Interactive comment on "Future projections of the Greenland ice sheet energy balance driving the surface melt, developed using the regional climate MAR model"

by B. Franco et al.

Anonymous Referee #2
Received and published: 3 September 2012

Dear Referee,
Thank you for the review and your comments. Please find below our responses.

Firstly, it has to be mentioned that we have added to this paper new simulations of the MAR model forced by the global circulation model MIROC5 from the CMIP5 data base, according to the Historical experiment (over 1979-2005) and the RCP experiments 4.5 and 8.5 (for the 2006-2100 period). These new simulations have been presented in Fettweis et al. (2012a)[1]. The revised tables and figures including these supplementary simulations are presented at the end of this document. The additional MIROC5-forced MAR runs do not change the conclusions of this study and contribute to improving the reliability of the different relationships highlighted here between the anomalies of surface melt, surface energy balance components and air temperature.

Major comments

1) This was not an easy paper to review. The English at places is rambling, the formulations at times incomplete. As a result, it is sometimes unclear what message the authors try to convey. I have highlighted the most significant ones under detailed comments, but stopped after a few pages. A thorough scientific and linguistic editing of the paper is necessary before it can be properly reviewed and finally published.

We have taken into account the detailed comments you have listed below and we have modified the manuscript accordingly. We will strive to correct similar "unclear" formulations in the rest of this paper to make it easier to understand eventually.

Concerning the linguistic editing, we have to mention that this manuscript has already been edited and corrected entirely by a scientific native speaker from the Editing and Translation Service of our institution (University of Liège, Belgium) before being submitted to TCD. In the past we used this Service with great success to edit our previously published studies in TC and Climate Dynamics.

2) Apart from this technical issue, my biggest concern is the model evaluation. Note that models are by definition an approximation of reality, so cannot be 'validated', rather evaluated. It is notoriously difficult for GCMs to correctly partition the surface energy balance over (seasonally) snow-covered surfaces, especially during/after melt conditions.

Indeed. We will use "evaluated" in the forthcoming revised manuscript instead of "validated".

On page 2274, section 3, the authors state that "Given that the ERA-INTERIM-forced MAR run has already been successfully validated (see Sect. 2)..."

1 Fettweis, X., Franco, B., Tedesco, M., van Angelen, J. H., Lenaerts, J. T. M., van den Broeke, M. R., and Gallée, H.: Estimating Greenland ice sheet surface mass balance contribution to future sea level rise using the regional atmospheric climate model MAR, The Cryosphere Discuss., 6, 3101-3147, doi:10.5194/tcd-6-3101-2012, 2012.

However, from section 2 it does not become clear what this successful validation entails. In the framework of this paper a successful validation would mean that the partitioning of energy balance components during melt was accurately simulated, yet I do not find a reference to such a comparison. Note that this is very different from comparing a model to observed wind speed, 2 m air temperatures or satellite melt extent, as has been done recently for a suite of regional climate models in Rae and others (TCD, 2012), including the model used in this paper.

The authors continue "…and given the lack of direct measurements of melt on the scale of the whole ice sheet..." This motivation is not strong: it is rather evident that there are no energy balance measurements (which I assume is what the authors mean by 'melt measurements') on the scale of the whole ice sheet: if that were the case, this modeling exercise would not be necessary. Modeling by definition is intended to fill the gaps between widely spaced observations in a physically meaningful way, and model evaluation should involve comparison with and tuning to those same observations.

The authors continue "...the melt outputs from MAR forced by the GCMs under current climate (1980–1999) are validated by comparison with the results from MAR-ERAINT (see Fig. 1b–d)." This is not sufficient: it merely tests for consistency in lateral/surface forcing fields from GCMs which does not replace an independent evaluation.

So before the scientific value of the results in the remainder of the paper can be assessed, a more in-depth model evaluation is necessary. This is especially important as the remainder of the paper assumes this partitioning to be correct! Numerous energy balance studies from Greenland have been published in literature, and those results must be used to see whether MAR-ERAINT is capable of providing the right partitioning of the energy balance during melt conditions.

We agree that the evaluation part of the partitioning of the energy balance components simulated by the MAR model could be improved. Therefore, we have compared the MAR (forced with the ERA-INTERIM reanalysis) outputs over a 7-yr period (September 2003 – August 2010) with observations from three automatic weather stations (AWS) located along the K-transect (west Greenland, a stake array along the 67 °N latitude circle), available in Van den Broeke et al. (TC, 2011). The related figure is presented below (Fig. A). The MAR pixel closest to each AWS was selected to perform this comparison. The AWS S5 is located at the ice sheet edge, S6 in the ablation zone and S9 in the accumulation zone. We refer to Van den Broeke et al. (TC, 2008, 2011) and Van de Wal (2005) for further details about the K-transect and the AWS.

This figure shows that the MAR model forced by ERA-INTERIM is able to simulate the seasonal cycle of the surface energy balance components with respect to the AWS in the ablation and accumulation zones, and that the partitioning of the energy balance during melt conditions match quite well the observations. The related monthly anomalies are generally less than one standard deviation over the investigated period. However, positive anomalies in the surface upward solar irradiance (SW_{net}) compared to the AWS data can be observed during summer (June-July-August), especially for the lower sites (S5 and S6). This is due to the fact that the bare ice albedo in the MAR model is 0.45 while it can reach values of 0.31 (Knap and Oerlemans, 1996[2]; Box et al., 2012) in the field when bare ice appears, resulting in an overestimation of the modelled SW_{net}. Furthermore, as already mentioned in Fettweis et al. (TC, 2011a), MAR tends to slightly underestimate the downward longwave irradiance, inducing underestimated LW_{net} and air temperature throughout the year. Nonetheless, part of these LW_{net} anomalies are less than one standard deviation over the 7-yr

2 Knap, W. H. and Oerlemans, J.: The surface albedo of the Greenland ice sheet: satellite-derived and in situ measurements in the Sondre Stromfjord area during the 1991 melt season, J. Glaciol., 42, 364-374, 1996.

period. The largest anomalies between MAR results and observations occur at S5, at the edge of the ice sheet. Since this station is located on Russell glacier (an ice sheet promontory) the 25 km resolution of the MAR model is not enough to reproduce it with accuracy, resulting in an underestimation of the modelled turbulent heat fluxes during summer.

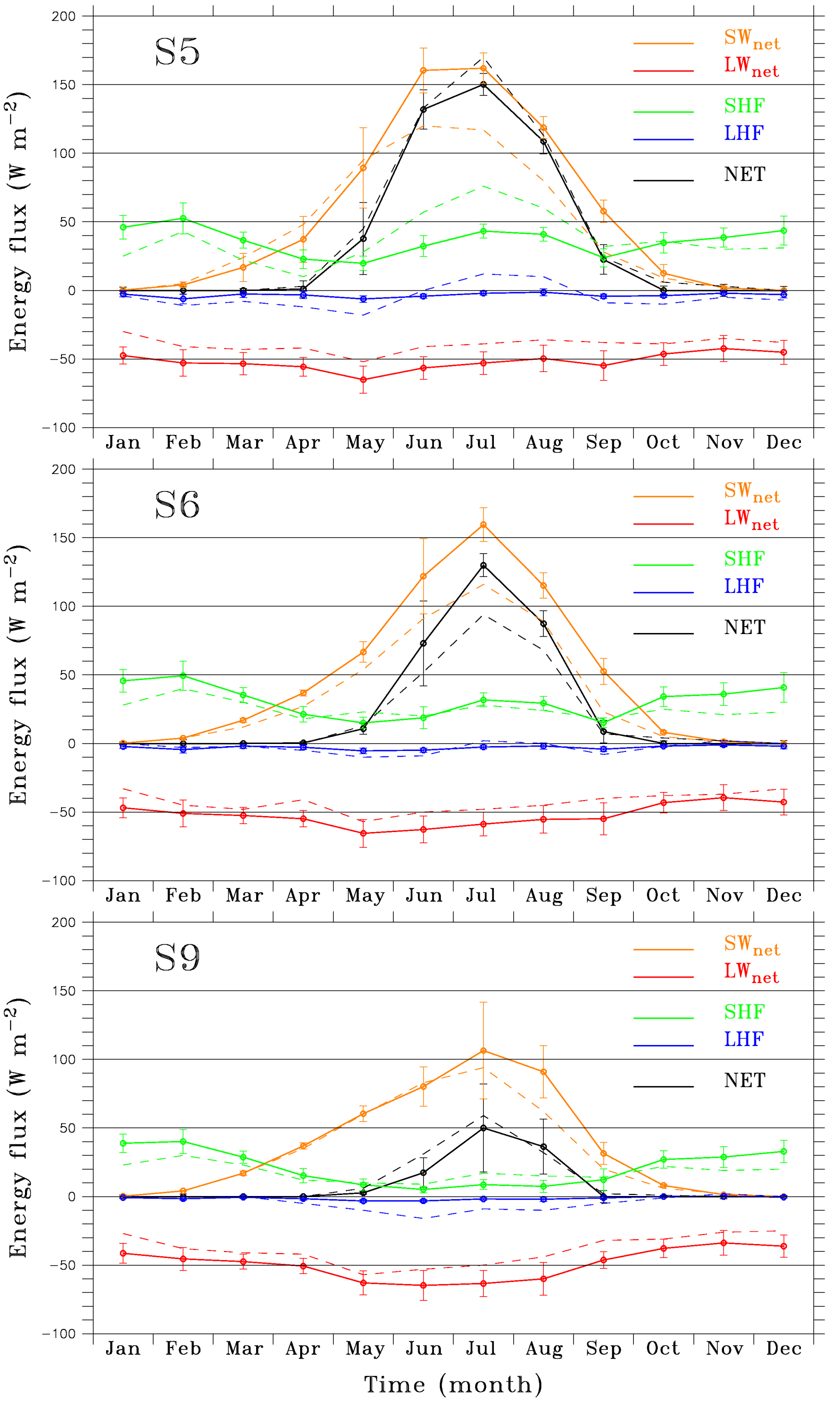


Fig. A. Average seasonal cycle of surface energy balance components (W m^{-2}) simulated by the MAR model (in solid lines) over a 7-year period (September 2003 – August 2010) at S5, S6 and S9, with standard deviation over this period indicated by the error bars. Observations from the automatic weather stations provided by Van den Broeke et al. (2011) are drawn in dashed lines.

We propose to add this figure and a short related analysis to the paper in order to improve the evaluation part of the partitioning of the surface energy balance.

The annual mean biases, standard deviations and RMSE of the MAR results compared to the AWS observations are presented in Table A.

Table A. Annual mean bias (W m^{-2}), standard deviation and RMSE of the monthly MAR results compared to the AWS (S5, S6 and S9) observations along the K-transect.

		NET	SW_{net}	LW_{net}	SHF	LHF
	Mean bias (W m^{-2})	-5.46	11.07	-12.37	-1.26	1.68
S5	Stdev (W m^{-2})	5.16	20.87	3.61	17.36	7.77
	RMSE	7.36	22.84	12.85	16.65	7.62
	Mean bias (W m^{-2})	4.39	13.44	-9.42	6.23	-0.02
S6	Stdev (W m^{-2})	13.46	15.19	4.11	8.08	3.06
	RMSE	13.62	19.80	10.21	9.93	2.93
	Mean bias (W m^{-2})	-3.86	4.51	-10.36	3.31	3.18
S9	Stdev (W m^{-2})	4.39	9.03	3.57	7.98	4.69
	RMSE	5.70	9.75	10.91	8.33	5.50

The albedo, incoming solar flux, melt extent and near-surface temperature from the MAR model have been successfully compared to satellite-derived observations over Greenland and to measurements from the GC-Net AWS (Fettweis et al., 2005, 2011a; Tedesco et al., 2011; Box et al., 2012). For example, Box et al. (TC, 2012) used GC-Net AWS observations to evaluate the accuracy of the surface downward solar irradiance provided by ERA-INTERIM-forced MAR over 2000-2010, revealing average monthly biases less than the specified GC-Net sensor error (15 W m^{-2}).

According to Fig. A and these previous studies, we may assume that MAR forced by ERA-INTERIM and its partitioning of the surface energy balance have been successfully evaluated for the GrIS.

By comparing RCMs with spaceborne SMMR-SSMI microwave data on a daily time scale, Fettweis et al. (TC, 2011a) and Rae et al. (TCD, 2012) highlighted that a reliable modelling of the melt extent and intensity over the GrIS is highly dependent on the ability of the RCMs to partition the energy balance at the surface of the ice sheet. For example, biases in the ratio SWD vs LWD affect the occurrence of the melt extent maximum. Consequently, it can be assumed that an RCM able to reproduce the melt extent and intensity of the GrIS, is primarily able to partition the surface energy balance with reliability. That is why we have chosen in this study to evaluate the different present-day MAR simulations performed with ERA-40 reanalysis and GCMs as forcing fields, by comparing directly their melt outputs with the ERA-INTERIM-forced MAR. Melt anomalies to the reference MAR run in such a comparison should reflect anomalies in the partitioning of the surface energy balance. As it was rather unclear currently in the paper, we propose to add this discussion to the forthcoming revised version of this study.

3) The chosen threshold of 'melt' is 1 mm WE day-1. I wonder how sensitive the ice sheet integrated results are to the choice of this threshold. If this value was chosen to be e.g. 0.1 mm WE

day-1, a much larger part of the higher ice sheet would be involved in the calculations, and the energy balance partitioning of that region would start to dominate the ice sheet averages. I invite the authors to comment on this and demonstrate that the results are robust with respect to the melt threshold chosen.

In order to answer this question, we have firstly compared the daily melt extent and daily meltwater production calculated for various melt thresholds, using the ERA-INTERIM-forced MAR data over the 1980-1999 period (see Fig. B below). As expected, this figure shows that while the percentage of the annually-cumulated daily melt extent resolved is decreasing very quickly with the increasing melt threshold (Fig. Ba), the different melt threshold used here resolves the largest part of the total meltwater production of the GrIS (Fig. Bb). For example, although a threshold of 1 mmWE day^{-1} allows for 32% of the cumulated melt extent only, it resolves 93.63% of the annual meltwater production.

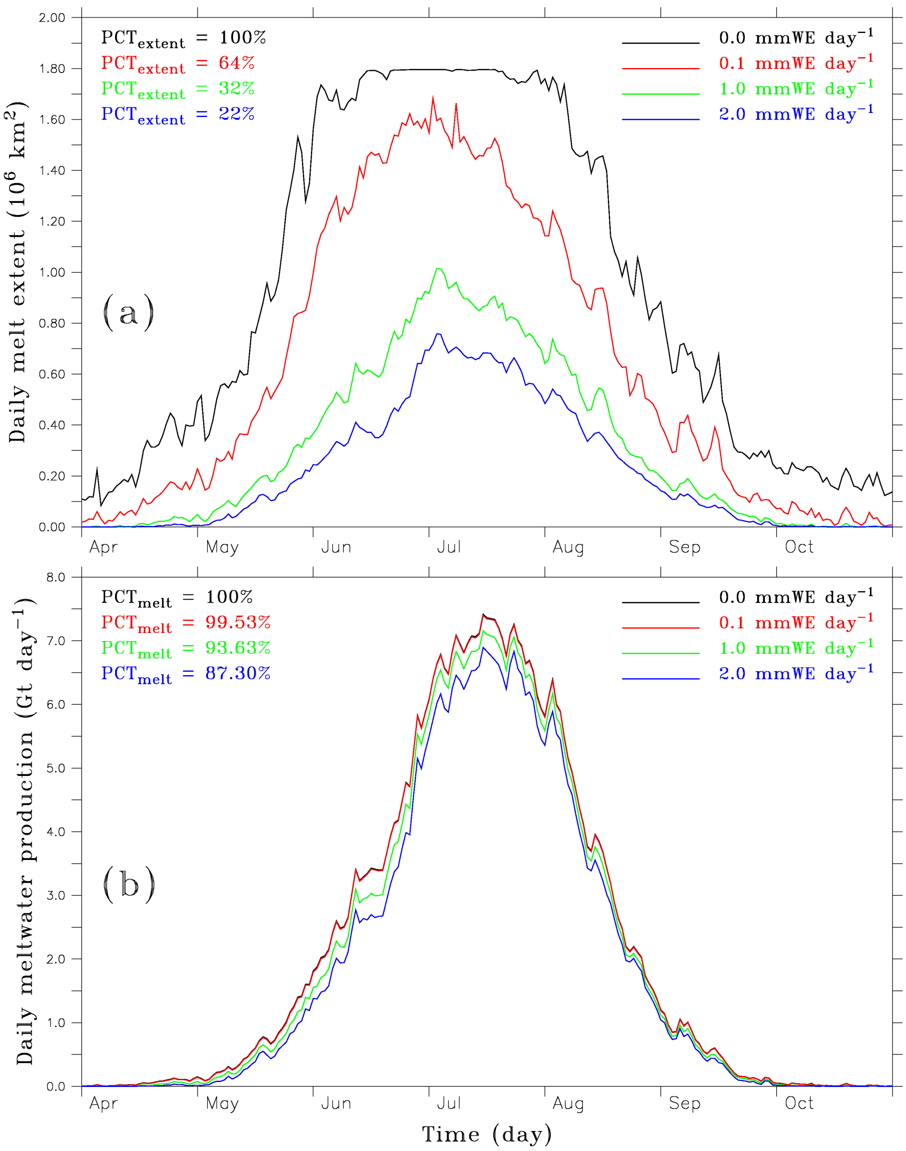


Fig. B. (a) Daily melt extent (10^6 km^2) over the GrIS simulated by ERA-INTERIM-forced MAR over the 1980-1999 period, for different daily melt thresholds. PCT_{extent} indicates the percentage of the annually-cumulated melt extent resolved for a given melt threshold. **(b)** The same as **(a)**, but for the daily meltwater production (Gt day^{-1}). PCT_{melt} indicates the percentage of the annually-cumulated meltwater production resolved for a given melt threshold.

We have also performed the same analysis of the SEB components anomalies according to air temperature anomalies as in the paper, but using this time a daily melt threshold of 0.1 mmWE day^{-1} instead of 1 mmWE day^{-1} as previously (see Fig. C below). The related results are very similar to those obtained previously (see Revised Fig. 4 below), but reveals nonetheless that the longwave radiations appear this time to be the most reactive SEB components to the increasing air temperature. This is mainly explained by the additional pixels from high-elevation areas included in the mask, for which only non significant melt events occur and which are hence almost unaffected by a decrease of the surface albedo. These additional pixels contribute toughly to the dampening of the surface albedo positive feedback in respect to the figure shown in the manuscript. Consequently, by decreasing the melt threshold (under 1 mmWE day^{-1}), we extent the study of the SEB partitioning over almost the entire ice sheet, which is not the aim of this work.

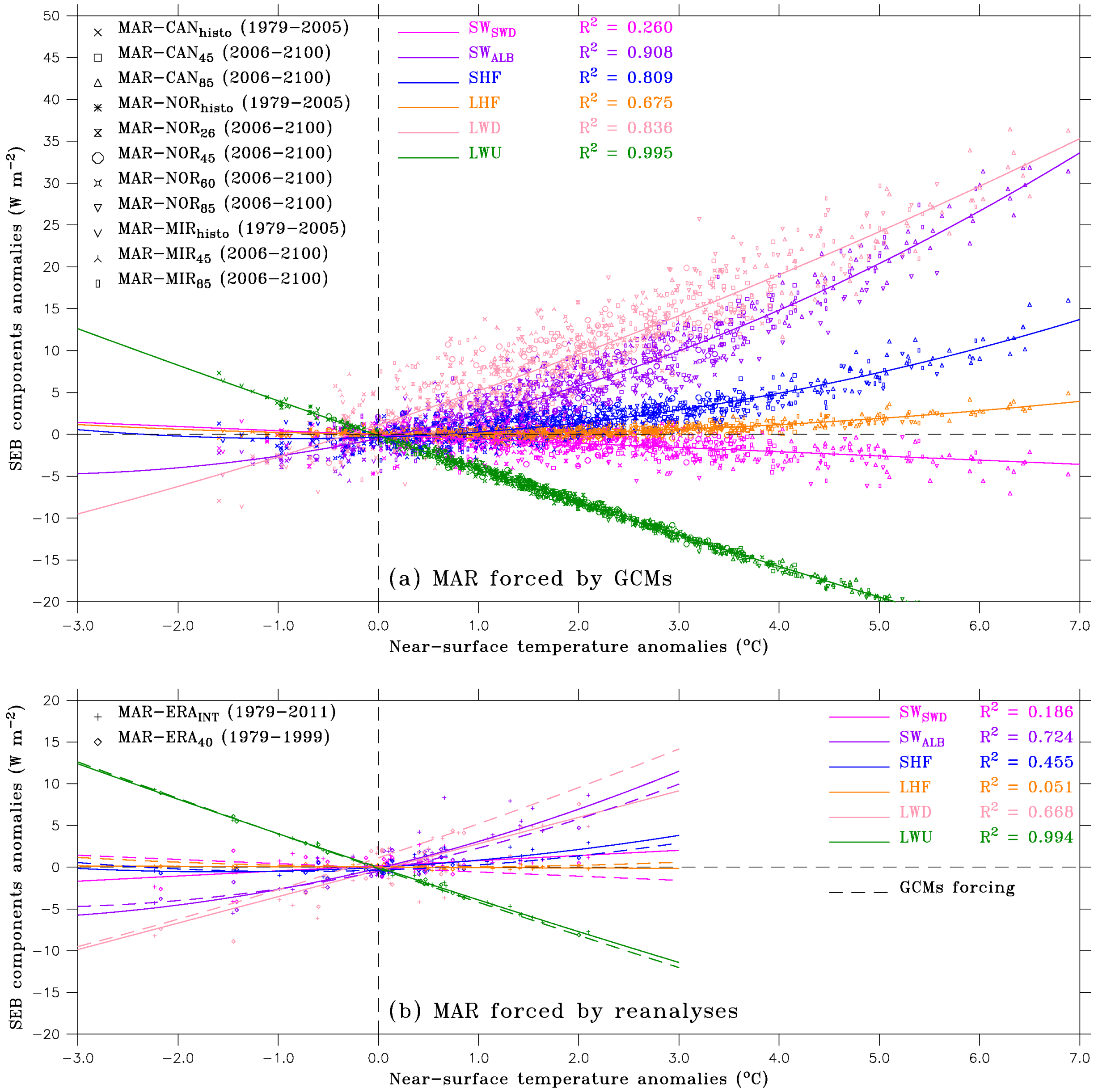


Fig. C. **(a)** SEB component anomalies (W m^{-2}) from the GrIS according to the near-surface temperature anomalies (°C) for the MAR simulations forced by CMIP5 GCMs, with regressions drawn in solid lines. All the anomalies are related to the 1980-1999 average outputs provided by MAR forced with the same forcing fields on the 1980-1999 MSK_{melt} (defined here with a daily melt threshold of 0.1 mmWE day^{-1}). **(b)** The same as **(a)**, but for the MAR simulations forced by the ERA-INTERIM and ERA-40 reanalyses, with the regressions from (a) drawn in dashed lines.

Conversely, an increase of the melt threshold leads to miss many short-lived melt events and rather restrains the investigated area to the lower part of the ice sheet. In such a case, the analysis of the SEB components anomalies according to increasing temperature should approach what has been highlighted over the bare ice extent only (see Revised Fig. 6 at the end of this document).

Consequently, a daily melt threshold of 1 mmWE day^{-1} appears to be an adequate compromise to highlight both the short-lived melt events in the higher ice sheet and the surface albedo positive feedback associated to the extension of the bare ice area during summer. We propose to discuss this issue briefly in the revised manuscript.

4) I am somewhat uncomfortable with the multitude of figures using 2 m temperature as independent or 'predicting' variable (Figs. 2, 3, 5, 6). The correlation between melt, energy balance components and 2 m temperature follows form the simple fact that all respond in first order to the surface energy balance and changes therein. This does not necessarily mean that 2 m temperature changes have good predictive skills for future melting, and that is the way in which many readers will interpret these results, e.g. you take a temperature perturbation and you get the perturbation in ice sheet mass balance; please discuss.

The near-surface air temperature (in reality it is the temperature at the first vertical level of MAR which is near 2.5 m) is used here because it is the variable the most suited to partition the SEB changes into component anomalies, as well as to account for the different feedbacks (albedo, snowfall...) affecting the surface melt changes, given the strong dependency between melt, energy balance and near-surface air temperature. This study does not aim to argue for the predictive skills of projected air temperature changes (we refer to Fettweis et al., 2012a, for this last), but is intended rather to highlight how the melt perturbations can be explained by the SEB components anomalies, using the near-surface air temperature as a common denominator. For example, we could rather evaluate the surface melt anomalies in respect to perturbations of the net energy flux received at the surface of the ice sheet, but in this case we would just get a linear relationship, which does not explain why the modelled surface melting is projected to be gradually amplified.

5) How was the model snowpack initialized? Was it in balance with climate before the melt started increasing, i.e. did temperature, liquid water content and density equilibrate before the scenario runs were started?

Subsequently, does this lead to a trend in subsurface heat flux, as the snowpack warms up in response to enhanced refreezing? I know that Polar MM5 had initialization issues over Greenland, and that the model had to be restarted every now and then, a problem that was likely associated with the drifting snowpack.

The MAR simulations are started at the end of the summer (the 1st of September) to allow the ice sheet and the tundra to be covered with the simulated winter snowpack. The location of the Equilibrium Line Altitude (ELA) at the beginning of the simulation is based on observations from Zwally and Giovinetto (2001). The percolation and the dry snow zones are initialized by 10 m of non-dendritic snow (with respective densities of 500 kg m^{-3} and 300 kg m^{-3}), and over the ablation zone, an ice pack is prescribed at the beginning of the simulation (with density of 920 kg m^{-3}). Subsequently, the snowpack evolves during the simulation according to the strategy explained briefly in the paper and fully detailed in Lefebre et al. (2003). The ice sheet mask and topography are kept fixed throughout the simulations. Five years of spin-up are at least used before using the MAR results. Using more than 5 years of spin-up does not change the MAR results. For example, the CMIP5-forced simulations have been started in September 1965.

A complete description of the thermodynamic and water balance modules of the snow model is given by Gallée and Duynkerke (1997) and Gallée et al. (2001), and further details about the snowpack initialization can be found in Lefebre et al. (2003, 2005).

Technical comments

Title: shorten considerably
We suggest: "Future MAR model projections of the Greenland ice sheet surface energy balance driving the surface melt."

p. 2266, l. 2: What are '25 km simulations'?
We mean "MAR simulations at 25 km resolution". It will be change in the revised manuscript.

p. 2266, l. 6: What does 'TAS' stand for? A more commonly used abbreviation is NSAT but I prefer 2 m temperature.
Indeed, "TAS" stands for the near-surface air temperature, and is the abbreviation used in the WCRP's CMIP5 data base for this variable. Due to the many CMIP5's datasets used in this study, we would prefer to continue to employ "TAS".

p. 2266, l. 12: When does the increase in melt 'surpasses' the effect of enhanced snowfall?
The surface albedo positive feedback induced by the increase in melt exceeds the effect of the snowfall negative feedback for anomalies of the near-surface air temperature higher than 3°C. This will be reformulated in the paper.

p. 2266, l. 17: Opposite trends in cloudiness: do you mean over the same period? If so, does this mean that the current melt trends are part of natural variability?
We mean that MAR forced by the ECMWF reanalyses (1979-2011) simulates a decrease in cloudiness for positive anomalies of air temperature, but an increase of the cloud cover when it is forced by the GCMs with respect to the CMIP5 Historical experiment (1979-2005). These opposite trends can be explained by the fact that the CMIP5 GCMs do not simulate the observed changes in atmospheric circulation (Belleflamme et al., 2012; Fettweis et al., 2012b[3]), as the increase of anticyclonic conditions (gauged by a negative NAO index) during the recent summers (Box et al., 2012). Reanalyses-forced MAR simulates a more important melt increase over the current period than GCMs-forced MAR, mainly explained by the atmospheric circulation anomalies (e.g. inducing a decrease in cloudiness) recently observed in the reanalyses (Fettweis et al., 2012b).

p. 2266, l. 21: What do you mean by 'timing'?
We will correct this as follow: "Finally, no significant change is projected in the length of the melt season, which highlights the importance of solar radiation absorbed by the ice sheet surface in the melt SEB."

p. 2267, l. 2: What do you mean by 'direct consequence'?
These studies present the significant increase of the surface melting as induced by an increased concentration of atmospheric greenhouse gas. Removing "direct" will be more appropriate, given

3 Fettweis, X., Hanna, E., Lang, C., Belleflamme, A., Erpicum, M., and Gallée, H.: Brief communication "Important role of the mid-tropospheric atmospheric circulation in the recent surface melt increase over the Greenland ice sheet", The Cryosphere Discuss., 6, 4101-4122, doi:10.5194/tcd-6-4101-2012, 2012.

the many physical processes that would be primarily influenced by an increased concentration of atmospheric greenhouse gas before affecting the surface melting.

p. 2267, l. 5: Please be accurate when describing the state of the art. Enhanced meltwater supply sometimes leads to a decrease, not an increase of basal sliding of land-terminating glaciers; anyhow, this effect has not led to measurable mass loss from land-terminating parts of the ice sheet, and this remark therefore is out of place in this context. Please adjust formulation to reflect this.
p. 2267, l. 7: Please make clear that increased discharge only occurs for marine-terminating glaciers.
Thank you for these remarks. We have made these sentences more accurate.
"Those parts of this surface freshwater flux that reach the bed of the ice sheet through crevasses and moulins may interact locally with the surmounting ice sheet by increasing the basal sliding of marine-terminating glaciers (Zwally et al., 2002; Van de Wal et al., 2008; Sundal et al., 2011). Combined with the increasing velocity and discharge recently observed for such outlet glaciers (Rignot and Kanagaratnam, 2006; Howat et al., 2008; Rignot et al., 2008), the surface meltwater is projected to substantially accelerate GrIS mass loss under a future warmer climate (Meehl et al., 2007) and to impact the sea level (Lemke et al., 2007)."

p. 2267, l. 10: What do you mean by 'concerns'? Concerns about the accuracy of the projections, or about their outcome?
We mean "concerns" about the accuracy of the projections, given the large uncertainties induced by the different warming scenarios, the models, etc. We will remove "concerns", which is out of place here.

p. 2267, l. 16: The transition to the discussion of surface albedo is abrupt.
p. 2267, l. 21: Albedo is not an SEB component.
p. 2267, l. 23-26: This sentence is unclear, remove or make more specific.
Please find below a new formulation of this paragraph taking into account your previous comments.

"The melt regime of the GrIS can be investigated by partitioning the energy available at the ice sheet surface to enable melt into the components of the surface energy balance (SEB), using data for example from automatic weather stations (AWS) combined with a SEB model (Van den Broeke et al., 2008, 2011). The incoming shortwave irradiance (i.e. solar radiation) absorbed by the ice sheet surface is highlighted as the largest energy source for enabling the surface melt in Greenland, mainly depending on the surface albedo and cloud cover (Van den Broeke et al., 2008). Indeed, the surface albedo is closely linked to surface melt: while the freshly fallen snow reflects most of the incoming solar radiation, the melt-induced lower albedo of the wet snow or the bare ice allows more solar energy to be absorbed by the ice sheet surface, which further fosters the melt. Because of this positive feedback loop, the surface albedo appears to be the dominant driver of surface melt variability in the ablation zone of the GrIS (Van den Broeke et al., 2008; Box et al., 2012) and is believed to amplify the general warming in the Arctic (Lindsay and Zhang, 2005; Stroeve et al., 2005). Such projected changing climatological conditions are expected to affect the surface melt of the GrIS (Meehl et al., 2007). Therefore, partitioning the projected SEB alterations during melt in response to a warmer climate over Greenland should offer an opportunity to investigate the melt regime perturbations therein."

p. 2268, l. 10: Please explain K-transect or show map.
We will add the following explanation about the K-transect to the revised paper.
"Using reanalysis data as forcing fields at the lateral boundaries, they have satisfactorily simulated the GrIS melt extent on a daily time scale with respect to the microwave satellite (Fettweis et al.,

2011a) and the SMB along the K-transect (Franco et al., 2012), a stake array at 67 °N in southwest Greenland that extends from the ice sheet margin towards the central part (see Van de Wal et al., 2005; Van den Broeke et al., 2008)."

p. 2268, l. 22: infrared is inaccurate, use longwave/terrestrial.
Indeed. It will be also corrected in the remainder of the manuscript.

p. 2269, l. 22: What was reduced by a factor of two, and compared to what?
The Greenland topography used for our MAR simulations is derived from the high-resolution (5km) digital elevation model implemented by Bamber et al. (2001) from radar altimetry. Nonetheless, such a detailed topography cannot be used directly in the MAR model and need to be smoothed for ensuring numerical stability during the runs. Beforehand, this topography passed through a smoothing process twice, but only once nowadays.

p. 2270, l. 6: Does this mean that the snow model allows a layer thickness of 1 mm? How small must the model timestep be for a layer with such small heat capacity (and hence very fast temperature changes) to be numerically stable? Does this comply with the Courant Friedrichs Levy condition for numerical stability?
Indeed, the SISVAT model allows such layer thickness in the upper snow layers. For performing MAR simulations numerically stable at 25km resolution, we use a model timestep of 150s.

p. 2270, l. 9: 'posits'? Do you mean 'assumes'?
Indeed, "assumes" looks more appropriate.

Etc...

Revised tables and figures

Revised Table 1. Forcing fields used to perform MAR simulations, scenario, covered period, and abbreviation of the simulations.

Forcing fields	Scenario	Covered period	Abbreviation
ERA–INTERIM	/	1979–2011	MAR–ERA_{INT}
ERA–40	/	1979–1999	MAR–ERA_{40}
CanESM2	Historical experiment	1979–2005	MAR–CAN_{histo}
CanESM2	RCP 4.5	2006–2100	MAR–CAN_{45}
CanESM2	RCP 8.5	2006–2100	MAR–CAN_{85}
NorESM1	Historical experiment	1979–2005	MAR–NOR_{histo}
NorESM1	RCP 2.6	2006–2100	MAR–NOR_{26}
NorESM1	RCP 4.5	2006–2100	MAR–NOR_{45}
NorESM1	RCP 6.0	2006–2100	MAR–NOR_{60}
NorESM1	RCP 8.5	2006–2100	MAR–NOR_{85}
MIROC5	Historical experiment	1979–2005	MAR–MIR_{histo}
MIROC5	RCP 4.5	2006–2100	MAR–MIR_{45}
MIROC5	RCP 8.5	2006–2100	MAR–MIR_{85}

Revised Table 2. Part (in %) of the GrIS area covered by the maximum extent of MSK_{melt} and MSK_{ice}, and percentage of the total GrIS melt resolved by the 1980-1999 mask (PCT_{melt} and PCT_{ice}, respectively), according to the forcing fields of the MAR model. MSK_{melt} and MSK_{ice} have been implemented over the 1980-1999 period for the present-day simulations, and over the 2080-2099 period for the future projections. PCT_{melt} and PCT_{ice} have been calculated on the basis of the 1980-1999 MSK_{melt} and MSK_{ice}.

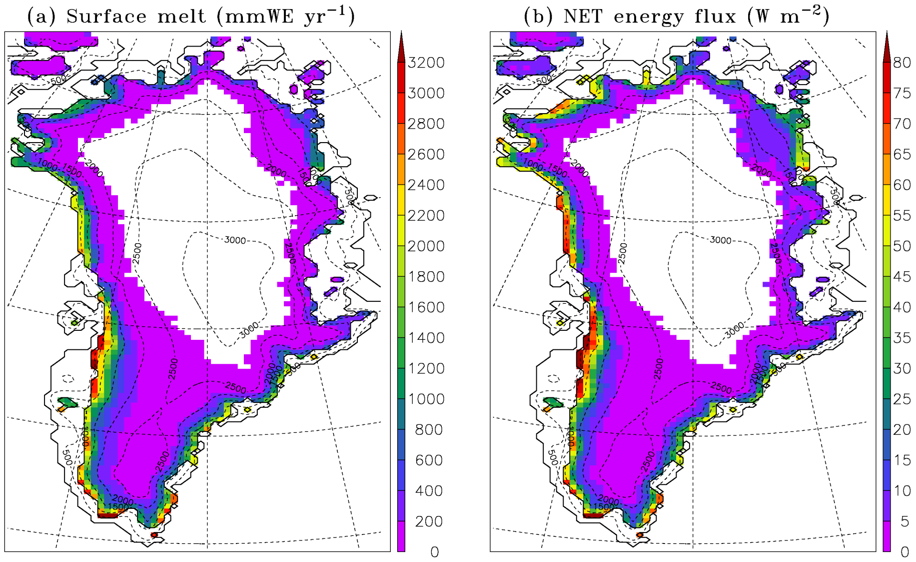
GrIS area covered by a mask (%) and part of the GrIS melt resolved (%)					
	MAR–ERA_{INT}	MAR–ERA_{40}		Greenland	Ice sheet
MSK_{melt} (%)	59.74	61.30		2.30×10^6 km^2	1.80×10^6 km^2
MSK_{ice} (%)	4.96	4.01			
PCT_{melt} (%)	93.63	93.27			
PCT_{ice} (%)	12.74	10.12			
	MAR–CAN_{histo}	/	MAR–CAN_{45}	/	MAR–CAN_{85}
MSK_{melt} (%)	59.08	/	90.59	/	100.00
MSK_{ice} (%)	4.84	/	16.48	/	30.90
PCT_{melt} (%)	93.19	/	84.66	/	74.69
PCT_{ice} (%)	19.15	/	10.55	/	7.13
	MAR–NOR_{histo}	MAR–NOR_{26}	MAR–NOR_{45}	MAR–NOR_{60}	MAR–NOR_{85}
MSK_{melt} (%)	56.51	73.94	77.67	82.74	98.94
MSK_{ice} (%)	3.29	8.02	8.18	10.52	16.09
PCT_{melt} (%)	92.74	88.48	87.11	85.65	78.95
PCT_{ice} (%)	9.74	6.95	6.26	5.59	4.34
	MAR–MIR_{histo}	/	MAR–MIR_{45}	/	MAR–MIR_{85}
MSK_{melt} (%)	63.67	/	85.35	/	100.00
MSK_{ice} (%)	4.98	/	11.76	/	25.05
PCT_{melt} (%)	93.74	/	87.59	/	78.68
PCT_{ice} (%)	14.02	/	9.06	/	5.99

Revised Table 3. Annual melt amount (Gt yr^{-1}) of the GrIS over the 1980-1999 period from different MAR simulations, and the melt energy flux (NET) and SEB components (W m^{-2}) averaged over the 1980-1999 MSK_{melt} specific to each MAR run.

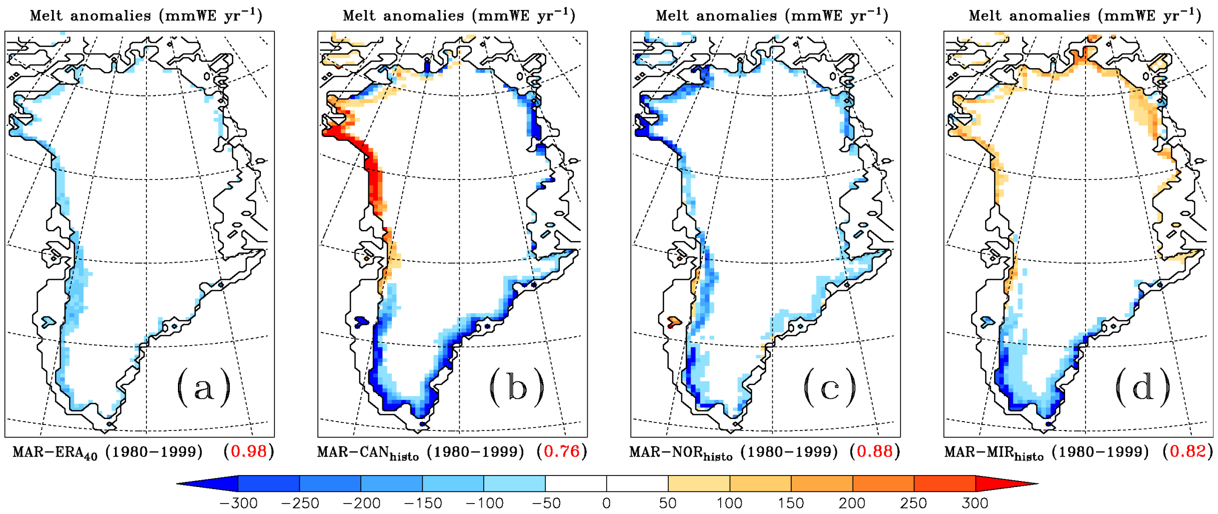
	MAR–ERA_{INT}	MAR–ERA_{40}	MAR–CAN_{histo}	MAR–NOR_{histo}	MAR–MIR_{histo}
Melt (Gt yr^{-1})	455.25	435.14	422.31	404.75	453.40
Stdev	93.36	98.22	116.44	63.31	103.79
Trend	4.08	6.16	8.65	0.61	3.56
NET (W m^{-2})	20.84	19.56	21.02	18.42	21.41
Stdev	4.59	4.77	6.19	3.26	5.67
Trend	0.18	0.28	0.46	0.07	0.16
SW_{net} (W m^{-2})	75.83	73.74	71.34	73.50	75.13
Stdev	4.97	4.89	6.44	4.40	6.37
Trend	0.20	0.22	0.36	0.09	0.04
LW_{net} (W m^{-2})	−61.57	−60.37	−57.10	−61.59	−60.91
Stdev	2.12	2.10	2.28	2.39	3.02
Trend	−0.06	0.01	0.00	0.00	0.09
SHF (W m^{-2})	9.86	9.20	9.27	9.50	10.19
Stdev	1.03	1.00	2.11	1.27	1.67
Trend	0.04	0.03	0.09	−0.04	0.02
LHF (W m^{-2})	−3.28	−3.01	−2.50	−2.99	−3.00
Stdev	0.29	0.24	0.45	0.38	0.55
Trend	0.00	0.01	0.01	0.01	0.01

Revised Table 4. (a) Relative contribution (%) of each SEB component to the NET anomalies of the 2080-2099 period compared to the 1980-1999 period, according to the forcing fields. Each future projection was compared to the 1980-1999 average of the present-day simulation performed with the same GCM as forcing fields, on the related 1980-1999 MSK_{melt}. **(b)** The same as **(a)**, but on the related 1980-1999 MSK_{ice}.

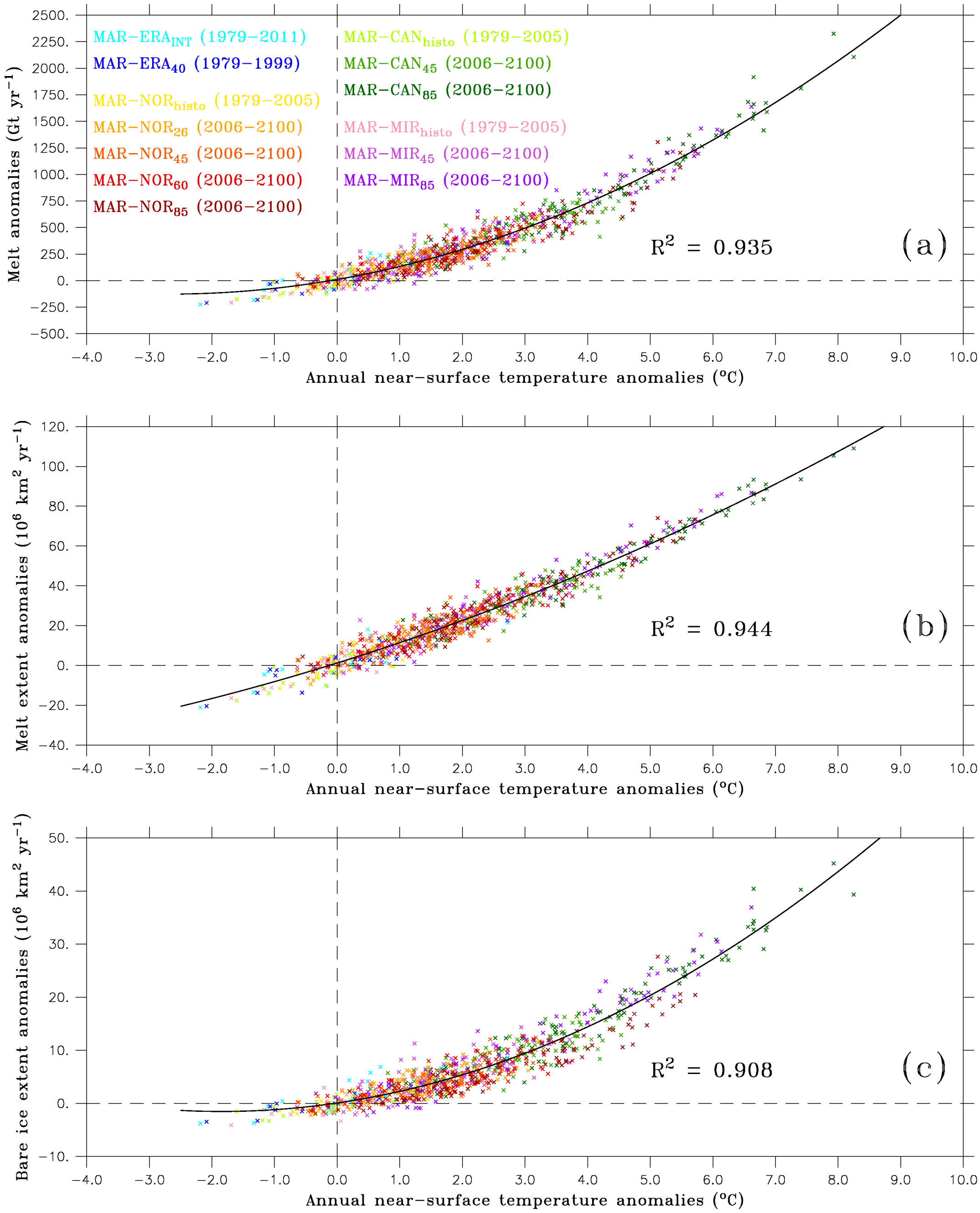
(a) Relative contribution (%) of the SEB components on 1980–1999 MSK_{melt}								
	SW_{net}	LW_{net}	SHF	LHF	SW_{alb}	SW_{swd}	LWD	LWU
MAR–CAN_{45}	56.37	11.45	26.49	5.69	66.69	−8.15	47.92	−36.46
MAR–CAN_{85}	46.49	16.18	29.81	7.51	53.86	−9.44	40.31	−24.12
MAR–NOR_{26}	60.12	9.31	28.56	2.01	74.26	0.15	59.96	−50.65
MAR–NOR_{45}	57.95	12.85	26.10	3.10	71.55	−3.32	59.51	46.67
MAR–NOR_{60}	51.69	18.38	24.52	5.41	65.70	−8.21	62.73	−44.36
MAR–NOR_{85}	43.21	23.82	26.23	6.74	56.39	−11.50	59.64	−35.82
MAR–MIR_{45}	58.97	18.31	17.22	5.50	73.38	−6.16	57.08	−38.77
MAR–MIR_{85}	50.23	17.85	25.14	6.79	59.08	−8.61	45.15	−27.31
Mean	**53.13**	**16.02**	**25.51**	**5.35**	**65.12**	**-6.91**	**54.04**	**-38.02**
Stdev	6.21	4.64	3.77	1.89	7.89	3.72	8.34	9.18
(b) Relative contribution (%) of the SEB components on 1980–1999 MSK_{ice}								
	SW_{net}	LW_{net}	SHF	LHF	SW_{alb}	SW_{swd}	LWD	LWU
MAR–CAN_{45}	1.91	31.62	54.22	12.25	10.42	−5.48	39.54	−7.91
MAR–CAN_{85}	0.37	30.94	54.61	14.08	5.90	−4.06	36.94	−6.00
MAR–NOR_{26}	10.26	25.07	56.23	8.45	18.37	−0.53	32.77	−7.70
MAR–NOR_{45}	13.45	25.11	53.92	7.52	16.88	3.77	32.95	−7.84
MAR–NOR_{60}	4.46	33.28	51.12	11.14	14.28	−4.60	41.20	−7.92
MAR–NOR_{85}	−3.30	37.71	52.10	13.49	9.89	−9.54	45.42	−7.71
MAR–MIR_{45}	22.14	26.41	39.12	12.34	20.79	8.28	33.31	−6.91
MAR–MIR_{85}	3.66	31.88	50.36	14.11	9.82	−3.71	38.27	−6.40
Mean	**6.62**	**30.25**	**51.46**	**11.67**	**13.30**	**-1.99**	**37.55**	**-7.30**
Stdev	8.23	4.44	5.35	2.50	5.10	5.66	4.51	0.76



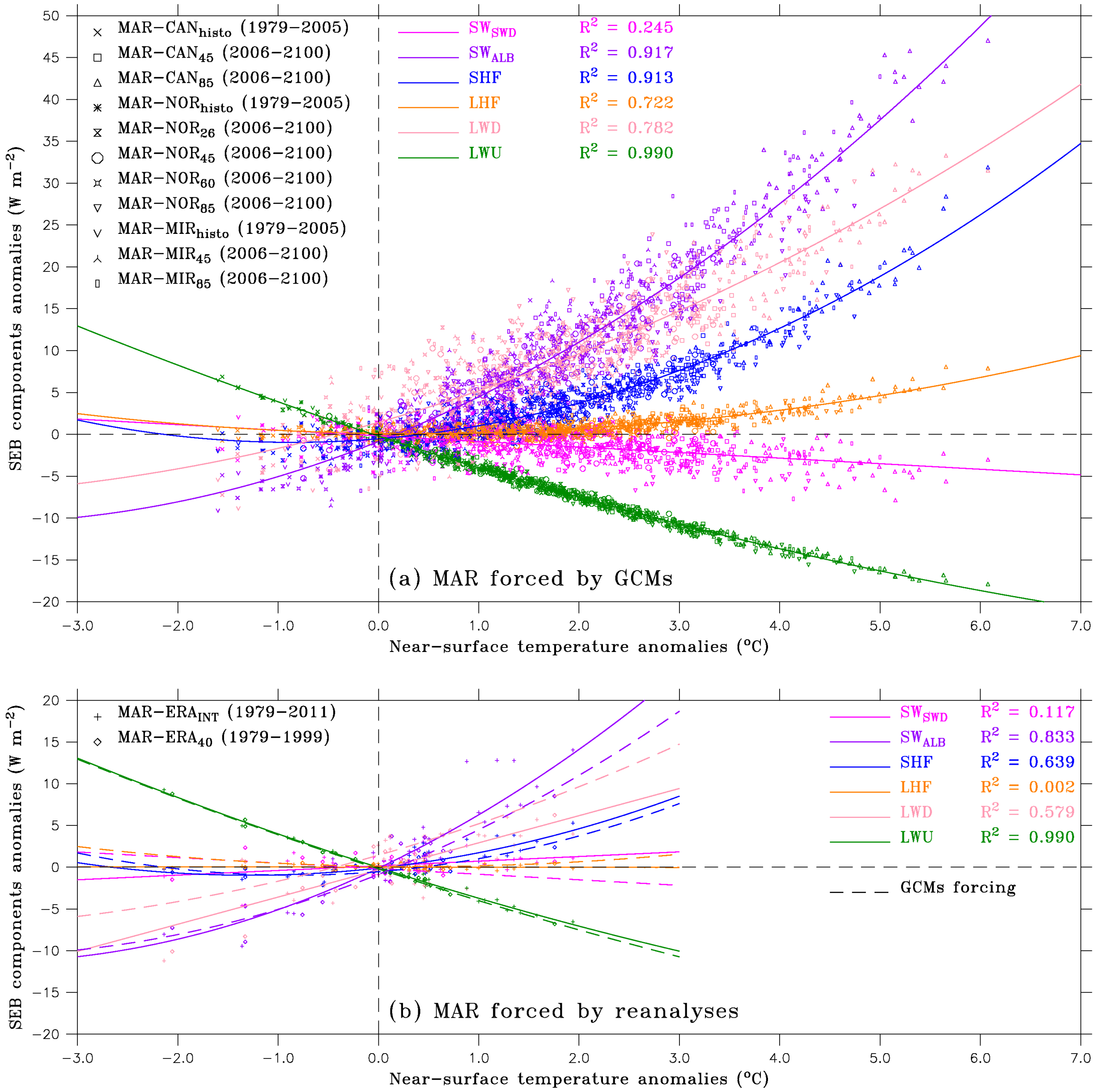
Revised Fig. 1. (a) Average annual melt (mmWE yr^{-1}) of MAR-ERA$_{INT}$ simulation over the 1980-1999 period. The surface height (m) is drawn in dashed line. **(b)** Average net energy flux (W m^{-2}) available at the surface of the ice sheet for enabling the melt in **(a)**.



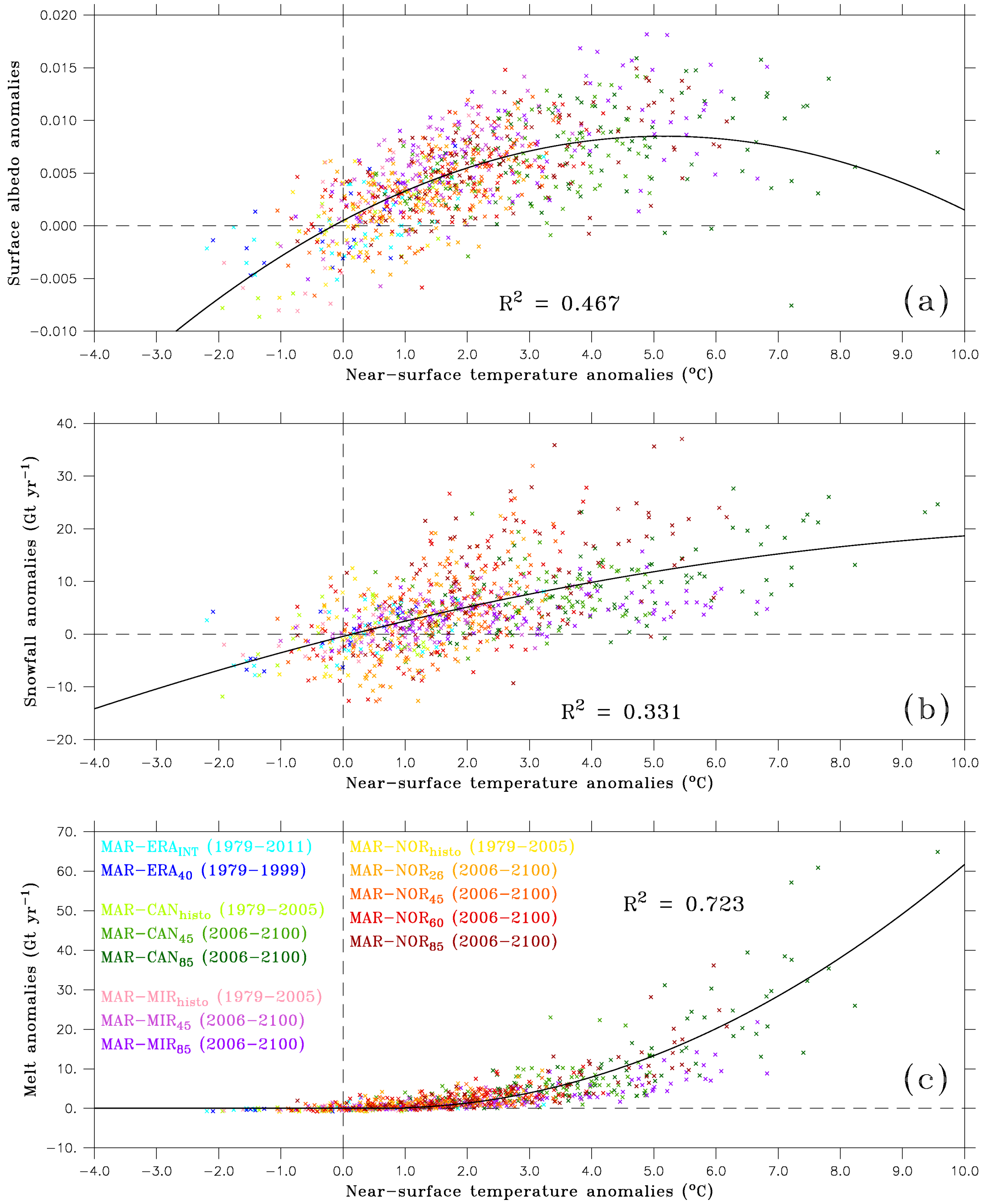
Revised Fig. 2. (a) Annual melt anomalies (mmWE yr^{-1}) of MAR-ERA$_{40}$ run compared to the MAR-ERA$_{INT}$ simulation (see **Revised Fig. 1**) over the 1980-1999 period. In the bottom right side of the view, in red, is the melt skill score of MAR-ERA$_{40}$ compared to MAR-ERA$_{INT}$. **(b-d)** The same as **(a)**, but for the MAR-CAN$_{histo}$, MAR-NOR$_{histo}$ and MAR-MIR$_{histo}$ simulations.



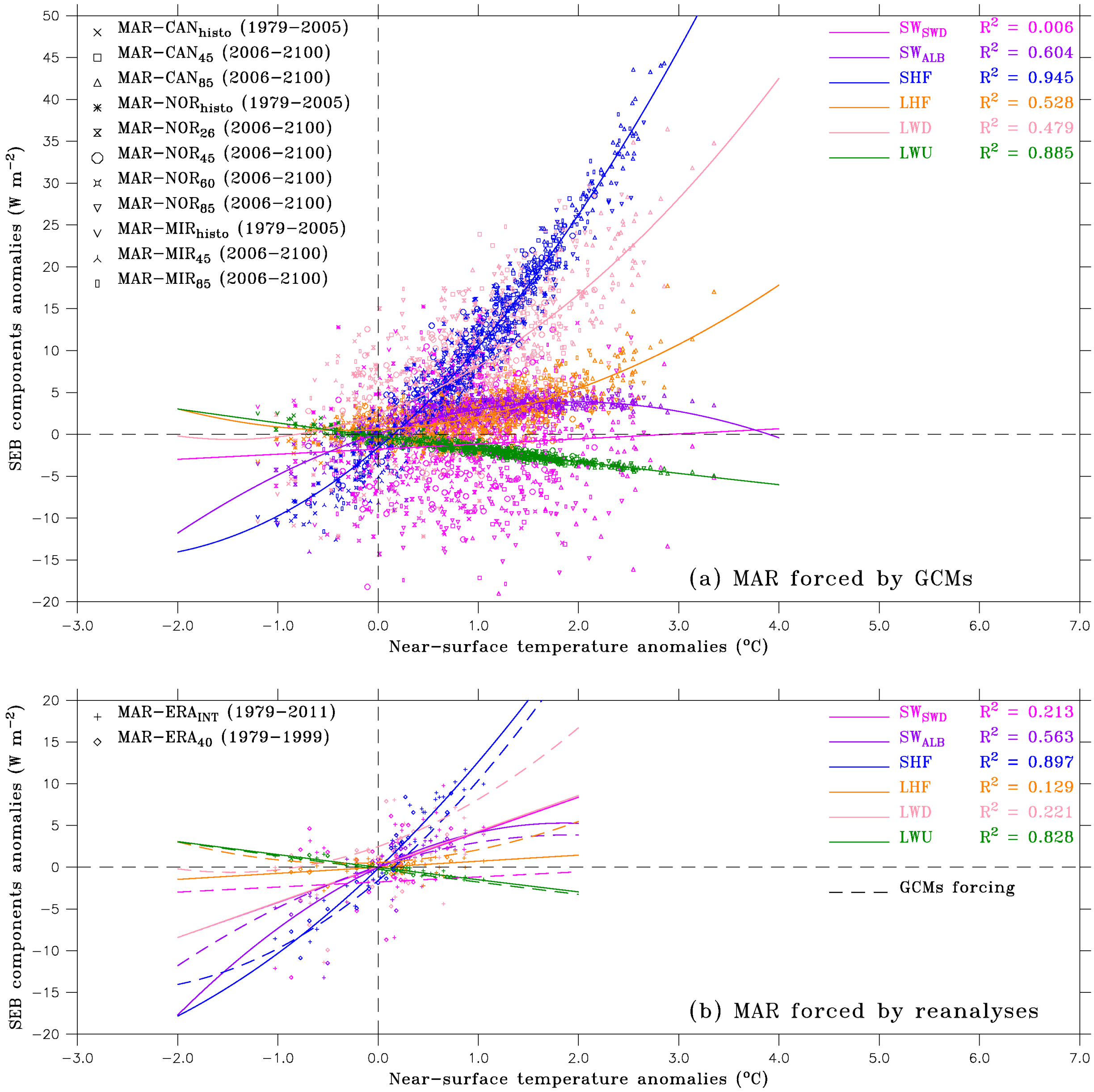
Revised Fig. 3. (a) Annual melt anomalies (Gt yr^{-1}) from the GrIS according to the annual near-surface temperature anomalies (°C), for the MAR simulations forced by the reanalyses and the CMIP5 GCMs, with regression drawn in a solid black line. All the annual anomalies are related to the 1980-1999 average outputs provided by MAR forced with the same forcing fields. **(b)** The same as **(a)**, but for the annual anomalies of cumulated daily melt extents (10^6 km^2 yr^{-1}) on the GrIS, based on significant melt rates higher than 1 mmWE day^{-1}. **(c)** The same as **(b)**, but for the annual anomalies of cumulated daily bare ice extents (10^6 km^2 yr^{-1}) on the GrIS.



Revised Fig. 4. (a) SEB component anomalies (W m^{-2}) from the GrIS according to the near-surface temperature anomalies (°C) for the MAR simulations forced by CMIP5 GCMs, with regressions drawn in solid lines. All the anomalies are related to the 1980-1999 average outputs provided by MAR forced with the same forcing fields on the 1980-1999 MSK_{melt}. **(b)** The same as **(a)**, but for the MAR simulations forced by the ERA-INTERIM and ERA-40 reanalyses, with the regressions from **(a)** drawn in dashed lines.



Revised Fig. 5. (a) Summer (from May to September) surface albedo anomalies according to the summer near-surface temperature anomalies (°C) over the central ice sheet (MSK_{centre}) for the MAR simulations forced by the reanalyses and the CMIP5 GCMs, with regression drawn in a solid black line. All the summer anomalies are related to the 1980-1999 average outputs provided by MAR forced with the same forcing fields. **(b)** The same as **(a)**, but for the summer snowfall anomalies (Gt yr^{-1}) on MSK_{centre}. **(c)** The same as **(b)**, but for the summer melt anomalies (Gt yr^{-1}) on MSK_{centre}.



Revised Fig. 6. The same as **Revised Fig. 4**, but on the 1980-1999 MSK_{ice}.