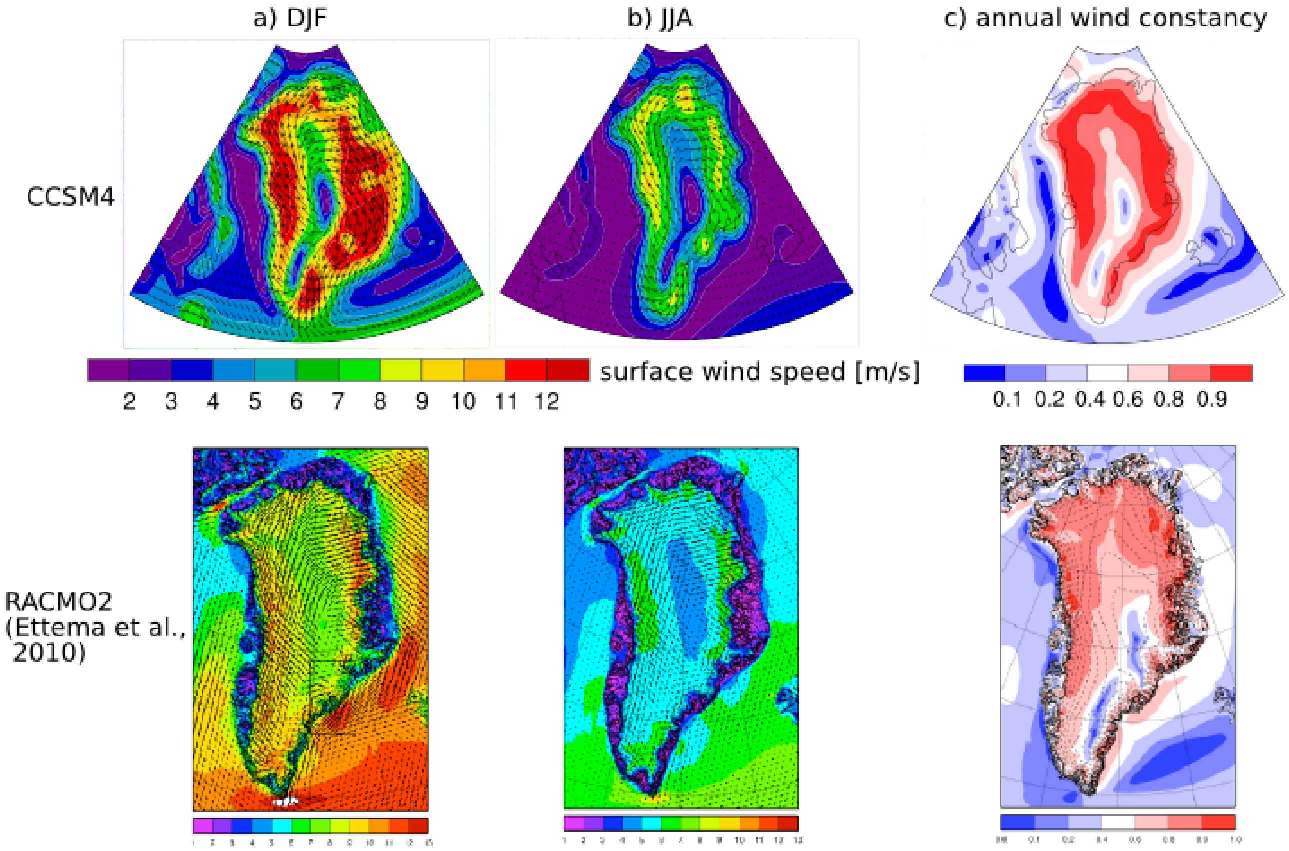

Fig. B1: Representation of surface winds [m/s] for CCSM4 (PI simulation) and the RACMO2 presented in Ettema et al., 2010: a) DJF mean winds, b) JJA mean winds and c) annual wind directional constancy. Note that the same levels are used for the color bars.

References:

Bakker, P., Stone, E. J., Charbit, S., Gröger, M., Krebs-Kanzow, U., Ritz, S. P., Varma, V., Khon, V., Lunt, D. J., Mikolajewicz, U., Prange, M., Renssen, H., Schneider & Schulz, M. Last interglacial temperature evolution-a model inter-comparison. *Climate of the Past*, *9*(2), 2013

Bromwich, D.H. An extraordinary katabatic wind regime at Terra Nova Bay, Antarctica. *Monthly Weather Review*, 117(3), 688-695. 1989

Huybrechts, P., Rybak, O., Pattyn, F., Ruth, U. & Steinhage, D. Ice thinning,upstream advection, and non-climatic biases for the upper 89%of the EDML ice core froma nested model of the Antarctic ice sheet. *Climate of the Past, 3*, 577–589, 2007.

Ettema, J., Van den Broeke, M. R., Meijgaard, E. V., Van de Berg, W. J., Box, J. E., & K. Steffen, Climate of the Greenland ice sheet using a high-resolution climate model–Part 1: Evaluation. *The Cryosphere*, *4*(4), 511-527, 2010a

Ettema, J., van den Broeke, M. R., van Meijgaard, E., and van de Berg, W. J.: Climate of the Greenland ice sheet using a high-resolution climate model – Part 2: Near-surface climate and energy balance, *The Cryosphere*, 4, 529–544, 2010.

Toon, O.B., McKay, C.P., Ackerman, T.P., and Santhanam, K. Rapid calculation of radiative heating rates and photodissociation rates in inhomogeneous multiple scattering atmospheres. J. Geophys. Res. 94, 1989

van den Broeke, M., Smeets, P., & Ettema, J. Surface layer climate and turbulent exchange in the ablation zone of the west Greenland ice sheet. *International Journal of Climatology*, *29*(15), 2309-2323, 2009

Vizcaino, M., Lipscomb, W. H., Sacks, W. J., van Angelen, J. H., Wouters, B., and van den Broeke, M. R.: Greenland Surface Mass Balance as Simulated by the Community Earth System Model. Part I: Model Evaluation and 1850-2005 Results, *Journal of Climate*, 26, 7793–7812, 2013.