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Interactive Comment

Interactive comment on "Climate of the Greenland ice sheet using a high-resolution climate model – Part 2: Near-surface climate and energy balance" *by* J. Ettema et al.

J. Ettema et al.

janneke.ettema@gmail.com

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Reply to the reviewers' comments on our manuscript

"Climate of the Greenland ice sheet using a high-resolution climate model – Part 2: Near-surface climate and energy balance"

First of all, we would like to thank Xavier Fettweis and Regine Hock for their constructive and valuable comments, which will certainly improve the manuscript. In this response we address their comments point by point.

Answers to comments of referee 1: X. Fettweis

1. I think it is more relevant here to show and discuss only DJF values and JJA values than annual values of the surface energy fluxes We have added the DJF and JJA plots for the surface energy fluxes as suggested. We decided not to include the DJF and JJA plots for the net solar radiation as this flux is near-zero in winter, so the spatial distribution in summer is very similar to the annual mean. To be able to consider the full SEB in summer, we have changed page 617, line 18-21 into: “Due to the lower albedo, SWnet increases to almost 50 W/m2 along the ice margins on an annual basis and to 125 W/m2 if averaged over the summer (JJA). This implies that more shortwave radiation energy is available for melt. On the adjacent tundra, the annual and summer mean values are even higher ($\sim$70 and 160 W/m2, respectively) due to the low summer albedo ($\alpha \sim$ 0.18) of the snow free tundra surface." For net LW radiation we did include the DJF and JJA fields. In the manuscript, the plots are discussed on page 618, line 21: “As seen in Figure 10, LWnet is rather constant throughout the year, between -60 and -40 W/m2, except for the northeast where in summer values of -65 W/m2 are found due to less LWâĘŞ.” With respect to the added seasonal net radiation plots the following paragraph is added to discuss the DJF and JJA fields page 619, line 18: “In winter, the net radiation is dominated by LWnet in absence of sunlight (Figure 11b). In summer, SWnet exceeds LWnet, especially along the margins where the net radiation flux reaches up to 75 W/m2 (Figure 11c). Only the northern part of the interior is exposed to small negative net radiation fluxes (-6 W/m2), which will be compensated by turbulent heat fluxes." With respect to the SHF the following sentence has been added to page 620, line 24: ”As a result, SHF is largest in winter (Figure 13b) and smallest in summer (Figure 13c).” Regarding LHF, we have only included references to the added plots, as the differences between summer and winter were already discussed in the manuscript. Adding the seasonal plots made adjustment of the contour interval used necessary, so the same legend could be used used for all three plots.

2. A figure showing the weight of each JJA surface flux in the SEB as well as the standard deviation of these fluxes should be very interesting for understanding which fluxes drive the melt events in summer For this paper, we have decided to focus on

explaining the underlying processes of the near-surface meteorological phenomena katabatic winds and temperature deficit, and not on the surface melt although it would be of great interest. As we want to present a summer, winter and annual climatology, the interannual variability of the components goes beyond the scope of this paper. We are planning to write a separate paper on the temporal variability and recent changes in the near-surface climate and SEB over Greenland.

3. Nothing is said about the variability around the climatological mean and extremes (in temperature and wind speed), while this will allow to better evaluate the climatic conditions over the Greenland ice sheet We have decided to focus this paper on the spatial variability of the mean near-surface climate and the surface energy fluxes for a better understanding of two main meteorological phenomena (temperature deficit and the katabatic wind flow). Therefore the extremes and the standard deviation are not included, although they are certainly very interesting. As mentioned above, we intend to write a separate paper on the variability of the near-surface climate, focusing on the recent climate changes over Greenland. In that paper, climatological extremes will be briefly described.

4. Minor remarks The proposed technical corrections have been changed in the text.

a. Abstract, pg 604: some general considerations about SEB miss in the abstract although the discussion about the SEB is more relevant in this paper We have rewritten the abstract to focus it more on the SEB, rather than general statements on the meteorological phenomena. The full abstract now reads: “The spatial variability of near-surface variables and surface energy balance components over the Greenland ice sheet are studied, using output of a regional atmospheric climate model for the period 1958-2008. The near-surface temperature over the ice sheet is affected by surface elevation, latitude, longitude, large-scale and small-scale advection, occurrence of summer melt and mesoscale topographical features. The atmospheric boundary layer is characterized by a strong temperature inversion, due to continuous longwave cooling of the surface. Together with the gently surface slope a persistent katabatic wind system develops. The radiative heat loss is mainly balanced by turbulent sensible heat transport towards the surface. In summer, the surface is near radiative balance, resulting in lower wind speeds. Absorption of shortwave radiation and positive subsurface heat flux due to refreezing melt water are heat sources for surface sublimation and melt. The strongest temperature deficits (> 13°C) are restricted to the northeastern slopes, where the strongest katabatic winds (> 9 m/s) and lowest relative humidity (< 65%) occur. Due to strong large scale winds, clear sky (cloud cover < 0.5) and a concave surface, a continuous supply of cold dry air is generated, which enhances the katabatic forcing and suppresses subsidence of the potentially warmer free atmosphere air."

b. Eq. 4., pg 608: what is the altitude 0 in $\theta 0$? What is the altitude of the free troposphere? We have added the following sentences to page 608, line 24, direct after the equation: "where $\theta 0(0)$ is the background potential temperature at the surface, determined from layers in the free atmosphere situated between about 425 and 570 hPa."

c. Sect 3.1, pg 610-611 The standard deviation of the annual and daily Z500 from RACMO2 should be compared with the one from re-analyses in additional plots as the variability of Z500 drives the daily near surface climate and interannual variability over the GrIS The focus of this paper is on the long-term averaged near-surface fields, not on the variability, although it is certainly a very interesting topic. We intend to write a separate paper on the variability of the near-surface climate, in which this suggestion will be considered. As the underlying ECMWF model for ERA-40 has the same physical parameterizations as RACMO, except for the surface model, the modeled 500 hPa from RACM2/GR does not differ much from ERA-40. Evaluation of the ERA-40 dataset for Greenland is already discussed in other publications. Therefore we decided not to include this suggestion in the manuscript.

d. Pg 611, line 24: A part of the difference in wind speed between the tundra and neighboring ice sheet pixels could be due to differences between surface schemes used over the ice sheet and tundra. Could the authors confirm this? In winter, the surface roughness lengths for momentum for tundra and ice sheet surface are the same, both 1 mm. The difference in wind speed can be explained by the strength of the temperature inversion and the disintegration of the katabatic wind system over the inhomogeneous tundra surface. Moreover, over the tundra, cold stagnant air builds up in all months apart from summer, inhibiting exchange with the free atmosphere.

e. Sec 3.2, pg 612-613: Perhaps less vectors and larger arrows should be more readable. For now we did not change the plots with the wind vectors, because reducing the plotted wind vectors in figure 2 by a factor 2.5, so one every 10 points, would not give an accurate representation of the wind climate close to the ice margins. With figure 3b, we not only wanted to show the barrier wind feature, but also the large amount of detail gained by running RACMO2/GR at 11 km. If the wind direction appears to be poorly readable in the final proof of the paper before publishing, we will consider reducing the number of wind vectors for figure 2 and choosing a smaller domain for figure 3b

f. Sec 3.2: a plot showing the maximum (DJF and JJA) 10 m wind speed should be interesting here to evaluate the extremes of the Greenland climate. We deliberately choose to present only seasonal and annual mean wind vectors. To interpret the extremes of the ice sheet climate accurately, a presentation of the temporal variability of these variables would be required. Including both would make this manuscript too lengthy and less focused.

g. Pg 614, lines 8-14: a plot showing the variability of T2m is needed here. In addition a plot showing the absolute (DJF and JJA) minimum and maximum of T2m over 1958-2008 should be useful here For the same reasons as mentioned with respect to the extreme wind climate, we choose not to include the variability and extremes of the T2m during winter and summer time. We intend to write a separate paper on the temporal variability and recent changes in the near-surface climate in the near future; in this paper we would like to keep the focus on describing the spatial resolution of the average climate.

h. pg 618, lines 24-25: the GrIS temperature parameterization from Fausto et al (2009) adding a dependence of longitude could be compared here The comparison between the mean annual 2 m temperature according to Fausto et al (2009) and RACMO2/GR has been added. A short description of this parameterization is included in page 608 line 13: "Fausto et al (2009) included the dependence of the annual mean 2 m temperature on longitude λ in °W. The coefficients were optimized by fitting the parameterization function to mean temperature observations from locations on land, in the ablation and in the accumulation zone of the GrIS." T_(2m,Fausto)=41.83-0.006309z-0.7189Φ+0.0672λ

The plot below has been added as Figure 5c:

A discussion of the findings has been added to page 615, line 2: "Using a different set of optimal coefficients and including the temperature dependence on longitude according to Fausto et al (2009) changes the sign of the bias, which is reduced to +0.7°C. Figure 5c shows that for this function the absolute bias is less than 1°C for most of the ice sheet. Including the longitudinal dependency could not remove the large positive biases along the eastern margins." After page 615, line 4 we have added: " For Fausto et al (2009), the bias slightly increased to 0.9°C, due to the fact that this parameterization is optimized for the period 1996-2006. All in all, the agreement is quite good, given the simplicity of these empirical relations."

i. page 618, line 28: Where is Dronning Louise Land? Dronning Louse Land is in the northeast of Greenland, as is stated in the manuscript. In our opinion, it is not necessary to provide additional information to the manuscript. A reader who does not know the exact location of Dronning Louise Land can grasp from the text that it is situated in the northeast of Greenland.

Answers to comments of referee 2: R. Hock

1. The abstract does not really reflect what is in the paper We have adjusted the abstract accordingly; see our reply to comment 4a of Referee 1, where we agreed on

TCD

4, C617–C626, 2010

rewriting the abstract with respect to SEB considerations.

2. Compared to the rest of the paper the conclusions are somewhat weak and I suggest that the authors rewrite them. More quantitative conclusions could be added extracting the most novel results that are useful to modelers, and go beyond basic knowledge on ice sheet meteorology. We have rewritten this section taking these comments into account and made the conclusions sessions more focused on the novel findings over the Greenland ice sheet. Based on the comparison of the two temperature parameterizations with the model output we concluded: "Compared to the model output, both functions show large negative temperature biases along the eastern lower margins, where the largest wind speeds and lowest relative humidities are modeled. For these elevations, both parameterizations are apparently too simplified, because other factors such as large scale heat/cold advection, mesoscale topography and the occurrence of summer melt appear to affect the local temperature." As the summer fields of the SEB components are added to the manuscript we included the following quantative conclusion: "In summer, the katabatic wind system is much weaker due to smaller surface temperature deficit and a smaller large-scale pressure gradient. For large parts of the ice sheet, the net radiation becomes positive due to enhanced shortwave radiation absorption by the darker surface as result of snow metamorphism. As the summer near-surface temperature gradient remains positive, but smaller compared to winter, the net radiative warming of the surface is not compensated by the \$SHF\$, but rather enhanced. As soon as the snow/firn/ice surface reaches the melting point, the remaining energy at the surface is available for melt and sublimation. In the percolation zone, the subsurface heat flux is an additional contributor of energy to the surface as the meltwater in the snowpack refreezes overnight." Also the conclusion that the northeastern part of the ice sheet stands out with respect to strong katabatic wind system and temperature deficit is now included in the manuscript: "With respect the spatial variability, the northeastern part of the ice sheet stands out. The RACMO2/GR output shows that close to the margins the largest mean wind speeds and smallest values for relative humidity can be found. The annual mean longwave radiative cooling is largest

due to a clear sky (lowest cloud cover and highest SW transmissivity). Moreover, the concave surface and a synoptic pressure gradient favorable for advection of cold air keep the air cold, further enhancing the katabatic forcing. As subsidence of warmer air from the free atmosphere is suppressed, the strongest temperature deficit occurs over the northeastern part of the ice sheet."

3. Please reduce the number of acronyms, especially of those that do not appear very often, to make the paper more readable for non-meteorologists We have changed the text accordingly, and spelled out the acronyms SL, ABL and TDL.

4. It would be nice to have model results compared to in-situ data. The first part of this tandem-paper is on the evaluation of RACMO2/GR with observations on and along the ice sheet. We have added an additional reference/link to this paper to make it clearer that this manuscript is part of a tandem-paper, which will be published simultaneously.

Detailed comments: All proposed technical corrections have been changed in the text.

6. Introduction, line 25: Explain what temperature deficit is to make the paper more readable for non-experts in this field We have added the definition of temperature deficit to page 604, line25: "a quasi permanent temperature deficit, which is the potential temperature difference between the atmospheric boundary layer and the free atmosphere (Van den Broeke et al, 1994), and the persistent low-level katabatic wind circulation (Heinemann, 1999)."

7. page 605, line 1: what is 'efficient emission'? Don't you mean here: 'and negative net longwave radiation'? We have changed this accordingly.

10.Is the symbol 'dc' for directional constancy well established? Yes, the use of dc for directional constancy is common practice.

11. Equation 7: Why minus is all fluxes directed towards the surface are defined as positive? Also not sure if the longwave part is correctly formulated. There was a mistake in equation 7.

13 page 613, line 3: which averaging period? Do you mean a ‘clear maximum of the annual averaged wind speed <14 m/s’? Yes, we have changed the manuscript accordingly.

14. page 614, line 4-5: ‘Limit’ seems to ‘hard’. We have changes the verb ‘limit’into ‘constrained’, which is softer.

15. page 616, line 23-24: why should this only be valid when Ts is at melting point? This is valid under any conditions (melt may just be zero under certain conditions). We agree with the referee, so we took out ‘whenever Ts=273.16 K’

16. page 617, first line: maybe more correctly: if the sum of all terms on the right hand side in Equation 7 is positive (or simpler: If M (Equation 7) is positive) We have changed the text accordingly.

18. Figures 1: a.s.l. and not m.s.l.: I suggest that you use the same contour increment for better comparability, Should not be a problem considering that increments do not differ so much (15-30) We have looked at this, but the pressure gradient in summer is much weaker than in winter. The winter plots would become unreadable when using a 15 hPa interval for Z500 and 0.5 hPa for the sea level pressure, whereas for the summer plot using a 30 hPa and 1 hPa interval would reduce the amount of information on the general circulation. Therefore we have decided not to adjust the contour intervals in figure 1.

Interactive comment on The Cryosphere Discuss., 4, 603, 2010.

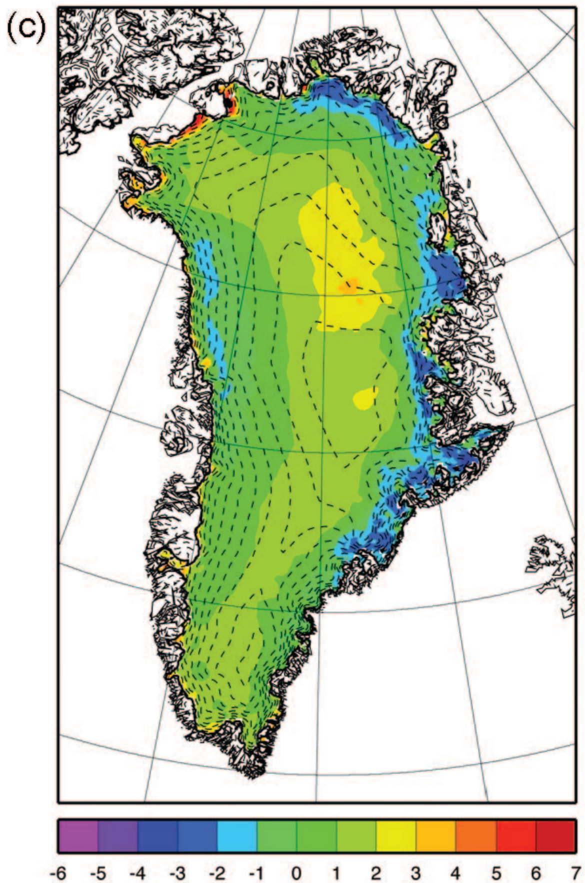

Fig. 1. 5c) difference between T2m computed according to Fausto et al. (2009) and mean annual 2 m temperature of RACMO2/GR [K]

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