Future projections of the climate and surface mass balance of Svalbard with the regional climate model MAR – tcd-9-115-2015

Author answer to the review of anonymous referee #1

Thank you very much for your comments and suggestions that will improve our paper a lot. We have included your comments in the revised version of the manuscript.

The fact that this is the first time a physically based snow model is used in combination with an atmosphere model to determine the surface mass budget of Svalbard may be stressed a bit more by the authors.

We replaced p117, L14-17 in the introduction with
"In the companion paper Lang et al. (2015) and this study, it is the first time that an atmospheric model fully coupled to a snow module physically solving the energy balance at the surface of the snow pack is used to simulate the surface mass balance of Svalbard. Compared to previously published studies, this coupling allows MAR to explicitly take into account the atmosphere-surface feedbacks in our projections of the surface mass balance."

P118: I am missing a bit the bigger picture here. What are the changes in the components determining the mass budget: atmospheric flow patterns, sea ice cover, sea surface temperature? The description immediately focusses on mass budget, while these components are crucial in determining the mass budget.

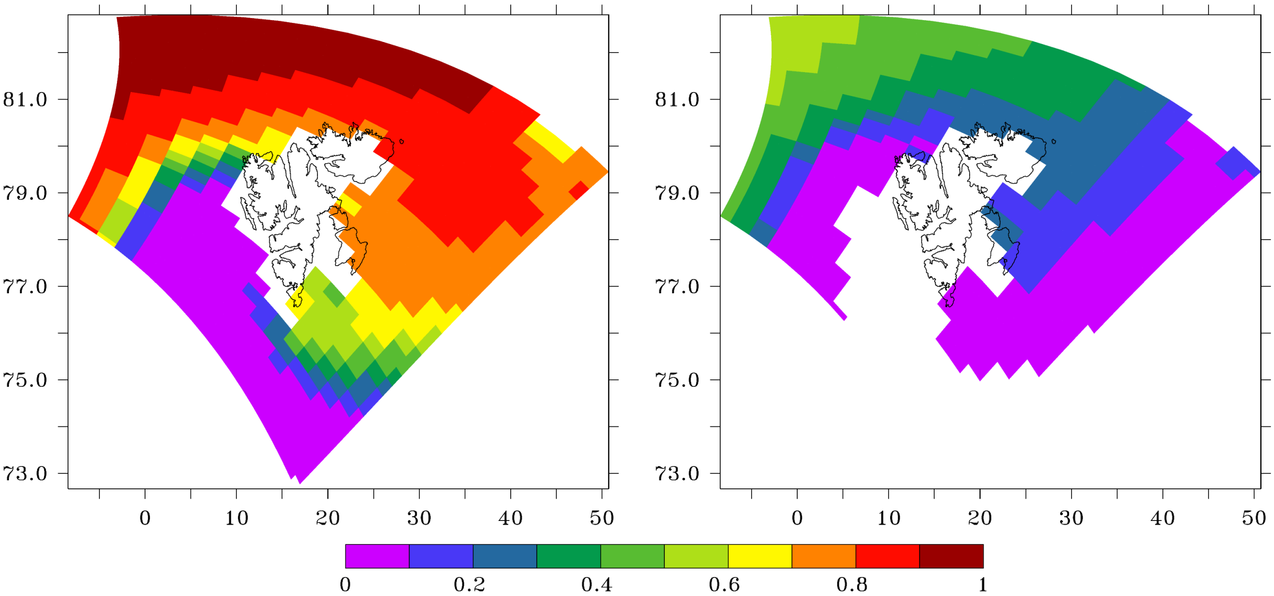

Fig. 1: SIC (0-1) from MIROC. Left: 1980 – 2005 annual mean. Right: 2070 – 2099 annual mean.

Figure 1 shows the annual sea ice cover (SIC) from MIROC5 averaged over the historical period (1980 – 2005, left) and at the end of the century using RCP85 (2070 – 2099, right). The decreasing SIC caused by the temperature rise contributes to enhance the sea surface temperature (SST) increase and therefore to furthermore near-surface warming (as explained in section 4 and in Day et al., 2012 and Førland et al., 2011), which accelerate the melt and precipitation increase. This additional warming also contributes to further decrease of SIC through a positive feedback. However, as there is already less sea ice during the melt season than in winter (see figure 2, showing the mean SIC from MIROC5 between April and November, as it correspond to the projected melt season at the end of the century), the potential temperature rise caused by the decrease of SIC is reduced during the melt season compared to winter (as we explained for summer temperature in sect. 4).

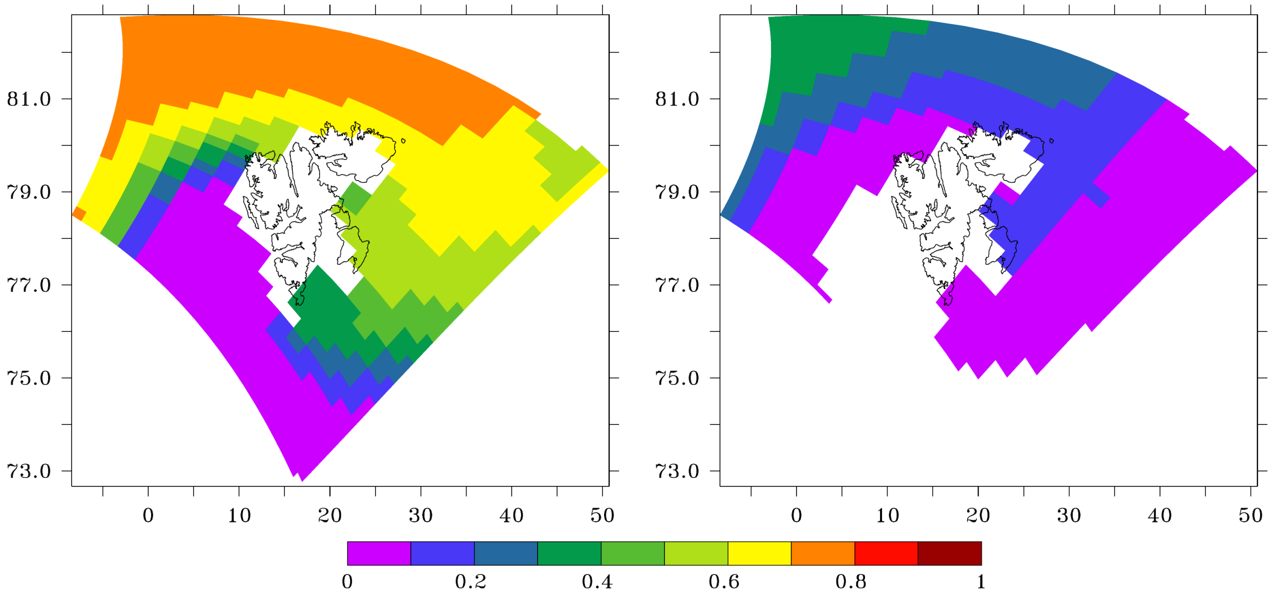

Fig. 2: April-November mean SIC from MIROC. Left: 1980 – 2005 mean. Right: 2070 – 2099 mean.

The SIC decrease has also a direct impact on precipitation as the sea ice disappearance allows more moisture exchange between ocean and atmosphere and this impact is reinforced by the fact that warmer air above the ocean can also contain more moisture. In winter, this means more snowfall contributing to accumulation as the MAR near-surface temperature is still projected to be negative at the end of the century.

In summer, the near-surface temperature, that can be positive or negative at present, is projected to become largely positive over most of Svalbard at the end of the century. This means more liquid precipitation that can increase the melt furthermore via the albedo feedback (rainfall wets the snow pack and then decrease its albedo).

Finally, SIC decrease will also influence the latent heat flux (LHF) over the land as explained in sect. 6. LHF is currently negative (dominated by evaporation and sublimation) and is projected to become positive (dominated condensation and deposition) in the future. This increase/change of sign will have two opposite effects:

- The condensation/deposition will directly contribute to accumulation, damping the melt increase in future.
- The positive value of the energy flux will give energy for the melt whereas in the present, the negative value means that energy is required and therefore not available for the melt.

In conclusion, the SIC decrease and the consequent SST increase contribute to both increasing ablation and accumulation.

As for atmospheric circulation changes, Belleflamme et al. (2012) classified current and future 500hPa circulation types over Greenland from CMIP3 and CMIP5 models and concluded that the GCMs do not project any circulation change in the Arctic over the 21st century.

Finally, it should be noted that the effect of the SIC decrease on temperature and precipitation has been discussed in sect. 4 (Near-surface temperature) and in the companion paper. The effect of the SIC decrease on LHF has been discussed in sect. 6 (Energy balance).

Belleflamme, A., Fettweis, X., Lang, C., and Erpicum, M.: Current and future atmospheric circulation at 500 hPa over Greenland simulated by the CMIP3 and CMIP5 global models, Clim.

Dynam., 4, 2061–2080, doi:10.1007/s00382-012-1538-2, 2012.

P119 L22-29: Rephrase: I don’t see any trend in cloud cover for any of the areas. Cloud cover is rather variable and all regions show a decreasing trend in incoming radiation. The strong decrease in incoming radiation therefore cannot be explained by changes in cloud cover. It might be related to changes in type of clouds, but that is not shown here.

What I see is that the albedo in West decreases more than in East and AV and that the net absorbed short wave radiation increases more than East and AV. The fact that net radiation in West resembles East and AV more than South and BE can be explained by the on average higher cloud cover in West, but does not explain the trends.

We didn't mean that there was a trend in cloud cover, we simply meant that higher cloud cover explain the projected decrease of incoming solar radiation. But we agree that the solar radiation trend can not be explained by the evolution of the cloud cover itself. That is why, we have replaced fig S2c by the cloud optical depth temporal evolution (COD, see fig. 3), which better explains SWD trends and regional differences (South and North West vs North East and AV).

Rem: The COD trends break around 2050 is not as obvious as the SWD trends change but is nevertheless present (e.g. for AV: 0.01/yr before 2050 and 0.02/yr after).

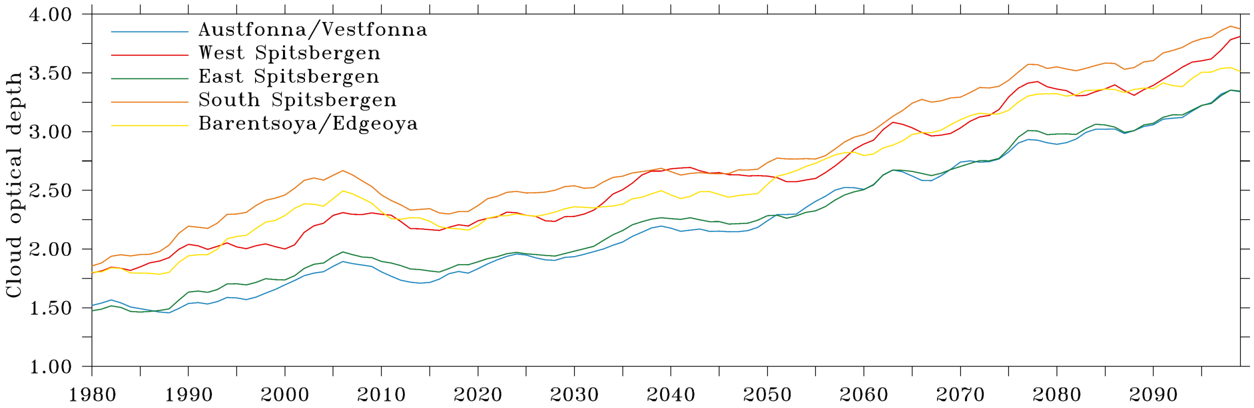

Figure 3: 10-year running mean evolution of the cloud optical depth for 5 different regions.

In short:

- The evolution of the net solar radiation at the surface explains the acceleration of the melt (and therefore runoff) around 2050 and why the acceleration is larger in the south of the archipelago and, to a lesser extent, in the north west than in the north east and on the ice caps.
- The evolution of the net solar radiation at the surface is both due to the evolution of the albedo and SWD (incoming solar radiation at surface): the lower values of SWD in the south and the northwest compared to the east and AV reduce the effect of a lowering of the albedo.
- In the west, the albedo decrease compared to the east is compensated by lower values of SWD, resulting in almost equal net shortwave radiation whereas, in the south, the albedo decrease can not be compensated entirely and the resulting amount of net shortwave radiation is higher than in the North (NW, NE and AV).
- Finally, the lower amount of SWD and its trends can be explain by the increasing cloud optical depth.

P120 L6: How is ’anomaly’ defined? (explain also further in the manuscript).
P120 L9: Why do you refer to m ice instead of w.e.? Since you do not consider ice flow these values do not refer to elevation change.
P120 L13: On what calculation is this based? Do you know how much ice is on BE? Have you calculated how much time it will take to melt all that? Is all the ice at 0 K or do you have to warm it first? You have to explain where this statement is based on.

We used m of ice to have an idea of the thickness of ice that could be lost over the course of the 21st Century due to surface processes. But if it can be confused with elevation changes, we will change the figure and use m w.e. in the revised version (Fig. 4).
All our anomalies are differences with the Historical mean (1980 – 2005). Here, the values we show are the sum over the 21st Century of the yearly SMB anomaly with respect to the 1980 – 2005 average . This gives an estimation of the impact on the ice caps topography of the SMB changes integrated over this century (assuming that there is no change in ice dynamics).

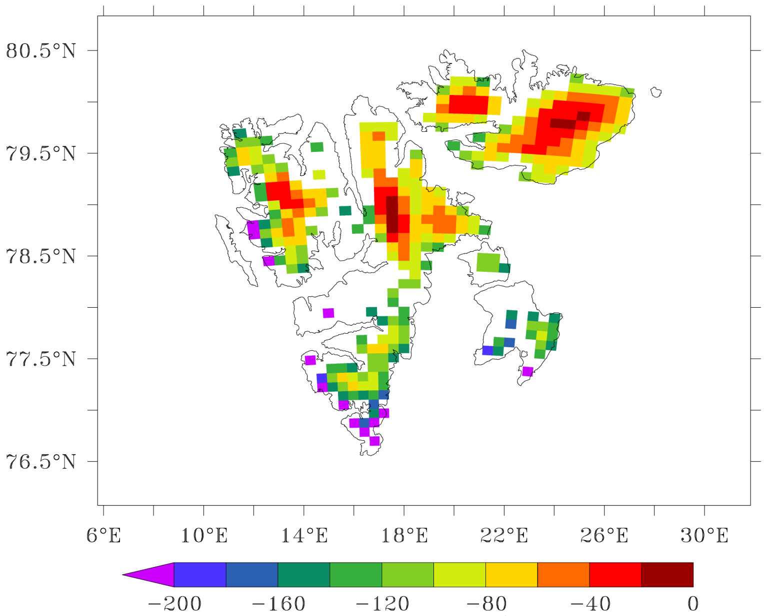

Figure 4: Cumulated SMB anomaly (m w.e.) over the 21st Century with respect to the 1980-2005 mean.

Concerning the disappearance of the permanent ice on BE by 2100, we could not find any ice thickness data and our statement is just an estimation based on the total thickness decrease due to surface loss (more than 100m and up to 200m in some places) and the fact that MAR projects ablation over the entire permanent ice area as soon as 2030 – 2040. However, we will remove this statement in the revised version of our paper as it is only an assumption and we will just stick to the facts: BE is projected to lose more than 100 m w.e. through surface processes and could undergo net ablation every year as soon as 2030 – 2040 according to the $\text{MAR}_{\text{RCP8.5}}$ future projection.

P120 L22: The conclusion of contribution to sea level and following discussion is out of place here, since you have not discussed any of the uncertainties related to the assumptions in your calculations (fixed ice mask, fixed DEM). Furthermore, you do not discuss the impact of possible changes in calving rates at all.
P120 L27: Explain the differences between this study and the sited studies.

As we discuss below, we estimate the error due to the use of fixed ice mask and topography to be relatively small (10%). The SLR contribution from MAR would still have been twice as small as Radić et al. (2014) and Marzeion et al. (2012) estimation if we had not used a fixed ice mask and topography.

Another difference between Radić et al. (2014) and Marzeion et al. (2012) and our study is the surface temperature limitation to zero degree above glaciated areas (damping the temperature increase) is not taken into account in most GCM.
Those studies are also based on empirical calculations of the energy balance while ours are physically based, which also explains the differences in SMB values.
These differences between the studies have been added to what was already mentioned (P120 L29 – P121 L3):
“However, these values [from Radić et al., 2014 and Marzeion et al, 2012] were based on large scale temperature and precipitation changes from global models in most of which Svalbard is not explicitly represented given their huge spatial resolution. Therefore , it is very likely that the snowfall increase with rising temperatures is not taken into account by GCMs”

P120 L25-29: In my opinion it is a guess that the net effect of these three uncertainties will cancel each other. You do not support it with any calculation or reference. Furthermore, Fettweis et al (2013) suggest an uncertainty of 5-10% for Greenland, which is not insignificant. They also state that it should be taken into account. Finally, Greenland is a rather different situation from Svalbard in size, topography, and likely sensitivity to changes. Which has to be taken into account when transfering results from Greenland to Svalbard.

It is true that the effect of a fixed ice mask and topography should be taken into account if possible. But, working with a fixed ice mask and topography as we did already gives a good idea of what could be SMB changes since the additional SMB changes coming from topography changes are about 10 times lower than SMB changes directly induced by climate warming according to Goelzer et al. (2013). Even if the uncertainty of 10 % mentioned over Greenland could be different for Svalbard, this uncertainty should be of the same order and will still be a lot of smaller than the uncertainties associated to the used different GCMs and scenarios.
This issue has been discussed in more details in the revised version.

Goelzer, H., Huybrechts, P., Fürst, J. J., Nick, F. M., Andersen, M. L., Edwards, T. L., Fettweis, X., Payne, A. J., and Shannon, S.: Sensitivity of Greenland ice sheet projections to model formulations, J. Glaciol., 59, 733 – 749, doi:10.3189/2013JoG12J182, 2013

P122 L6: What about changes in calving rates due to climate changes? Especially for Austfonna an important factor.

MAR is not able to simulate calving and we can therefore not estimate the changes in calving rates.

P122 L10: I do agree that the increase in JJA near surface temperature is small, but I do not agree that it is spatially homogeneous.

We compared the temperature increase in summer to the increase in winter and by "spatially homogeneous" we meant that the range of temperature increase in summer over our domain (from +3.0 to +6.5°C, i.e. a range of 3.5°C) is much smaller than the spatial range of temperature increase in winter (almost 15°C over our domain). The increase in summer is lower and more spatially homogeneous because the surface temperature of glaciated areas can not exceed 0°C and present summer temperature is already close to the melting point whereas winter temperature is still far from it.
We have rephrased this paragraph to make it more clear.

L19: Explain why this is to be expected based on the representation of the scenarios.

RCP scenarios are now used by the majority of the scientific community and therefore it seems enough to us to refer to just one paper comparing AB and RCP8.5 scenarios

P124: What is the impact of the limitations/uncertainties introduced by the limited horizontal resolution of 10 km, and fact that you keep your mask and topography fixed, on the extent of the melt season?

We can not evaluate or quantify the impact of the fixed mask and topography on the extend of the melt season as we do not know for certain which one will be dominant.
As for the use of a 10km topography, Franco et al. (2012) showed that, even if there are (local) differences between estimates made using different resolutions, the main trends remains the same. The general message of our paper will therefore hold whether we use a 10km resolution or a higher one.

P124 L25: To my knowledge, MAR does not include a rooting scheme and is therefore not capable in showing a delay in runoff to the ocean. Although this delay will be there in reality, the timing difference in melt and runoff in the model as shown in the figure is not a result of that.

Although MAR does not include a rooting scheme, the delay in runoff to the ocean is parametrized in the model according to the Zuo and Oerlemans (1996) formulation (see Equations 21-22 in their paper).

L17: I find the use of SWD for the short wave radiation rather confusing. In general SW is used. Since D refers to downward it ignores the fact that there is also a reflected and therefore upward component.

We agree that using SWnet makes more sense than SWDnet, especially because we were already using LWnet for the net longwave radiation. But SWD is the amount of incoming radiation when it reaches the surface. The upward part corresponding to the amount that is reflected in the atmosphere (e.g. reflection on the cloud) before reaching the surface is already substracted here so it really makes sense to us to use "downward" here and we believe that it is not specifying that it is the downward component that could be confusing.

P126 L5-7: Explain better: I guess you manipulate the albedo and short wave radiation output. You did not do additional runs in which you kept the albedo or radiation constant.

Yes. We have replaced it by
"In order to distinguish the albedo and solar radiation effects in SWDnet, we have estimated two additional variables for the net solar radiation, as done in Franco et al. (2013).
First, we computed SWDswd by using the 1980 – 2099 values of SWD and the 1980 –2005 mean value of surface albedo. Secondly, we computed SWDalb by using the 1980 – 2099 values of the albedo and the 1980–2005 mean value of SWD."

P126 L11: Add total amounts to the table. That is more informative than the percentages.

The first column gives the anomaly of the 2080 – 2099 mean of each energy balance component with respect to the historical mean (1980 – 2005) in W m^{-2}. The second one gives the relative contribution of each flux to the NET anomaly (as already given in table S1). The first column has been added to the table as your suggested.

	Anomaly (W m^{-2})	**% of NET anomaly**
SWDnet	25	33
SWDalb	38	49
SWDswd	-6	-7.5
SHF	19	24
LHF	17	22
LWnet	16	21
NET	77	