Dear Dr. Radić,

Please find our responses to the comments (**bold**) of two reviewers below, along with the relevant amendments to the manuscript (*italics*).

Please note that the revised manuscript is based on a new simulation including two corrections to the code. First, a problem with unphysical subsurface melting was identified in the original simulation. This was mentioned in the first version of this manuscript, where an attempt was made to correct for this problem in a simple way. However, both referees asked for a better explanation of this issue and a demonstration that it did not impact the results in a significant way. After further investigation, we found that this problem was related to a numerical issue: the Crank-Nicolson scheme used to solve the heat equation in the glacier subsurface can result in small temperature oscillations. This problem was enhanced by the use of predominantly single precision numbers in the WRF code. Although the conclusions of the manuscript were unaffected, we decided to redo the simulations, so as to provide as best a reference as possible for future modelling studies of mass balance on Svalbard. The second correction was a change to the lateral boundary specification, unrelated to the glacier CMB model, which was recommended to reduce noise around the boundaries produced by round-off errors (Heimo Truhetz, personal communication, 2015). When re-running the simulations, we also decided to do one transient 10-year simulation (instead of two 5-year simulations), to eliminate the need for additional spin up (as commented by referee #2).

These improvements do not have a very noticeable impact on the results and figures in our manuscript, and our model results still compare favorably with observations (Table 3). The conclusions of the paper – on the ability of the model to capture regional and temporal variations in mass balance, and the dependence on spatial resolution – are therefore unchanged, as expected. However, several of the individual mass fluxes were altered, so that total net mass balance was changed from -167 to -257 mm w.e. yr⁻¹. In particular, the new simulated fields of precipitation and refreeze were both reduced with about 25 mm w.e. yr⁻¹ each, whereas surface melt was increased by 27 mm w.e. yr⁻¹, all of which contributed to more negative simulated mass balance. The sub-surface melt, which originally showed the unphysical behavior, was only changed with about 10 mm w.e. yr⁻¹ on average.

We have addressed the other referee comments to the best of our ability, which we believe has improved the manuscript in several ways. It now includes more details on the model setup and coupling, a table with average and standard deviations of the mass fluxes, changed layout to several figures, as well as a note about the effect of glacier dynamics, which the model does not account for.

Thank you for your consideration of our revised manuscript for publication in *The Cryosphere*.

Best regards, Kjetil Aas & co-authors

Referee #1:

General Comments:

This paper uses WRF regional atmospheric model coupled with the CMB climatic mass balance model to simulate the climatic mass balance of Svalbard glaciers over a ten-year period. The paper provides an extensive but concise evaluation of the simulations through comparison with AWS data, stake data, GPR data and satellite altimetry data and demonstrates that the modelling scheme has good skill (in most regions) in calculating the climatological mass balance. The paper also investigates the impact of WRF horizontal resolution using both the 9 km outer grid, the 3 km inner grid and a special 1 km grid for a one-month test. The paper is clearly written and concise.

Specific Comments:

1. Abstract and elsewhere. I suggest keeping the same units when reporting mass balances. At the moment mm w.e. y-1 and m w.e. y-1 are both used.

Thank you for this comment. We now only use mm w.e. y^{-1} .

2. I would like to see more details on the WRF model set up.

a. More information on how the ERA –Interim is used for lateral BCs. Is there a nudging or relaxation scheme used at the edges of the 9 km domain? If so, how is this applied? What is the time frequency of the ERA Interim dataset.

b. What is the vertical resolution? Is it the same on the 9/3/1 km domains?

We have now included this information in the model description section:

As boundary conditions for this domain we use the ERA-Interim reanalysis (Dee et al., 2011) with a 6hour temporal resolution. We employ the default boundary configuration in WRF, with the outermost grid-point specified, followed by a four-grid-point relaxation zone. And:

All three model domains use the same vertical resolution (40 eta layers up to a model top of 25 hPa) and physical parameterizations, with the exception of the cumulus convection scheme that is only employed in the outer (9-km) domain.

3. At the end of section 2.2 the authors point out an issue with some grid cells giving unrealistic sub-surface melting in the climatic mass balance (CMB) model, but do not provide any reasons for this. This is problematic and casts doubt on the integrity of the CMB simulation. I suggest that the authors do some debugging and testing to determine why this error is occurring. (I would not insist that the redo their entire simulation – just that they provide an explanation or the error and demonstrate that it is not impacting their simulation in a significant way.

After further testing and debugging, we found that the unrealistic sub-surface melt was related to small oscillations in the Crank-Nicolson (CN) scheme used to solve the heat equation in the CMB model. This commonly used scheme can result in small (decaying) oscillations (e.g. Østerby 2003). For most applications, the issue is not very problematic. However, for an ice field at melting point, these oscillations were enough to result in sub-surface melt even when there was no external forcing to heat the ice below the surface. Through isolated testing of this scheme in MatLab, we found that the magnitude of these oscillations was sensitive to the number precision. The WRF model normally uses single precision numbers (i.e. an accuracy of 7-8 digits), which contributed to making this problem significant in these simulations.

The main solution to this problem was therefore to introduce double precision numbers in the subsurface module of the CMB code, which removed the unrealistic sub-melt pattern seen in the previous results. By comparing the calculated sub-surface melt with the penetrating solar radiation (QPS), we confirmed that this largely solved the problem. There were, however, still some instances where some overestimation of sub-melt occurred. To further mitigate this problem, we therefore repeated the calculation of the CN solution twice in the timesteps when the issue arose and used the average of the solutions. As the CN oscillations are alternating around the true solution, this

approach has been suggested as a method to reduce their impact (Østerby 2003). Each of these two changes reduced the problem with approximately 1-2 order of magnitude, to the point where the sub-melt exceeding the heating from penetrating solar heating (QPS) was reduced to less than 0.01 mm w.e. yr^{-1} on average. This we consider to be insignificant in the context of this study.

Test simulations with these modifications indicated that the main conclusions would not be changed. However, the effect on the total net mass balance (as the difference between large positive and negative terms) was larger than previously thought, and we therefore decided to redo the entire simulation. Before redoing the simulation, we also incorporated a bug fix to WRF code, namely a change to the lateral boundary specification. Originally, the lateral boundary conditions in WRF were calculated based on tendencies rather than the actual numbers, which for long simulations resulted in round-off errors. This could be seen as noise along the boundaries, which propagated into the interior of the domain. This correction also contributes to altering the new results compared with the original simulation, with the mean annual b_n changing from -167 to -257 mm w.e. yr⁻¹. The test simulation without the boundary condition update, covering only the first year, differed only with about 30 mm w.e. yr⁻¹.

4. The authors use a modified version of the CMB model from Molg et al (2008,2009). It would be helpful if they could briefly describe how CMB differs from the land surface schemes that are part of the normal WRF model.

We added to the manuscript:

The land surface schemes in WRF have become more advanced in terms of representing snow processes in recent years, but still only simulate a few snow layers (up to three for NoahMP). They therefore have limitations when it comes to simulating the development of deep multiyear snow packs in the accumulation area of Svalbard glaciers, as well as realistically representing different glacier facies (snow, firn and ice) during the ablation season. We therefore used a modified version of the glacier climatic mass balance (CMB) model of Mölg et al. (2008, 2009) to simulate glacier grid cells.

5. Section 3.1 compares the simulation output with weather station data. Many atmospheric parameters, like temperature, depend strongly on altitude, but the WRF surface elevation and actual (AWS) surface elevations were not reported. Was there any difference between the WRF surface elevation and the actual surface elevation at the AWS locations? Was any adjustment made to account for this difference?

The model grid points were 44 m and 29 m lower than the AWS elevations at Kongsvegen and Etonbreen, respectively. We made no corrections based on this, as these deviations are relatively small. We included these numbers in the text:

Note that the model grid points are 44 m and 29 m lower than the station heights at these two locations, respectively.

6. Page 5787 line 22: change "(Fig. 5b)" to "(Fig. 5c)" (I think this is a typographical error) This has now been corrected. Thank you for pointing this out.

7. Section 3.4 – comparison with Satellite altimetry. You note that geodetic mass balance does not include glacier dynamics, however in Table 4 you only include mean elevation changes for whole glaciers. Is it possible that glacier dynamics "cancels out" at this scale of analysis (in other words emergence in some areas offsets submergence in others)?

The model does not include the glacier dynamics, whereas the geodetic measurements do. For landterminating glaciers, the flux divergence terms cancels when integrating over the entire glacier area, but this is not the case for tidewater glaciers where the mass-flux over the glacier boundaries causes a gap between the area-averaged CMB and the geodetically observed volume change. Many, and especially the largest glaciers on Svalbard, are tidewater glaciers (see Nuth et al., 2012). This is why the text focuses on the overall agreement between the sign and magnitude of the surface height changes in the different regions, rather than the exact values. However, we now include also an estimate of the mass flux from calving for comparison:

The mass loss from calving flux has been estimated to be 6.75 km3 yr-1 (w.e.) for the years 2000-2006 (Blaszczyk et al., 2009), which corresponds to an additional lowering of about 0.2 m yr-1. This suggests that the model in general simulates too much surface lowering in this period. However the time periods are different and the estimate of Moholdt et al. (2010) does not include the effect of retreat or advance of the calving front. One must therefore still be cautious when comparing these numbers.

8. Figure 7 should include a scale indicating the correspondence between colours and topography. This is now included.

9. Blowing snow is not accounted for. How important is this likely to be? Only at Hansbreen?

There are few studies that quantify the effect of this on Svalbard, and they only cover limited regions. Jaedicke (2002) estimated that only 0.2 % of the annual precipitation in a valley on the west coast of Spitsbergen was lost to sea due to wind redistribution, even though the wind was blowing out of the valley 80% of the time. However, a model study of Vestfonna ice cap indicated that ~ 10-20% of the accumulated snow at the highest elevations was lost to other regions of the ice cap due to wind (Sauter et al. 2013). We focus on this effect mainly on Hansbreen, where it is known to be an important process, but mention it now also for the other glaciers:

However, resolution alone does not explain the large b_w bias at Hansbreen. Instead it is likely that processes like wind drift and snow redistribution are important for the accumulation pattern on this glacier. These processes likely also affect the accumulation at the other glaciers, however their influence is largely unconstrained.

10. In Figure 8, comparing October precipitation at the three model resolutions, are observational data available for comparison too? If so, it would be interesting to include that as a fourth profile line.

Unfortunately, we do not have precipitation estimates from these glaciers on sub-seasonal time scales.

11. In Figure 10 – define all the terms in the energy balance and mass fluxes.

This is now included in the figure caption.

Referee #2

This manuscript presents a thorough evaluation of a regional atmospheric model (WRF) coupled to a mass balance/snow model (CMB) using an extensive and divers data set. The manuscript is well written and well structured. It adds to available publications in using a smaller grid spacing, resulting in a better representation of the topography and topographic related processes, and the thoroughness of the evaluation.

I do have some (minor) comments, which are listed below.

General comments

Explain the use of the term 'Climatic Mass Balance'. This paper addresses the surface mass balance and covers a period of 10 years. The term 'climatic mass balance' is not a generally used term and a bit confusing.

We use the term climatic mass balance as recommended by Cogley at al. (2011). The climatic mass balance includes subsurface processes like refreezing and melting from penetrating radiation in addition to the surface mass balance processes, while the effect of dynamics on the mass balance is not included. This is now explained in the text:

Throughout this study we distinguish between the surface mass balance (SMB) and the CMB as recommended by Cogley et al. (2011). The SMB specifies mass changes between the surface and the last summer surface, whereas the CMB also accounts for internal accumulation and ablation (i.e. below the last summer surface). We consider internal ablation as negligible and it is therefore not explicitly treated in our application.

In the title you state that the atmospheric model is coupled to a glacier model. Without reading more, this might suggest coupling to a dynamical glacier flow model, while the coupling is in fact to a mass balance/snow model.

We have now changed the title to:

The climatic mass balance of Svalbard glaciers: a 10-year simulation with a coupled atmosphere - glacier mass balance model

Specific comments

Abstract:

See comment above, add that you study the surface mass balance. You do not address the total mass balance since this setup does not provide any information about dynamics.

As described above, the term "climatic mass balance" is used instead of surface mass balance, as mass fluxes in the subsurface are accounted for in the model.

Introduction:

P5777 L17: I don't think MAR is a statistical model. Thus is the reference to Lang et al., 2015b correct?

It is correct that MAR is not a statistical model. However, Lang et al., 2015b pointed to the fact that most simulations of Svalbard glaciers were with statistical or empirical models, which is what we refer to. We have now changed this sentence to make this clear:

Regional model estimates of surface or climatic mass balance of Svalbard glaciers have so far mainly focused on individual or a few glaciers, and as noted by Lang et al. (2015b) typically been based on empirical or statistical models.

P5778 L5: Rephrase this goal. I don't see the goal of this work as to reduce the spatial and temporal gap between observations an models. I think the goal is to thoroughly evaluate the surface mass balance product from a coupled atmosphere-snow model system and to investigate what spatial resolution is sufficient to describe the observations.

The aims of this study have been clarified:

In this study, we aim to i) simulate the climatic mass balance (CMB) of Svalbard glaciers with a higher resolution than previously done with dynamical downscaling, ii) validate the model with a more extensive set of observations in this region, and iii) investigate the spatial resolution needed to describe the observations.

Methods:

P5779 L23: How is your glacier mask defined and how do you deal with grid boxes partially covered by ice and partially land?

The glacier mask is based on Nuth et al. 2013. Grid boxes are treated as either glacier, land (tundra) or sea, as WRF does currently not allow for different land types within each grid box when the NoahMP land surface model. Including the CMB model does not change this basic structure.

P5779 L24: I don't understand why 2 transient runs of 5 years instead of 1 of 10 years will save computational time. I have the impression that they are run one after the other. Furthermore, this way the second one also needs to spin up.

The two simulations were originally simulated simultaneously. This did not save CPU hours, but made it possible to complete the simulation in less time. The new simulation is however simulated as one transient 10-year simulation.

P5780 L9: I guess that 'climatic mass balance model' is the name of this model but that it is basically a surface energy/mass balance model including a subsurface snow/ice model. See explanation of the term "climatic mass balance" above.

P5780 L16: I agree that it is not necessary to include all the details of the GMB model, nor the details of how it is coupled to MAR, but you do have to state how it is coupled in general, and what input parameters CMB needs. This coupling is what makes this research stand out compared to other efforts to determine the surface mass balance using WRF. How does this model compare to the standard WRF surface scheme? Furthermore, Collier et al., 2013 describe that there are 2 options how to couple: only one way, or two way, and that is a major difference. Which method do you use? What is calculated by WRF and what is calculated by CMB? What parameters from WRF does CMB use and what is feed back into WRF (in case of 2 way coupling).

This has now been included in the description of the CMB model:

The CMB <u>model uses near surface temperature, humidity, pressure, winds, as well as incoming</u> <u>radiation and precipitation as input from WRF, and</u> computes the column specific mass balance from solid precipitation, surface and subsurface melt, refreezing, and liquid water storage in the snowpack, and surface vapor fluxes. The model solves the surface energy balance to determine the energy available for surface melt, and resolves the glacier subsurface down to a user defined depth (here 20 m divided into 17 vertical layers). For glacier grid cells, the <u>CMB model updates surface mass and</u> <u>energy fluxes in the WRF model, as well as surface temperature, roughness, and albedo, resulting in a</u> <u>two-way coupled model system (WRF-CMB).</u>

P5781 L 3-11: I am not sure I understand the problem and its impact on the results. Furthermore, if you don't know what the problem is, how is the reader to judge the value of the results in general? L4 'low' mass balance values refers to negative values? L6 Why do you not exclude internal melting in all months? (I guess that internal melting results from readiation penetration?). L9 the values stated here are not very clear. What is compared here to give these numbers? ANd how can I judge whether this is big or small?

See answer to comment 3. of referee #1.

Model validation

P5785 L19: The temperature signal is dominated by the diurnal cycle, thus these high correlation coefficients are not surprising.

This correlation is calculated from daily mean values and does therefore not include the diurnal cycle. It is clear that the high correlations are partly due to the annual cycle. However, the temperature variations within especially the winter season can be larger than the difference between mean summer and winter temperatures (e.g. Aas et al. 2015). This correlation therefore mainly reflects that the WRF model forced with ERA-Interim boundary conditions is able to reproduce large scale weather in a good way.

P5785 L23: Can you explain the biases in temperature and long wave fluxes?

This is discussed in detail by Aas et al. 2015 for a similar WRF simulation of Svalbard, who found these biases to be mainly related to cloud and boundary layer processes. As mentioned in section 6.2.1 these biases are however small compared to other similar studies.

P5787 L7: Since individual years correspond less well than the mean, there are compensating errors.

This might be part of the explanation. However, Fig. 3 shows only two extreme years in addition to the mean, and it seems that the model has more problems with accurately simulating these years than the more average years, as seen from Fig. 4. This has now been clarified in the text as below: *The agreement, however, is not as good for these two years as for the mean values*.

P5787 L13: My guess is that it is not the simple ELA estimate that results in wrong ELAs, but the model being not capable of representing the surface MB correctly, resulting in wrong ELA estimates.

For the three first glaciers we agree that the differences in ELA are related to the simulated CMB. However, at Hansbreen, it is more challenging to find a single ELA, as the measured MB profiles suggest multiple ELA for some years (see figure 3). We have however modified the text to better reflect this:

To look further at temporal variations, we compare modeled ELA to that derived from stake measurements (Fig. 4). In general there is good agreement both in terms of ELA as well as interannual variability, with the exception again being Hansbreen. Here the model strongly overestimates ELA, in accordance with the underestimation of b_w (Fig. 3). However, at this glacier, the observed mass balance – elevation relationship shows considerable non-linearity, with the observations indicating zero b_n at several elevations during some years, rendering ambiguous ELA estimates. For the other three glaciers the model simulates ELA well, including the large difference between Kongsvegen and Holtedahlfonna, which are located close to each other (Fig. 1).

P5787 L27: Do you have any information from observations about the role of snowdrift redistribution and evaporation on Svalbard?

See reply to comment 9 by referee #1.

P5788 L9: Do you have any idea on how large the contribution of dynamics is? Without any knowledge about that the statement that the comparison is good has no real value.

We have now included the estimate of calving flux (dynamics) from Blaszczyk et al. (2009). These numbers are however still not entirely comparable as is now described. In addition we changed the statement from the comparison being good, to that the model reproduces regional differences very well:

Note that measured height changes are also a result of glacier dynamics (although the retreat or advance of the calving front was not accounted for). The model, however, does not include any glacier dynamics and the numbers are therefore not directly comparable. Still, both model and satellite data show Austfonna and northeast Spitsbergen to be the only regions with positive surface height change during these years, and northwest Spitsbergen as the region with the largest surface lowering (Table 4). The other three regions all show moderate lowering in both estimates. The model therefore seems to capture regional differences very well during this period. The mass loss from calving flux has been estimated to be 6.75 km3 yr-1 (w.e.) for the years 2000-2006 (Blaszczyk et al., 2009), which corresponds to an additional lowering of about 0.2 m yr⁻¹. This suggests that the model in general simulates too much surface lowering in this period. However the time periods are different.

and the estimate of Moholdt et al. (2010) does not include the effect of retreat or advance of the calving front. One must therefore still be cautious when comparing these numbers.

Sensitivity to model resolution:

P5789 L6: Why did you choose an extreme case instead of an average/representative case?

Due to the high computational cost of simulating 1km resolution, we chose a period with many precipitation events in all regions of Svalbard in relatively short time. Selecting a more average year would mean that the simulation period would have to be extended to get the same number of precipitation days or the same amount of precipitation.

P5789 L9: How is this difference related to the different estimated glaciated area on 9 an 3 km resolution.

This difference does not seem to be related to different glaciated area in the two resolutions. For the BE region, where the difference in specific mass balance is largest, the glaciated area is almost the same (R9: 2592 km2, R3: 2628 km2).

Climatic mass balance:

P5790 L26: Consider adding a table presenting average and standard deviations of the information presented in figures 9 and 10 in order to quantify the interannual variability and the regional variability therein.

Thank you for this suggestion. We have now included this in a new table (Table 5).

Discussion:

P5792 L4 and L21: I guess the better results are largely related to the resolution of your model run, 3 km vs 10 km for Lang et al, and 25 km for Day et al. Furthermore, Day et al do not actually calculate the surface mass balance since they do not have a snow model that calculates the melt. I am therefore not surprised by the better results. This should be stressed more.

Thank you for this comment. We have now modified the text to make both of these points more clear:

Both of these studies compare their results with ice core measurements in accumulation areas (Pinglot et al., 1999; Pinglot et al., 2001), <u>although DA12 only includes accumulation and not melting</u> <u>in their simulation</u>.

<u>Some of the improvement found in the present study can probably be attributed to the increased</u> <u>model resolution. Both smaller elevation differences between stations and the model grid cell and</u> <u>better resolved surrounding topography likely improved the results.</u> We also note here that our results do not cover the same time periods as DA12 and LA15b, so that the quality of the boundary conditions might differ. <u>However, LA15b reports relatively small biases for ERA-Interim (between -</u> <u>1.95 and 2.24 °C) despite similar or larger elevation differences and covering the same period as</u> <u>LA15b. Also, the large increase in resolution from DA12 (25 km) to LA15b (10 km) is not accompanied</u> <u>with a clear improvement in the mass balance simulation.</u> It therefore seems clear that the WRF-CMB model with the setup used here offers a real improvement over DA12 and LA15b.

P5794 L14: Explain how you apply this 30%? Or perhaps phrase differently: we had to limit the stability correction of turbulent fluxes to prevent too stable conditions to occur.

Thank you for this comment. We have now rephrased this in the following way: Based on their results, and to avoid runaway cooling of the glacier surface during stable conditions in the winter, we limited the reduction in the turbulent fluxes in stable conditions to 30%, consistent with previous studies (Martin and Lejeune, 1998; Giesen and others, 2009; Collier et al., 2015).

Conclusion:

P5795 L24: Thus the year to year variability is temperature driven? In combination with length of the melt season?

It seems that temperature is an important factor in the year to year variability. This study is however not suited to draw definite conclusions about this, which should be better reflected in the new text: *The largest component in the summer surface energy balance driving this melting is the radiation imbalance, even though temperature dependent latent and sensible heat fluxes also contribute to much of the year-to-year variability, especially during the years with anomalously large mass loss. More research is however needed to better understand the drivers of this variability.*

Tables:

T1: Is the depth scale in cm w.e. or cm snow?

This refers to the physical snow depth, which is now specified in the table. A error in this table has also been corrected: the depth scale should be 3.0 cm, not 30 cm.

Figures:

In general ALL your figures must be bigger.

All figures have now been made larger. In particular, we have increased the size of most individual figure panels. It should however be noted that the discussion paper layout makes the figures appear very small, and should appear larger in a final printed version.

F1: Increase figure size, especially axis labels of overlay figure bottom right.

This has been increased.

F2: Increase figure size, especially the bars indicating precipitation.

The four panels have now all been made bigger. We have also tested increasing the size of the bars, but this would make them overlap for Kongsvegen 2013.

F3: Increase figure size, I can't judge the differences, they are too small. Furthermore, consider adding uncertainty bars indicating interannual variability in terms of standard deviation.

Again the individual panels have been made larger, as well as the lines smaller, which should make it easier to see the differences. With data from only 10 years we considered the two extreme years to give as much information about the spread of the results as the standard deviation.

F4: Increase vertical axis in size to enhance the interannual variability.

This has now been done.

F5: Increase figure size, especially the inset figures in b and d are much too small. Furthermore, check the caption, it refers to 2005 while above the figure it states 2006.

We agree that the inset figures here became too small. We have therefore replaced figure b and d with the inset figures, as well as corrected the figure caption. Thank you for pointing this out.

F7: Check spelling of Kongsvegen in the caption.

This has now been corrected.

F9: Increase vertical axis in size to enhance the interannual variability.

The vertical axis has now been increased.

References:

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- Simulating the climatic mass balance of Svalbard glaciers
 from 2003 to 2013 with a high-resolution coupled
 atmosphere-glacier model
- 4 The climatic mass balance of Svalbard glaciers: a 10-year
 5 simulation with a coupled atmosphere glacier mass
 6 balance model
- 7
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- 16

17 Abstract

18 In this study we simulate the climatic mass balance of Svalbard glaciers with a coupled atmosphere-glacier model with 3-km grid spacing, from September 2003 to September 2013. 19 We find a mean specific net mass balance of $-\frac{167}{257}$ mm w.e. yr⁻¹, corresponding to a mean 20 annual mass loss of about 8.75.7 Gt, with large interannual variability. Our results are 21 22 compared with a comprehensive set of mass balance, meteorological and satellite measurements. Model temperature biases of 0.197 and -1.9 °C are found at two glacier 23 24 automatic weather station sites. Simulated climatic mass balance is mostly within about $\frac{0.100}{0.00}$ mm w.e. yr⁻¹ of stake measurements, and simulated winter accumulation at the Austfonna ice 25 cap shows mean absolute errors of $\frac{0.0547}{0.0547}$ and $\frac{0.067}{0.067}$ mm w.e. y⁻¹ when compared to radar-26 derived values for the selected years 2004 and 2006. Comparison of modelled surface height 27

changes from 2003 to 2008 from model, and satellite altimetry reveals good agreement in 1 both mean values and regional differences. The largest deviations from observations are 2 found for winter accumulation at Hansbreen (up to around 1000 mm w.e. yr⁻¹), a site where 3 sub-grid topography and wind redistribution of snow are important factors. Comparison with 4 5 simulations using-a 9-km grid spacing reveal considerable differences on regional and local scales. In addition, the 3-km grid spacing allows for a much more detailed comparison with 6 7 observations than what is possible with-a 9-km grid spacing. Further decreasing the grid 8 spacing to 1 -km appears to be less significant, although in general precipitation amounts 9 increase with resolution. Altogether, the model compares well with observations and offers possibilities for studying glacier climatic mass balance on Svalbard both historically as well 10 11 as based on climate projections.

12

13 **1** Introduction

The Svalbard archipelago has a glacierized area of ca. 34,000 km² (Nuth et al., 2013), 14 representing ~4 % of the world's land-ice mass outside the Greenland and Antarctic ice 15 sheets. If completely melted, the glaciers on Svalbard could potentially contribute to sea level 16 17 rise of 17 ± 2 mm sea level equivalent (SLE; Martin-Espanol et al., 2015). The archipelago has already experienced significant warming during the 20th century (Førland et al., 2011) 18 19 and, with the expected retreat of the sea ice margin, further warming as well as precipitation 20 increases areis expected (Day et al., 2012). Projections presented in the latest assessment report of the IPCC (AR5) shows that annual-mean temperatures in this region could rise 21 22 between 7 and 11 °C by the end of the 21st century under the RPC8.5 scenario, accompanied 23 by a projected precipitation increase between 20-50% (IPCC 2013). Svalbard glaciers are 24 therefore expected to undergo significant changes during this century (Day et al., 2012; Lang 25 et al., 2015a). However, reliable estimates of future glacier changes require modelling tools that we are able to reproduce recent observations. Current model estimates based on global 26 climate datasets (Marzeion et al., 2012; Marzeion et al., 2015) show significantly more 27 28 negative mass balance in this region than satellite altimetry and satellite gravimetry over the 29 last decade (Moholdt et al., 2010; Matsuo and Heki 2013).

Regional model estimates of surface or climatic mass balance of Svalbard glaciers have so far
mainly focused on individual or a few glaciers, and as noted by Lang et al. (2015b) typically
been based on empirical or statistical models (Lang et al., 2015b). A number of dynamical

downscaling simulations focusing on Svalbard glaciers also exist have been performed (Day 1 2 et al., 2012; Claremar et al., 2012; Lang et al., 2015a; Lang et al., 2015b). However, only two of these studies compare their output with mass balance observations: Day et al. (2012; 3 hereafter DA12) compares precipitation from HadRM3 RCM (25-km grid spacing) with 4 5 surface mass balance estimates from Pinglot et al. (1999), and Lang et al. (2015b; hereafter LA15b) compares output from the MAR model (10 km) to Pinglot et al. (1999, 2001) as well 6 7 as a number of altimetry and gravimetry studies of Svalbard glacier mass balance (Wouters et 8 al., 2008; Moholdt et al., 2010; Nuth et al., 2010; Mémin et al., 2011). Both studies show fair 9 agreement with multi-year accumulation records from Pinglot et al. (1999,2001). LA15b also finds Svalbard mean elevation changes in good agreement with satellite estimates, even 10 11 though the differences are substantial for some regions. However, DA12 and LA15b do not 12 validate mass balance estimates on time scales shorter than 4 years, nor do they validate on 13 spatial scales that can capture variations on individual glaciers. DA12 also suggests that a grid 14 spacing of 1-5 km may be needed to simulate surface mass balance in the complex terrain that 15 is typical for Svalbard.

16 In this study, we aim to i) simulate the climatic mass balance (CMB) of Svalbard glaciers 17 with a higher resolution than previously used with dynamical downscaling, ii) validate the model with an extensive set of observations in this region, and iii) investigate the spatial 18 resolution needed to describe the observations. further reduce the spatial and temporal gap 19 between observations and models, as well as to utilize a more extensive set of in situ 20 21 measurements available in this region for model validation. We apply a coupled atmosphere-22 glacier mass balance model to the entire Svalbard region with a horizontal grid spacing of 3 23 km, thereby capturing both regional averages for the period 2003-2013 as well as temporal and spatial variations of individual glaciers. The results are validated with (i) observations 24 25 from weather stations, (ii) mass-balance stakes from four glaciers, (iii) snow accumulation 26 across Austfonna, measured by ground-penetrating radar (GPR), and (iv) satellite altimetry. 27 To examine the importance of model resolution in this region we also compare results from 28 domains with 9-km and 3-km grid spacing, and for a selected month, precipitation results 29 from 9-km, 3-km and 1-km grid spacing domains. Through this high-resolution simulation 30 and extensive model evaluation, we aim to provide a detailed estimate at enhanced reliability of the simulated recent climatic mass balance (CMB) of Svalbard glaciers, including its 31 32 spatial and temporal variations. and related variables required to quantify the state of Svalbard 33 glaciers.

2 2 Methods

1

3 In the following sections, we describe the two components of the coupled modelling system: the Weather Research and Forecasting model (WRF; Sect. 2.1) and the CMB climatic mass 4 5 balance model (Sect. 2.2), including optimizations made in this study for high-Arctic conditions made in this study. In Sect. 2.3, we describe the different validation data and sites 6 7 before clarifying comparison methods in Sect. 2.4. Throughout this study we distinguish 8 between the surface mass balance (SMB) and the CMB as recommended by Cogley et al. 9 (2011). The SMB specifies mass changes between the surface and the last summer surface, whereas the CMB also accounts for internal accumulation and ablation (i.e. below the last 10 summer surface). We consider internal ablation as negligible and it is therefore not explicitly 11 treated in our application. 12

13 2.1 The Weather Research and Forecasting model (WRF)

The WRF model is a state-of-the-art mesoscale atmospheric model (Skamarock and Klemp, 14 2008) widely used for research and forecasting applications. In Svalbard, the model has been 15 16 used to study both atmospheric boundary layer processes (Kilpeläinen et al., 2011; 17 Kilpeläinen et al., 2012), and atmosphere-land surface interactions over both tundra (Aas et 18 al., 2015) and glaciers (Claremar et al., 2012), with horizontal grid spacing ranging from sub-19 kilometer scales to several tens of kilometers to sub-kilometer scales. In this study, we use the advanced research WRF version 3.6.1 configured with two nested domains of 9-km and 3-km 20 21 horizontal grid spacing. For a single month we also simulate the main regions of interest with 22 additional nested domains at 1-km. The WRF model setup and forcing strategy follows that of 23 Aas et al. (2015). The outer domain (9-km) covers a region of 1080 x 1080 km. As boundary 24 conditions for this domain we use the using ERA-Interim reanalysis (Dee et al., 2011) with a 25 6-hour temporal resolution. We employ the default boundary configuration in WRF, with the 26 outermost grid-point specified, followed by a four-grid-point relaxation zone. as lateral 27 boundary conditions. It From the outer domain the model is one-way nested down to the 3-km 28 domain covering all of Svalbard (Fig. 1). Within both domains the model is allowed to freely evolve (i.e. no nudging or re-initialization), and sea surface temperatures and sea ice fractions 29 30 are prescribed based on the OSTIA dataset (Donlon et al., 2012). The physical 31 parameterization options in WRF follow Aas et al. (2015) with the exceptions of the boundary

layer and surface layer parameterizations, the vertical model resolution, and the use of explicit 1 2 6th order horizontal advection diffusion, which are selected following Collier et al. (2013). In addition, we use the newer NoahMP land surface scheme to simulate surface conditions and 3 fluxes at non-glaciated grid cells, as it includes improved snow physics and multiple layers in 4 5 the snowpack over the original Noah scheme (Niu et al., 2011). All three model domains use the same vertical resolution (40 eta layers up to a model top of 25 hPa) and physical 6 7 parameterizations, with the exception of the cumulus convection scheme that is only 8 employed in the outer (9-km) domain.

9 To reduce computational time, we perform two five year, transient simulations (2003-2008 10 and 2008-2013), both with a one-day spin-up for the atmosphere. We initialize glacier grid cells using results from an earlier simulation with a non-optimized version of WRF-CMB 11 12 covering the same period. The first period has been initialized with the results for the year 2007, as no spin-up results are available for 2003, whereas the second period has been 13 initialized with results for that year (2008). Comparing the initialization of the second period 14 (starting in 2008) and the final results from the first period show there is good agreement for 15 firn and snow outlines, making it far superior to the default uniform initialization. The 16 17 simulation was performed as one transient 10-year simulation, with a one-day spin up for the 18 atmosphere. The glacier grid points were initialized with output from an earlier simulation 19 with another version of the WRF-CMB model. This did not include results valid for 2003, so a representative year (2007) was used for initialization. Although not accurate, this was 20 considered far more realistic than the default uniform initialization. The one-month sensitivity 21 22 simulation with 9-km, 3-km and 1-km grid spacings has been performed as an isolated 23 additional simulation with initialization directly from ERA-Interim to avoid problems with 24 different spin up times for the different domains.

25 **2.2** The glacier CMB climatic mass balance model

The land surface schemes in WRF have become more advanced in terms of representing snow processes in the recent years, but still only simulate a few snow layers (up to three for NoahMP). They therefore have limitations when it comes to simulating the development of deep multiyear snow packs in the accumulation area of Svalbard glaciers, as well as realistically representing different glacier facies (snow, firn and ice) during the ablation season. We therefore used For glacier grid cells, a modified version of the glacier climatic mass balance (CMB) model of Mölg et al. (2008, 2009)-is used_to simulate glacier_grid cells

processes and surface fluxes. The CMB model uses near surface temperature, humidity, 1 2 pressure, winds, as well as incoming radiation and precipitation as input from WRF, and computes the column specific mass balance from solid precipitation, surface and subsurface 3 melt, refreezing, and liquid water storage in the snowpack, and surface vapor fluxes. The 4 5 model solves the surface energy balance (SEB) to determine the energy available for surface melt, and resolves the glacier subsurface down to a user defined depth (here of 20 m divided 6 7 into 17 vertical layers). For glacier grid cells, the CMB model updates surface mass and 8 energy fluxes fields used in the WRF model, as well as surface (e.g., temperature,; surface 9 roughness, and albedo), resulting in a two-way coupled model system (WRF-CMB). Further information about the interactive coupling between the CMB model and WRF is given by 10 11 Collier et al. (2013, 2015).

12 We make two adjustments to the CMB model to improve its suitability for Svalbard 13 conditions. First, the albedo scheme (originally based on Oerlemans and Knap, 1998) has been modified to include a separate value for firn albedo (in addition to the standard 14 15 categories of fresh snow, old snow, and ice). Firn is defined here as snow remaining from the last summer. Secondly, we introduce different aging models for snow (which determines the 16 17 transition from fresh to old snow) for melting and sub-melting temperatures, by multiplying the snow aging parameter by a factor (warmfact, Table 1) when skin temperatures are at the 18 19 melting point. The various albedo parameters (Table 1) have been selected based on 20 observations at Austfonna, and thereafter adjusted to improve the simulated summer mass 21 balance compared to in situ observations during one test year (2005-2006; see also Sect. 22 6.1.1).

23 Finally, we note that some glacier grid cells are affected by a numerical issue causing 24 unrealistic sub-surface melting in the bottom snow layer, leading to unrealistically low 25 corresponding CMB values. We were not able to pinpoint and remove the exact problem and therefore excluded sub-surface melting during the months October to May. This greatly 26 reduced the effect of this problem with very little effect on all other grid cells. When averaged 27 over the entire glacier area, this correction gave a CMB contribution of 1-17 mm w.e. yr⁻¹, 28 with an average value of 8 mm w.e. yr⁻¹ (less than 1% of the average annual surface melt). 29 This can therefore be considered as a minor correction to the total CMB, even if it is locally 30 31 important.

1 2.3 Validation data and sites

2 Table 2 provides an overview of the datasets used for model evaluation. We selected four 3 glaciers, described in more detail below, all of which have mass balance stake measurements 4 at six or more locations, covering all or most years in our study period. The selected sites 5 represent different conditions in terms of glacier geometry, geographical location, local 6 meteorology, altitudinal range, and spatial extent (Fig. 1). Annual measurements of stake 7 heights above the snow surface, snow depth, and density yield specific values of summer and 8 winter mass balance (b_s and b_w), which are combined to give the specific net mass balance, $b_{n_{\overline{1}}}$ or surface mass balance (SMB) for each balance year (i.e. between two consecutive end-of-9 10 summers).

GPR measurements of snow accumulation along several transects across the Austfonna ice cap were made each spring in the period 2004-2013. Snow water equivalent (SWE) values are derived from the radar estimated snow depths multiplied with by snow density determined at several snow pits, as described in more detail by Dunse et al. (2009).

15 Meteorological records at hourly resolution are available from two AWSs, one at Austfonna and one on Kongsvegen. Both datasets contain some data gaps. We extract hourly 16 17 measurements of air temperature (~2 m) and radiation (incoming and outgoing short- and 18 long-wave), to calculate daily means, excluding days with incomplete records. Albedo is 19 calculated as the ratio of the outgoing (SW_{out}) to incoming (SW_{in}) shortwave radiation, excluding observations outside the range [0.15, 0.95] or with $SW_{in} < 10 \text{ W m}^{-2}$. We estimate 20 21 daily mean albedo using the five hourly observations closest to solar noon, to minimize the 22 effect of low solar angle with associated large variations in measured albedo (Schuler et al., 23 2013).

A geodetic mass-balance estimate from repeat satellite altimetry for the period 2003-2008 (Moholdt et al., 2010) serves as an independent validation of the surface height changes due to climatic mass balance processes. However, it should be kept in mind that the geodetic mass-balance reflects both climatic and dynamic mass balance, i.e. it includes mass transfer from higher to lower elevations and losses due to calving at marine termini. We use the regional mean values between 2003 and 2008 according to Fig. 1.

1 2.3.1 Austfonna ice cap, Northeast Svalbard

The Austfonna ice cap in the northeastern part of Svalbard (centered at 79.7° N, 24.0° E) is 2 the largest ice cap of the archipelago. It covers an area of 7800 km² and has a simple dome-3 shaped topography, rising from sea level up to an elevation of ~800 m a.s.l. (Moholdt and 4 5 Kääb 2012). The recent CMB of Austfonna was nearly in balance (Moholdt et al., 2010), yet 6 the ice cap was losing mass due to calving and retreat of the marine margin (Dowdeswell et 7 al., 2008). Snow accumulation is spatially and temporally heterogeneous; and accumulation 8 is asymmetrical across the ice cap, with amounts in the southeast being double the amounts in 9 the northwest, and there is large interannual variability along all profiles (Pinglot et al., 1999; 10 Taurisano et al., 2007; Dunse et al., 2009).

Since spring 2004, field measurements have been performed annually by the University of Oslo and the Norwegian Polar Institute. Available data include records from about 20 mass balance stakes, annually repeated GPR and kinematic GNSS (Global Navigation Satellite System) profiling across the ice cap, and snow pit investigations of snow depth and density (Taurisano et al., 2007; Dunse et al., 2009). In the present study we compare GPR-derived winter accumulation with the corresponding WRF-CMB results, averaging all available in situ measurements within a particular WRF-CMB grid cell (Sect. 3.3).

Etonbreen is located at the western part of Austfonna, with six stakes, and an AWS operated since 2004. The AWS is located at 22°25'12'' E, 79°43'48''N and 370 m a.s.l., just below the mean equilibrium line altitude (ELA) atof ~400m (Schuler et al., 2013).

21 2.3.2 Kongsvegen and Holtedahlfonna, Northwest Spitsbergen

22 Kongsvegen (78.8°N, 13.0°E) and Holtedahlfonna (79.0°N, 13.5°E) are both located near Ny-

- 23 Ålesund, in northwest Spitsbergen.
- 24 Kongsvegen is a $\sim 100 \text{ km}^2$, ~ 27 -km long valley glacier extending from an ice divide at ~ 800

25 m a.s.l. down to sea level. Outflow at its marine terminus is restricted by its fast-flowing

- 26 neighbor Kronebreen, with which Kongsvegen shares a small fraction of the calving front.
- 27 The Norwegian Polar Institute has measured winter and summer mass balance at nine stakes
- since 1986 (Hagen et al., 2003; Nuth et al., 2012; Karner et al., 2013). Kongsvegen is a surge-
- 29 type glacier, currently in its quiescent phase, since the last surge around 1948. Observed
- 30 elevation changes are dominated by the SMB (Melvold and Hagen 1998).

- 1 North of Kongsvegen is Holtedahlfonna, the upper catchment of the Holtedahlfonna-
- 2 Kronebreen glacier system, whose total area is \sim 390 km², and which extends up to an
- 3 elevation of ~1400 m a.s.l. SMB has been studied on Holtedahlfonna since spring 2003, using
- 4 ten mass-balance stakes.
- 5 Stakes at both glaciers are measured in nearly all years in spring and at the end-of-summer,
- 6 typically in early September. During the last two decades, the SMB of both glaciers has
- 7 changed from close to zero to increasingly negative values (Kohler et al., 2007; Nuth et al.,
- 8 2012). Since spring 2000, an AWS has been operated on Kongsvegen, at 78.76°N, 13.16°E at
- 9 537m a.s.l., close to the equilibrium line altitude (ELA; (Karner et al., 2013).
- 10 2.3.3 Hansbreen, Southern Spitsbergen

Hansbreen (77.1°N, 15.6°E) is located in the southern part of Spitsbergen, and covers an area
of ~56 km². It is a 15 km long valley glacier, extending from its ~1.5km wide active calving
front in Isbjornhamna, Hornsund, up to an ice divide at ~490 m a.s.l. The Hansbreen system
consists of the main trunk glacier and 4 tributary glaciers on the west side (Grabiec et al.,
2011). SMB on Hansbreen has been is studied since 1989 when 11 mass balance stakes were
deployed along centerline of the glacier. Since 2005 these stakes are measured on <u>a</u> weekly
basis in ablation zone and on <u>a</u> monthly basis in accumulation area (Grabiec et al., 2012).

Snow accumulation on Hansbreen is highly variable. Earlier studies show that there is a strong asymmetry between eastern and western side of the glacier. Minimal snow accumulation is observed in southern part of the tongue and along eastern side of the glacier. On the east side, the glacier is bordered by the massif of Sofiekammen, which forms an orographic barrier for advecting air masses. Therefore, a foehn effect is widely observed during strong easterly winds, causing deflation of snow and redeposition towards the western side of the glacier (Grabiec et al., 2006).

25 **2.4 Comparison methods**

We compare our model results with AWS (Sect. 3.1) and stake (Sect. 3.2) data using the WRF-CMB grid point nearest to each data point. All stakes on a glacier are compared with the corresponding grid cells to yield information both about mean values as well <u>as</u> gradients along the glacier. The ELA (also Sect. 3.2) is calculated by linear interpolation of the two stakes or grid cells with the least positive and negative mass balance. When all stakes or grid cells have the same sign, we use the maximum and minimum value to extrapolate to the ELA.
 Note that the CMB simulated by WRF-CMB also includes internal refreezing below the last
 summer surface (LSS), which is not captured by the stake SMB.

4

5 3 Model validation

6 The main goal with this study is to evaluate the ability of the WRF-CMB model to reproduce 7 measured CMB and height changes at Svalbard over the study period, both on the regional 8 and local scales. In the following sections, we assess the model performance by comparing 9 the simulated SEB and temperature with the AWS data (Sect. 3.1); the CMB at the four 10 glaciers with stake measurements (Sect. 3.2); the winter accumulation at Austfonna with GPR 11 measurements (Sect. 3.3); and, finally, the simulated regional height changes over the first 12 five years of the study period with the altimetry data (Sect. 3.4). All model results in this 13 section are from the 3-km domain.

14 **3.1 Weather stations**

15 The AWSs provide key information about the conditions at the glacier surface throughout the 16 year, and therefore permit a detailed evaluation of important aspects of the model. Table 3 17 compares simulated and observed air temperature, radiation fluxes, and albedo at Kongsvegen 18 and Etonbreen. Note that the model grid points are 44 m and 29 m lower than the station 19 heights at these two locations, respectively. At Kongsvegen the simulated temperature compares very well with observations, with a bias of less than 0.192 °C and correlation of 20 daily mean values of 0.98. At Etonbreen the simulated temperatures are somewhat too low (-21 22 1.9 °C), but with a similar correlation (0.967). The radiation components also show better agreement at Kongsvegen than at Etonbreen. At Kongsvegen, biases ranging from 0.34 W m⁻² 23 (outgoing longwave, LW_{out}) to -6.96 W m⁻² (incoming longwave, LW_{in}), whereas the 24 radiation biases at Etonbreen vary from -4.0 (LW_{out}) to -123 W m⁻² (SW_{in} and LW_{in}). There is 25 also a noticeable albedo bias of -0.1008 at Etonbreen, compared to only -0.053 at 26 27 Kongsvegen.

A more detailed comparison of simulated and observed albedo from the summers of 2008 and 29 2013 is shown in Fig. 2, along with simulated solid and liquid precipitation. Overall, the 30 model simulates well both the magnitude and temporal changes in albedo. The close 31 connection between simulated solid precipitation events and observed albedo increase

indicates that the model adequately captures both the timing and phase of the summer 1 2 precipitation. The simulated albedo response to solid precipitation is also similar to 3 measurements, except for at Etonbreen in 2013. Here the model does not simulate a large enough increase in albedo after snow events, which might indicate that the model is not 4 5 sensitive enough to small amounts of snow on ice (i.e. too large depth scale in Table 1), or underestimates precipitation or its frozen fraction simulates too little snow on these occasions. 6 7 Additionally, the model underestimates snow albedo during much of the summer in 2008, and 8 at Etonbreen also simulates some periods with blue ice. While the observations show a very 9 slow decrease in albedo over this summer, the modeled albedo quickly drops to values below 0.7. This could be related to the almost complete lack of rain events during the summer of 10 11 2008. In 2013, on the other hand, the model simulates numerous and large rain events during 12 the summer, which seems to coincide with observed drops in albedo. This suggests that snow 13 wetness needs to be accounted for in the albedo parameterization to realistically simulate 14 snow albedo on Svalbard, and that the snow aging parameters used here (Table 1) are more 15 appropriate for wet rather than dry summer conditions.

Altogether, the model seems to reasonably reproduce the local conditions at the AWS stations. Individual radiation biases are found, which are likely to impact the quality of the CMB estimations negatively. However, this is a known challenge in the Arctic, where atmospheric models often show significant biases in key cloud properties (Morrison et al., 20 2009).

21 3.2 Stakes

Fig. 3 shows mean annual (b_n) , winter (b_w) , and summer (b_s) CMB at each stake over the study period. Overall, the model reproduces the mean observed mass balances well, including differences in mean values between the four glaciers and the gradients at each glacier. The main exception is the winter balance at Hansbreen, which is considerably underestimated by the model (see also-Sect. 4). Hansbreen also shows large variations along the glacier, both in b_s and b_w , which the model is not able to reproduce.

Looking at individual years, the model correctly identifies the years 2004 and 2008 as having anomalously low and high mass balance, respectively (Fig. 3, stippled lines). The agreement,

30 however, is not as good <u>for these two years</u> as for the mean values.

1 To look further at temporal variations, we compare modeled ELA to that derived from stake 2 measurements (Fig. 4). In general there is good agreement both in terms of ELA height as well as inter-annual variability, with the exception again being Hansbreen. Here the model 3 4 strongly overestimates ELA, in accordance with the underestimation of b_w (Fig. 3). However, 5 Aat-Hansbreen this glacier, the observed mass balance – elevation relationship showsreveals considerable non-linearity, with the observations indicating zero b_n at several elevations 6 7 during some years, rendering ambiguous ELA estimates., and the simple ELA estimation (Sect. 2.4) used here might be inappropriate. For the other three glaciers the model simulates 8 9 ELA well, including the large difference between Kongsvegen and Holtedahlfonna, which are 10 located close to each other (Fig. 1).

11 **3.3 GPR-derived snow profiles**

12 To evaluate the winter-mass balance simulated by WRF-CMB, we compare simulated 13 precipitation across Austfonna between early September and early May with observations of 14 snow accumulation by GPR. The results from May 2004 and May 2006 (Fig. 5) demonstrate the large inter-annual variability in the total amount of snow, with 2004 and 2006 15 representing a low (Fig. 5a) and high (Fig. 5bc) accumulation year, respectively. WRF-CMB 16 17 captures the spatial pattern and total amount of snow very well, with average biases of less than 1% and ~3% about 2% and 6% and mean absolute errors (MAEs) of 0.0547 and 0.067 18 mm w.e. yr⁻¹ in 2004 and 2006 respectively. Local differences, for example an overestimation 19 of snow within the ablation area towards the lower end of the western profile in both years 20 21 (Fig. 5b,d) may partly be explained by wind erosion, which is not represented in the model. 22 The model also tends to slightly underestimate snow accumulation in the summit area, which 23 again could be related to wind redistribution of snow, or by a negative elevation bias of the 24 WRF-CMB DEM which is on average $\sim 20-50$ m lower than the average position of the GPR 25 measurements.

26 3.4 Satellite altimetry

We perform a regional evaluation of the simulations by comparing surface height changes
with those measured by satellite altimetry in the period 2003-2008 (Moholdt et al., 2010).
Note here that measured height changes include the effect of are also a result of glacier
dynamics (although the retreat or advance of the calving front was not accounted for). The
model, however, does not include any glacier dynamics and the numbers are therefore not

directly comparable. which are not simulated by the model. Still, the comparison shows good 1 2 agreement for each of the six regions, as well as for Svalbard as a whole (Table 4). B, both model and satellite data show Austfonna and northeast Spitsbergen to be the only regions with 3 positive surface height change during these years, and northwest Spitsbergen as the region 4 5 with the largest surface lowering (Table 4). The other three regions all show moderate lowering in both estimates. The model therefore seems to capture regional differences very 6 7 well during this period. The mass loss from calving flux has been estimated to be 6.75 km3 yr-1 (w.e.) for the years 2000-2006 (Blaszczyk et al., 2009), which corresponds to an 8 additional lowering of about 0.2 m yr⁻¹. This suggests that the model in general simulates too 9 10 much surface lowering in this period. However the time periods are different and the estimate 11 of Moholdt et al. (2010) does not include the effect of retreat or advance of the calving front. 12 One must therefore still be cautious when comparing these numbers.

Together, these results show that the model captures the spatial and temporal variability in 13 CMB across Svalbard well, with mean values in fair agreement with observations. both the 14 mean CMB value, as well as its spatial and temporal variability across Svalbard well. The 15 largest model errors are found at Hansbreen, but this glacier alsowhich has both the largest 16 17 cross-glacier variability in accumulation, as well and as a relatively steep accumulation 18 gradient, such that the stake measurements may not correlate as well to the model as at other 19 sites with a greater degree of spatial homogeneity. This raises the question about the 20 sensitivity of model resolution in relation to capturing the main topographic features.

21

22 4 Sensitivity to model resolution

Svalbard topography is relatively rugged, with fjords, tundra, glaciers and mountains all 23 found in close proximity to each other. Dynamical downscaling requires a discrete 24 25 representation of the topography and has therefore limited spatial resolution, which potentially can be insufficient to resolve a number of small-scale processes. In thise following 26 27 section, we investigate the sensitivity of simulated CMB to model resolution by comparing CMB-results from the 9-km and 3-km domains for the entire model period. We then evaluate 28 29 precipitation amounts and distribution in a separate-the simulations with 9-km, 3-km and 1km grid spacings (hereafter R9, R3 and R1, respectively) in the selected of the month of 30 31 October 2007, which was among the wettest months in the 10-year period, with a number of 32 smaller and larger precipitation events.

1 Fig. 6 shows the mean annual R9 and R3 CMBs in R9 and R3 over the entire period. When 2 averaged across all of Svalbard, the difference in CMB is relatively small (less than 10~30 mm w.e. yr⁻¹). On a regional scale, however, differences are more substantial, with the 3 southeastern islands (BE region in Fig. 1) having <u>almostmore than</u>_100 mm w.e. yr⁻¹ more 4 5 negative mass balance in R9 than in R3. The small-modest difference found when averaging across the entire archipelago is therefore seems to be at least partly due to compensating 6 7 regional differences. On the local scale, differences are even more pronounced. The lack of 8 small glaciers in R9 gives large ice-free areas compared with R3 (e.g. in much of central 9 Spitsbergen). The CMB gradient is also often larger in R3 than R9, as higher maximum and 10 lower minimum values are resolved, which is likely key .- Ffor long-term model simulations, 11 where geometry adjustments of glaciers are to be considered, resolving the adequate range of 12 CMB would be important.considered.

13 The level of detail resolved also plays an important role in model evaluation, especially when 14 comparing to in situ point measurements. Fig. 7 shows the terrain height in the three regions 15 with stake measurements, at the resolutions for R9, R3 and R1. Here we see new topographic features and a more detailed coastline emerging with each increase in resolution. In R9 the 16 topographic gradients along the glaciers with stakes are mostly too low, and many stakes 17 18 maps on to the same grid cell. Conversely, in R3 most stakes maps on to individual grid cells 19 and the altitudinal range is in better agreement with the stakes (see also Fig. 3). Still, there are 20 distinct topographic features around these four glaciers that only emerge in R1. For example, 21 the model represents Hansbreen, Kongsvegen and the upper part of Holtedahlfonna as valley 22 glaciers only at this resolution. The simulated precipitation from October 2007 with the three 23 resolutions (Fig. 8) also shows distinct differences between the three resolutions. At Etonbreen, the shape of the precipitation curve along the glacier is very different in R9 24 25 compared with R3 and R1. The other three glaciers show more linear increases in precipitation with altitude during this month at all three resolutions. Still the precipitation 26 27 amount varies and mainly increases with higher resolution, with local differences of up to 28 about 50 mm (25 %), at Hansbreen (~300 m a.s.l.).

We therefore conclude that increasing resolution from 9-km to 3-km grid spacings is important for simulating precipitation and CMB on local and regional scales, as well as for reliable comparison with in situ point measurements. Increasing the resolution further to 1-km grid spacing seems to have a smaller effect on the four glaciers investigated, although the precipitation amount is further increased. Model resolution might therefore explain some of the negative model bias in b_w (cf. Fig. 3). However, resolution alone does not explain the large b_w bias at Hansbreen.; Instead it is likely that processes like other processes are important for the accumulation pattern at this glacier, for instance wind drift and snow redistribution, are important for the accumulation pattern on this glacier. These processes likely also affect the accumulation at the other glaciers, however their influence is largely unconstrained.

8

9 **5** Climatic mass balance

10 We now turn to simulated annual and seasonal CMB results for Svalbard and the different 11 sub-regions (Fig. 1). As has also been reported in other Consistent with previous studies (e.g. Hagen et al., 2003; Lang et al., 2015b) we find large inter-annual variation in CMB (Fig. 9 12 and Table 5), which precludes trend analysis on the timescales considered in this study. 13 Likewise, our mean mass balance value of -257167 mm w.e. yr⁻¹ is dependent depends on the 14 model period considered; five-year mean values vary from -313227 mm w.e. yr⁻¹ (2009-2013) 15 and -2748 mm w.e. yr⁻¹ (2006-2010). Multiplied with a glacier area of 34 000 km² (Nuth et 16 17 al., 2013), these values is corresponds to a mean annual mass loss of 8.75.7 Gt, 117.7 Gt, or a mean annual mass gain of 1.60.92 Gt, respectively. 18

19 Comparing the two seasons reveals that summer mass balance varies about twice as much as 20 winter mass balance (Fig. 9), indicating that ablation processes vary more from year to year than winter accumulation. This is confirmed from the annual mass fluxes shown in Fig. 10b, 21 with solid precipitation showing much less variability than surface melting. Melting is in turn 22 23 largely a result of the radiation imbalance during the summer months (JJA; Fig. 10a), which on average accounts for about 80 % of the net energy to the surface during these months. 24 25 However, years with anomalously large melting (especially 2004 and 2013) are characterized by much larger than normal sensible and latent heat fluxes at the surface. As these fluxes 26 require indicate warmer and moister air in the atmosphere relative to the glacier surface, these 27 melting anomalies likely result from advection of warm air from outside the region, as was 28 29 also found by Lang et al. (2015b) for the year 2013.

30 For the individual regions we find large differences in simulated CMB that persists 31 throughout the whole period (Fig. 9; right axis). Most noticeably the northeastern regions 32 (AF, VF and NE) show less negative summer balance than the Svalbard average and mostly lower than average winter accumulation. The regions with high winter accumulation in the
 south and east correspond to the regions with the lowest ELA reported by Hagen et al. (2003;
 see also mean annual precipitation and ELA estimates in the Supplement).

4

5 6 Discussion

6 6.1 Comparison with earlier studies

7 We will focus our comparison here with the two regional model studies that report 8 comparison with surface or climatic mass balanceSMB or CMB measurements, namely DA12 9 and LA15b (Sect. 1). Both of these studies compare their results with ice core measurements in accumulation areas (Pinglot et al., 1999; Pinglot et al., 2001), although DA12 only includes 10 accumulation and not melting in their simulation.- DA12 finds biases ranging from -0.240 to 11 0.130 mm w.e. y⁻¹ with a mean absolute error close to 0.100 mm w.e. y⁻¹, whereas LA15b 12 reports biases between -0.310 and 0.140 mm w.e. y⁻¹, also with a MAE of 0.100 mm w.e. y⁻¹. 13 14 Our simulation period does not cover these ice core measurements so that a direct comparison is not possible. Still, the MAEs in winter accumulation at Austforma (Fig. 5) are $\frac{0.0547}{0.0547}$ and 15 16 0.067 mm w.e. y⁻¹ for 2004 and 2006 respectively. At the stake locations, the simulated CMB (Fig. 3) are is mostly within about $\frac{0.100}{0.100}$ mm w.e. y⁻¹ of the observations, except at Hansbreen 17 where it ranges from close to zero to about 1000 mm w.e. y⁻¹. Our CMB results are therefore 18 19 an improvement compared to DA12 and LA15b for CMB-when Hansbreen is ignored (where processes not represented in our model are believed to be important). 20

The near surface temperature biases are in both DA12 and LA15b larger than ours. DA12 reports annual biases "less than 2 °C" for two stations, and "less than 6 °C" for the third (Kongsvegen) and LA15 showed annual biases between -1.3 and -4.0 °C (all negative). We only use data from the two AWSs on the glaciers here, with biases of 0.<u>192</u> and -1.9 °C at Kongsvegen and Etonbreen respectively. These biases span the two-year mean biases found by Claremar et al. (2012), and are also similar to those found by Aas et al. (2015) for the year 2008-2009 (including also tundra sites), both using the WRF model.

Some of the improvement found in the present study can probably be attributed to the increased model resolution. Both smaller elevation differences between stations and the model grid cell and better resolved surrounding topography likely improved the results. We also note here that our results do not cover the same time periods as DA12 and LA15b, so that

the quality of the boundary conditions might differ. Smaller elevation differences between the 1 2 station and the corresponding model grid cell in our 3-km domain compared to DA12 and LA15b probably also contribute to the improvement seen here. However, LA15b reports 3 relatively small biases for ERA-Interim (between -1.95 and 2.24 °C) despite similar or larger 4 5 elevation differences and covering the same period as LA15b. Also, the large increase in resolution from DA12 (25 km) to LA15b (10 km) is not accompanied with a clear 6 7 improvement in the mass balance simulation. It therefore seems clear that the WRF-CMB 8 model with the setup used here offers a real improvement over DA12 and LA15b.

9 6.2 Model uncertainties

In the following section we discuss the main uncertainties in the model results, starting with the atmospheric forcing, before discussing the representation of albedo, turbulent fluxes and sub-surface processes in the CMB model. Although we recognize that the observations have uncertainties and limitations, it is beyond the scope of this study to go into those here.

14 6.2.1 Atmospheric forcing

15 The quality of any CMB simulation depends largely on the atmospheric forcing used. In this study we have used a coupled atmosphere-glacier model in which the atmospheric component 16 17 (WRF) has been well tested for this region. It has been shown to produce temperatures that are in good agreement with observations, and relatively small biases in energy fluxes on 18 19 annual time scales, although they can differ significantly on seasonal and shorter time scales 20 (Aas et al., 2015). Deviations from observations can come both from insufficient 21 representation of processes within the WRF model and from errors in the boundary conditions (here ERA-Interim and OSTIA). However, comparison with weather stations (Sect. 3.1) and 22 23 the results from Aas et al. (2015) show that there is good agreement with observations for the 24 atmospheric part, compared to similar studies (Claremar et al., 2012; DA12; LA15b).

25 6.2.2 Albedo

The albedo parameterization in the CMB model uses a set of parameters that <u>cannot be</u> universally set, but instead<u>likely</u> varies considerably for different locations <u>but is treated as</u> spatially invariant. Initially, these parameters were set based on data from the AWS at Austfonna, where we had the longest series of radiation data. This, however, gave too little summer ablation in general, and these parameters were therefore instead tuned to give

summer mass balance values in line with observations based on a set of sensitivity 1 2 simulations of the year 2005-2006 with the 9--km grid spacing domain. The resulting values (Table 1) are similar to those used by van Pelt et al. (2012). With the complex model system 3 4 used here we cannot perform a set of simulations at the full resolution and time period, but 5 only acknowledge that these values are uncertain, and should ideally vary across the region. Greuell et al. (2007) found MODIS ice albedo values at different glaciers across Svalbard 6 7 between 0.44 (Etonbreen) and 0.13 (Lisbethbreen), which also explains why our initial values 8 from Etonbreen gave too little summer ablation in general. A large step forward for CMB 9 modelling of this region would therefore be to include spatially varying albedo parameters based on satellite measurements. Including snow wetness could also offer improvements for 10 11 simulation of changes in snow albedo with time (see section 3.1).

12 6.2.3 Atmospheric stability

13 We have seen that the sensible and latent heat fluxes are an important part of the SEB during 14 the ablation season (Sect. 5). However, the simulation of these fluxes in stable conditions is a 15 major challenge subject to ongoing research (e.g. Holtslag et al., 2013). In our setup of the 16 CMB model, we use a stability correction based on the bulk Richardson number (Braithwaite, 17 1995) to directly calculate the stability correction of the turbulent fluxes. Conway and Cullen 18 (2013) found that this correction gives to give too low fluxes during stable conditions and low wind speeds at a New Zealand Southern Alps glacier, with simulated turbulent fluxes close to 19 zero when observations showed values between 50-100 W m⁻². Based on their results, and to 20 21 avoid runaway cooling of the glacier surface during stable conditions in the winter, we limited 22 the reduction in the turbulent fluxes in stable conditions to 30%, consistent with previous studies (Martin and Lejeune, 1998; Giesen et al., 2009; Collier et al., 2015).had to limit the 23 24 stability correction of turbulent fluxes to 30% in stable conditions (Collier et al., 2015). Due 25 to these issues, and since they are not measured at the study glaciers, these fluxes also 26 contribute to the overall model uncertainty.

27 6.2.4 Sub-surface processes

As can be seen from Fig. 10b, the sub-surface components of the CMB (refreezing, superimposed ice, subsurface melting, and change in liquid water content) contribute considerably to the total simulated CMB. An important simplification in the CMB model is the use of a bulk snow density, as it is not intended for detailed snowpack studies. For the

highest areas on Austfonna and Northeast Spitsbergen, where the simulated snow and firn 1 2 accumulation depth-reaches values of 14 m during the simulation, this simplification is 3 likelymay be inappropriate. In addition, the CMB model currently calculates superimposed ice as a specified fraction of the internal refreezing of liquid water. Modeling this process is 4 5 challenging, even with a vertically resolved treatment of snow density. Thus, while the inclusion of the sub-surface processes likely offers an important step forward compared to 6 7 only simulating the surface mass balance, the accuracy of these sub-surface processes in the 8 model is uncertain.needs to be improved.

9

10 7 Conclusions

In this study, we have simulated the <u>climatic glacier mass balance (CMB)CMB</u> of the Svalbard archipelago with a coupled atmosphere-glacier model, for the period 2003 to 2013 with 9-km and 3-km grid spacings, as well as with 1-km grid spacing for a shorter period. The results have been compared with extensive observational data from weather stations, mass balance stakes, ground penetrating radar and satellite altimetry. Our main findings are:

- The WRF-CMB model with 3_-km grid spacing and the configuration used here
 reproduces observed CMB on Svalbard very well, from local to regional scales.
- We confirm the need for high <u>spatial</u> resolution (1-5 km grid spacing) to realistically simulate CMB at glacier scale, as suggested by Day et al. (2012). The results from 3-km and 1-km grid spacings show distinct features at local scales that are not present at 9-km, and mean CMB at regional scale differed <u>by</u> up to <u>~-0.100</u> mm w.e. yr⁻¹
 between the 3-km and 9-km simulations.
- Large variations in CMB on small spatial scales reduce the representativeness of
 individual point measurements when compared with grid cells larger than 1-5 km.
- We find large year-to-year variability in average Svalbard CMB on Svalbard during our simulation period, which can be mainly attributed to variations in melting. The largest component in the summer surface energy balance driving this melting is the radiation imbalance, even though temperature dependent latent and sensible heat fluxes also contribute to much of the year-to-year variability, especially during the years with anomalously large mass loss. More research is however needed to better

understand the drivers of this variability.the main feature separating the years with larger than normal melting is large sensible and latent heat fluxes.

3 For the first time, this study presents results from dynamical downscaling of Svalbard CMB at 4 the resolution suggested by Day et al. (2012). In addition, we have utilized a large number of 5 observations on different spatial scales to get a robust evaluation of model performance, 6 thereby representing a considerable step forward in the pursuit of reliable simulations of the 7 CMB on Svalbard. Further improvements to several aspects of the WRF-CMB would be 8 desirable for this region, including using spatially variable albedo parameters and improved 9 representation of sub-surface processes. Still the WRF-CMB model - which has not 10 previously been validated for Arctic conditions - has here been shown to be an appropriate 11 tool for studying Svalbard CMB.

12

1 2

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Parameter	Value
Ice albedo	0.33
Firn albedo (new)	0.50
Old snow albedo	0.63
Fresh snow albedo	0.87
Time scale	15 days
warmfact (new)	5
Depth scale <u>*</u>	3 <u>.</u> 0 cm

Table 1. Albedo parameters used in the CMB model.

* Refers to physical snow depth.

Region	Data	Time period	References			
Austfonna, including Etonbreen	AWS	Hourly, since 2004, some data gaps	Schuler et al., 2013			
	MB stakes	Annually, since 2004	Moholdt et al., 2010; Østby et al., 2013			
	GPR	Annually, since 2004	Taurisano et al., 2007 ; Dunse et al., 2009			
	Snow pits	Annually, since 2004	Dunse et al., 2009			
Kongsvegen	AWS	Hourly, since 2004, some data gaps	Karner et al., 2013			
	MB stakes	Biannually, since 1986	Nuth et al., 2012			
Holtedahlfonna	MB stakes	Biannually, since 2003	Nuth et al., 2012			
Hansbreen	MB stakes	Biannually, since 1988 (two years missing). Weekly/monthly since 2005.	Grabiec et al., 2012			
Svalbard	Satellite altimetry		Moholdt et al., 2010			

Table 2. Description of observations

		Etonbreen		Kongsvegen					
	Bias MAE		Corr.	Bias	MAE	Corr.			
T ₂ (°C)	-1.9	-1.9 2.4		0.1 <u>9</u> 7	1. <u>4</u> 5	0.98			
$SW_{in} (W m^{-2})$	SW _{in} (W m ⁻²) -1 <u>3</u> 2 4 <u>3</u> 2		0.8 <u>1</u> 2	<u>-</u> 0. <u>28</u> 35	2 <u>1</u> 0	0.96			
SW _{out} (W m ⁻²)	W _{out} (W m ⁻²) - <u>109.6</u> 1 <u>76</u>		0.9 <u>3</u> 4	- <u>6.7</u> 4.4	1 <u>9</u> 7	0.96			
LW _{in} (W m ⁻²) -12 25		0.8 <mark>2</mark> 3	-6. <u>9</u> 7	17	0. <u>8990</u>				
LW _{out} (W m ⁻²) - <u>3.8</u> 4.0 11		0.95	0. <u>32</u> 4 3	6. <u>1</u> 3	0.97				
Albedo	Albedo -0. <u>10</u> 08 0.1 <u>2</u> 1		0.7 <u>3</u> 4	-0.0 <u>5</u> 3	0.08	0. <u>80</u> 78			



Table 3. Bias, mean absolute error (MAE) and correlation between simulated and observeddaily mean temperature, radiation and albedo at Etonbreen and Kongsvegen.

	WRF-CMB	Moholdt et al., (2010)
Northwest Spitsbergen	-0. <u>44</u> 36	-0.54
Northeast Spitsbergen	0. <u>02</u> 10	0.06
South Spitsbergen	-0. <u>3325</u>	-0.15
Barenstøya/Edgeøya	-0. <u>35</u> 25	-0.17
Vestfonna	-0. <u>34</u> 22	-0.16
Austfonna	0. <u>05</u> 13	0.11
Svalbard	-0. <u>18</u> 10	-0.11

Table 4. 2003-2008 mean surface elevation change rates (m yr⁻¹) from WRF-CMB and

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 Moholdt et al., 2010. The Svalbard mean value from Moholdt et al. (2010) used here is the mean of the regions included here (Fig. 1) weighted by area.

	<u>Svalbard</u>		NV	V	<u>N</u> E		<u>SS</u>	<u>.</u>	BE		<u>VF</u>		<u>AF</u>	
	<u>Mean</u>	<u>SD</u>	<u>Mean</u>	<u>SD</u>	<u>Mean</u>	<u>SD</u>	<u>Mean</u>	<u>SD</u>	<u>Mean</u>	<u>SD</u>	<u>Mean</u>	<u>SD</u>	<u>Mean</u>	<u>SD</u>
<u>SPR</u>	<u>639</u>	<u>107</u>	<u>588</u>	<u>107</u>	<u>647</u>	<u>118</u>	<u>774</u>	<u>138</u>	<u>703</u>	<u>113</u>	<u>491</u>	<u>91</u>	<u>586</u>	<u>111</u>
<u>REF</u>	<u>141</u>	<u>21</u>	<u>126</u>	<u>23</u>	<u>151</u>	<u>23</u>	<u>143</u>	<u>21</u>	<u>125</u>	<u>18</u>	<u>112</u>	<u>23</u>	<u>152</u>	<u>27</u>
<u>SUI</u>	<u>60</u>	<u>9.2</u>	<u>54</u>	<u>10</u>	<u>65</u>	<u>10</u>	<u>61</u>	<u>9.0</u>	<u>54</u>	<u>7.7</u>	<u>48</u>	<u>10</u>	<u>65</u>	<u>12</u>
<u>DEP</u>	<u>51</u>	<u>7.9</u>	<u>50</u>	<u>7.1</u>	<u>45</u>	<u>6.5</u>	<u>64</u>	<u>11</u>	<u>64</u>	<u>13</u>	<u>47</u>	<u>8.7</u>	<u>44</u>	<u>6.8</u>
<u>MLT</u>	<u>-1000</u>	<u>262</u>	<u>-1090</u>	<u>243</u>	<u>-837</u>	<u>250</u>	<u>-1350</u>	<u>315</u>	<u>-1260</u>	<u>398</u>	<u>-876</u>	<u>271</u>	<u>-776</u>	<u>256</u>
<u>SUM</u>	<u>-124</u>	<u>27</u>	<u>-147</u>	<u>38</u>	<u>-111</u>	<u>26</u>	<u>-148</u>	<u>33</u>	<u>-132</u>	<u>36</u>	<u>-114</u>	<u>32</u>	<u>-98</u>	<u>26</u>
<u>SBL</u>	<u>-26</u>	<u>2.6</u>	<u>-28</u>	<u>3.3</u>	<u>-27</u>	<u>2.3</u>	<u>-23</u>	<u>2.6</u>	<u>-22</u>	<u>3.1</u>	<u>-26</u>	<u>3.2</u>	<u>-28</u>	<u>3.2</u>
<u>DLW</u>	<u>4.0</u>	<u>12</u>	<u>3.1</u>	<u>10.3</u>	<u>5.8</u>	<u>16.8</u>	<u>2.2</u>	<u>10.7</u>	<u>1</u>	<u>6.4</u>	<u>2.7</u>	<u>10.2</u>	<u>5.5</u>	<u>19</u>
<u>CMB</u>	<u>-257</u>	<u>358</u>	<u>-439</u>	<u>376</u>	<u>-62</u>	<u>347</u>	<u>-481</u>	<u>464</u>	<u>-465</u>	<u>484</u>	<u>-314</u>	<u>337</u>	<u>-49</u>	<u>323</u>

Table 5. Mean annual CMB fluxes (mm w.e. yr⁻¹) and standard deviations (SD) for Svalbard

and each sub-region in Figure 1. SPR: solid precipitation, REF: refreeze, SUI: superimposed

ice, DEP: deposition, MLT: surface melt, SUM: sub-surface melt, SLB: sublimation, DLW:

change in snow liquid water.





Figure 1. Main figure: Land areas in the 3-km model domain. Colors indicate glacier grid
cells in different sub-regions and gray indicate non-glacier land grid cells. Stake and AWS
locations at the four main validation glaciers are shown as red * and black *, respectively.
NW: northwestern Spitsbergen, NE: northeastern Spitsbergen, SS: southern Spitsbergen, BE:
Barentsøya and Edgeøya, VF: Vestfonna and AF: Austfonna. Overlay figure: Glacier
hypsometry from 3-km model domain compared with 90m DEM (Nuth et al., 2013).



Figure 2. Simulated (blue) and observed (red) albedo at Etonbreen and Kongsvegen for the
summers 2008 and 2013, with simulated solid (blue) and liquid (yellow) precipitation
indicated as bars.



Figure 3. Simulated (blue) and observed (red) annual, winter and summer mass balance at the
four main validation glaciers. The 10-year mean is indicated by solid lines and the years 2004
and 2008 (negative and positive anomaly, respectively) are shown as dashed lines. Stars
indicate elevation of individual stakes (red) or grid cells (blue).



Figure 4. Estimated ELA from WRF-CMB (blue) and stakes (red) at the four main validationglaciers.



Figure 5. a) Simulated and GPR-derived winter accumulation at Austfonna 1 May 2004. b)
Ratio of simulated to GPR-derived winter accumulation. -Scatterplot of data from GPR
locations in a). Red dots show points located northwest of summit, and black dots show points
located southeast of summit. c) Same as a) for 1 May 20065. d) Same as b) for 1 May 2006.



2 Figure 6. Mean annual CMB (mm w.e. yr⁻¹) from 2003 to 2013 simulated with 9-km (left)

3 and 3-km (right) grid spacings.



Figure 7. Model topography at 9-km-, 3-km and 1-km grid spacings around Etonbgreen (top), Kongsevegen and Holtedahlfonna (middle) and Hansbreen (bottom). Red dots indicate stake locations.



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2 Figure 8. Precipitation during October 2007 at stake locations with 9-km (blue), 3-km (green)

3 and 1-km (red) grid spacing.



Figure 9. (a) annual mean mass balance (m w.e. yr⁻¹) for Svalbard (black, left y-axis) and
regional deviations (colors, right y-axis). (b) same as (a) but for winter mass balance (Sept. to
April). (c) same as for (a) but for summer mass balance (May to August).



Figure 10. (a) Mean summer (JJA) surface energy balance fluxes. Q_R: net radiation, Q_M: melt
energy, Q_{SL}: sensible and latent heat flux, Q_{PRC}: heat from precipitation, Q_C: ice heat flux and
Q_{PS}: penetrating solar radiation. (b) Annual mass fluxes averaged over Svalbard. <u>SPR: solid</u>
precipitation, REF: refreeze, SUI: superimposed ice, DEP: deposition, MLT: surface melt,
<u>SUM</u>: sub-surface melt, SLB: sublimation, DLW: change in snow liquid water. The resulting
CMB is indicated by white dots.