Documentation of the revision

PLEASE NOTE:

• Major changes are listed here below – in addition many small alterations / corrections / additions were made following the suggestions of the referees.

• In the revised manuscript new parts or substantially changed parts are *shaded*. I tried to work with the text editor, but it became very messy.

• Figures have been changed and one new figure has been added (sensitivity for the calving parameter *c*).

• I tried to draw basin outlines in Fig. 2 as suggested by one of the referees. However, the result really disturbs the satellite image and it adds no new information (basin characteristics given in Table 2). So in the end I did not change the picture.

• New references have been added.

• I now use the BCE / CE system to indicate years in the text.

Explaining in more detail the significance of the study (lines 83-94 were added / revised):

> Monacobreen, with a distinct calving main stream and a large number of tributaries, represents a glacier system that is typical for Spitsbergen. The complexity of the geometry as well as the limited amount of data make it a real challenge for a modelling study. Nevertheless, the question of how the mass of such glacier systems will change in the near future has to be considered, and the approach taken in this study is an attempt to do this in a meaningful way. A MGM provides a reasonable match between the paucity of data and an integrated mass budget approach, in which glacier mechanics are parameterized in a simple way. The larger glacier systems on Svalbard presumably have long response times. The strategy of using observations on former glacier stands for calibration before integrating the model into the future is tested in this paper. It is envisaged that the methodology can be applied to other complex glacier systems in Svalbard and the Arctic.
> With respect to Monacobreen, the following more specific questions will be addressed: (i) Is it possible to simulate the broad characteristics of the late Holocene evolution of Monacobreen ?; (ii) To what extent does regular surging effect the mass budget and long-term evolution of the glacier ? ; and (iii) What is the likely range of mass loss in the coming centuries for different scenarios of climate change ?

A further explanation on the interaction between geometry and ice thickness in the MGM, as well as a few lines on the method of solution (lines 130-138 were added):

> Eq. (4) is the prognostic equation for the model. Although there is no spatial resolution it should be stressed that the incorporation of eq. (3) implies that the height-mass balance feedback is fully taken into account. In fact, as has been demonstrated in Oerlemans (2011; Figure 5.8), the model fairly accurately reproduces the hysteresis implied by an overdeepening. When the balance profile with height is linear, only the *mean* ice thickness enters the expression for the surface mass budget (see next subsection). So the fact that the ice thickness is not calculated as a spatial variable has no effect on the calculated climate-driven evolution of the glacier.
> For a given bed topography, the mean bed slope depends on L. So for a concave bed, a retreating glacier will become thinner because of its reduced length *and* a steeper bed. The MGM thus captures the feedback between geometry, glacier thickness and mass budget.
> Eq. (3) is a nonlinear equation, because L appears implicitly in B_{tot} as well as in H_m and $\bar{s}$. However, it is not a stiff equation and a stable numerical solution can easily be obtained by integration with the explicit Euler scheme. Test have shown that for all applications in this paper a 1 a time step is practical and adequate. Computational demands are negligible: a 1000 a simulation typically takes 1 second on a laptop.

An expanded explanation and motivation for the use of a simple calving model with fixed parameters in the MGM, including the addition of two references (lines 186-191):

> critical thickness for flotation. The use of eq. (10) allows the model glacier to undergo a smooth transition between a land-based terminus and a calving front, which is a prerequisite for long-term simulations in which a model glacier should have the possibility to grow from zero volume to a long calving glacier, and backwards. Recent model studies with more comprehensive numerical models have focused on

simulating and explaining the short-term (seasonal to decadal) fluctuations in calving fluxes and glacier front behaviour (e.g. Otero et al. 2017; Todd and Christoffersen, 2014). It should be stressed that the parameterization in the MGM is not meant to simulate such short-term fluctutations, but attempts to quantify the calving flux as a long-term component of the total mass budget. With respect to the use of comprehensive numerical models of calving glaciers it should be noted that validation against long-term fluctuations of individual glaciers (including the LIA maximum stand) has not yet been attempted / published.

Inclusion of a table (Table 1) listing the model parameters, their values and the sources on which the values are based.

Added text in the beginning of section 2:
In the following sections a number of parameterizations are introduced concerning the global ice mechanics, geometry, calving, and climate forcing. An overview of the parameters and their values (including the sources) is given in Table 1.
Table 1:

Param.	*value*	*meaning*	*reference*
ν	10	eq. (3) - relation between ice thickness and slope	Oerlemans (2001)
α	1.70 $m^{1/2}$	eq. (3) - calibrated to give observed surface height	Map, Norsk Polarinstitutt
β	0.0045 m w.e. a^{-1} m^{-1}	balance gradient, observed on nearby glaciers	Oerlemans and Van Pelt (2015)
b_a	-175 m	'asymptotic' depth of fjord	Based on map Hansen (2014)
b_h	1100 m	note: $b_a + b_h$ is highest point of bed	Map, Norsk Polarinstitutt
λ	15000 m	calibrated to give observed water depth at front	Based on map Hansen (2014)
κ	0.4	ice thickness at front (fraction of H_m)	Oerlemans et al. (2011)
c	1.15 a^{-1}	calving parameter, as observed for Hansbreen	Oerlemans et al. (2011)
S_0	0.027 a^{-1}	calibrated with amplitude of 1991-1997 surge	Mansell et al. (2012)
t_s	8 a	calibrated with observed duration of 1991-1997 surge	Mansell et al. (2012)
$\partial E/dT$	35 m K^{-1}	based on energy-balance modelling	Van Pelt et al. (2012)
$\partial E/dP$	-2.25 m $\%^{-1}$	based on energy-balance modelling	Van Pelt et al. (2012)
E_0	582 m	reference ELA for time < 1899, tuning parameter	tuning to length record
E_1	642 m	reference ELA for time >1899, tuning parameter	tuning to length record

A better explanation of the choice of geometric parameters for the main stream, showing that the ambiguity in this choice is small because there are sufficient contraints (text added / improved):

The bathymetry of Liefdefjorden is well known (e.g. Hansen, 2014). The water depth varies considerably, but is mostly between 50 m and 200 m (far away from the glacier in the fjord). It is therefore appropriate to use $b_a = -175$ m. The value of λ is then determined by requiring that the water depth at the glacier front is close to the observed value of about 75 m (averaged over the width of the glacier). The resulting bed profile is shown in Fig. 3. Note that with this choice of parameters calving occurs whenever the glacier is longer than about 28 km.
With the observed surface elevation and the parameterized bed profile, the corresponding mean ice thickness is 247 m. This is reproduced by the model when α in eq. (3) is set to 1.70 $m^{1/2}$. This is a fairly small value compared to the measured value for Hansbreen (3.0 $m^{1/2}$), but somewhat larger than that found for Kronebreen (1.43 $m^{1/2}$; Van Dongen, 2014). Apparently both Kronebreen and Monacobreen have beds that provide a relatively low resistance to ice flow. The parameter values derived above are also listed in Table 1.

A more extensive explanation of why the ELA is set to lower values for basins 1, 2 and 3:

This is done to take the decline of the ELA as mapped in Hagen et al. (1993) into account. In fact, without the lowering of the ELA the net mass budget of basin 1 (Seligerbreen) would be negative and the tributary could never supply mass to Monacobreen (as it did until recently). Altogether, the ELA map of Hagen et al. (1993) appears to be consistent with the mass budgets of the tributaries.

A further comment on the sensitivity of the ELA to temperature and precipitation anomalies, explaing why the temperature sensitivity is relatively low on Spitsbergen (incl. a new reference), as well as a discussion on temperatures during the Holocene Climati Optimum:

The relation between the ELA and temperature / precipitation is based on calculations with an energy balance model, as described in Van Pelt et al. (2012) and Oerlemans and Van Pelt (2015). The sensitivities are $\partial E/\partial T = 35$ m K^{-1} and $\partial E/\partial P = -2.25\ m\ \%^{-1}$, where T and P are perturbations of the annual mean temperature and precipitation. It should be noted that the value of $\partial E/\partial T$ is rather small compared to values found for glaciers in a midlatitude alpine setting, which are of the order of 100 m K^{-1}. This stems from the fact that summer temperature anomalies over Spitsbergen (and in general over the Arctic region) are much smaller than mean annual temperature asnomalies. Since summer temperature determines to a large extent the ELA perturbation, the net effect is that the sensitivity to an *annual* temperature anomaly is relatively small (for a further discussion on this point, see Van Pelt et al. (2012).

As shown in Fig. 6a, the variation of reconstructed ELA values from mid-Holocene times until today have a typical range of 200 m. If this would solely be a temperature effect the drop in ELA since the mid-Holocene would correspond to a 5.7 K decrease in temperature (according to the sensitivity referred to above). This is more than reconstructions of mid-Holocene warmth in the Arctic actually suggest, which are in the 2 to 4 K range (e.g. CAPE, 2006; Bradley, 2016; Axford et al., 2017). However, there is also a direct effect of changes in orbitally-driven insolation variations. The differences in summer insolation between mid-Holocene and present day are between 5 and 10%, depending on the precise location and definition of the summer season (Berger and Loutre, 1991). The increased insolation certainly caused higher melt rates in the mid-Holocene, and thereby a higher equilibrium line.

A comment on the time scale (section 2.5):

With the adjusted value of α, the e-folding response time is about 250 years. A short discussion has been added to put this value in perspective (including some additional references):

The time scale of about 250 years can be compared with an estimate of the much used volume time scale τ_J defined by Jóhannesson et al. (1998):

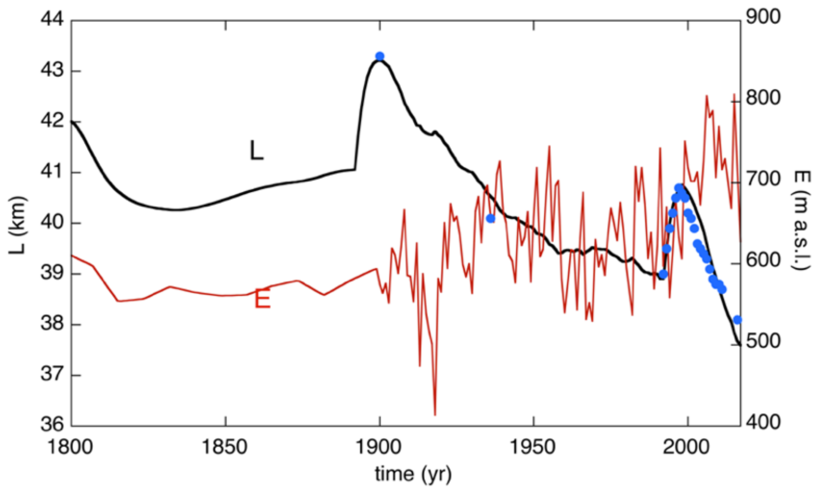
$$\tau_J = -H^*/\dot{b}_{x=L} \ , \qquad (15)$$

where H^* is the maximum ice thickness and $\dot{b}_{x=L}$ is the balance rate at the glacier front. Using 350 m as a maximum ice thickness and -2.5 m a^{-1} as a typical balance rate yields a value of about 140 a. However, as demonstrated by Oerlemans (2001) and confirmed by Leysinger Vieli and Gudmundsson (2004) with a higher order numerical glacier model, for glaciers with small slopes the altitude-mass balance feedback makes the time scale considerably longer. Since Monacobreen has a very small average slope (0.027), the value of ~ 250 a is a plausible one.

Fig. 6c (close-up of simulated glacier length):

The observed glacier stands are now shown in Fig. 6b as blue dots, illustrating that the calibration with the parameters E_0, E_1, S_0, t_s works. A sentence is added to make clear that the calibration procedure is transparent:

At this point it should be recalled that the tuning procedure is straightforward: four calibration parameters $\{E_0, E_1, S_0, t_s\}$ have been used to match: (i) the LIA maximum stand, (ii) the glacier stand at the onset of the surge, (iii) the amplitude of the surge, and (iv) the time scale of the surge.



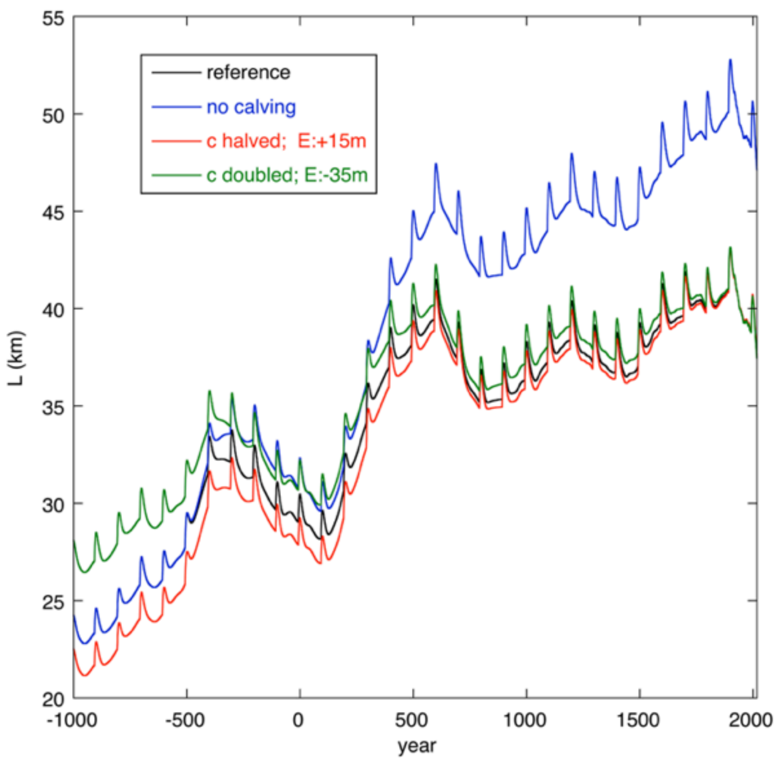
Special section on sensitivity tests

Section 4 (Holocene evolution of Monacobreen) has been split up into two subsctions to provide a more elaborate treatment of the sensitivity to some model parameters (balance gradient, surge amplitude, calving parameter). This also involves an additional figure. The text has been adjusted accordingly, in short:

The balance gradient β has been varies across a wide range, and for one particular value the effect on the simulation is shown (in Fig. 8). Since the larger value of β implies a larger glacier, the model has been recalibrated by adjusting the ELA (also shown in the figure). The conclusion is that the choice of β is not crucial for the simulation, and that the Holocene evolution does not change in a qualitative sense.

The effect of the surge amplitude has also been investigated as described in the text. In the figure the result of a run without surghing is shown.

Fig. 9 (new figure, see below) focuses on the role of the calving parameter c. Cases of no calving, calving parameter halved and calving parameter doubled are compared. In each case recalibration has been done to match the observed glacier length record. The effect of changing c on the long-term evolution of Monacobreen appears to be modest.



Main changes in section 5 (Future evolution of Monacobreen).

An additional remark on the relation between changes in the ELA and meteorological variables.

A more extreme scenario has been added, e.g. one in which the ELA increases by 6 m/yr.

The choice of reference period: apparently the explanation was not quite adequate, and the relevant paragraph has been changed into:

> When making projections future climate change scenarios the outcome depends on the choice of the reference period. Starting from a warm year (e.g. 2015, ELA = 809 m) and increasing the ELA by a certain amount will give a very different result from starting in a cold year (e.g. 2014, ELA 668 m). Therefore the reference ELA should be a mean value over a longer period. Moreover, it is unclear to what extent the very high ELA values since 2000 represent an expression of natural variability on the decadal time scale, or are a direct response to greenhouse-gas induced warming. To deal with this uncertainty, two 30-yr reference periods were used to define the ELA perturbation associated with the projected climate change: (i) 1987-2016, i.e. the most recent 30-yr period; and (ii) 1961-1990 as the last official period to define the climatology. The resulting eight projections of glacier length are shown in Fig. 10a. The integrations are extended until 2200, and the ELA-perturbation is kept fixed after 2100. The curves immediately make clear that typically half of the response to 21st century warming will come after 2100.

Main changes in section 6 (Discussion).

An additional remark on the conclusion that surging is relatively unimportant for the long-term evolution of Monacobreen:

> It should be noted that the perturbation of the mass budget is solely determined by the redistribution of mass, not by the details of how this distribution actually takes place. When a glacier increases its length during a surge, the change in mean surface elevation is entire dictated by the conservation of mass, not by the details of the surging mechanism. This implies that conclusions about the effect of surging on the long-term mass budget can be drawn even when the surging process is not fully understood.
>
> *Note: Referee 1 actually suggests to leave out the surging mechanism. On this point I really disagree. It is simple to include it (just a few lines of code), it makes the tuning more straighforward (how should I do this without the surge?), and it does not violate any conservation law or physical principles. I think I use an elegant way to study the effect of surging. There is no solid argument to leave it out.*

A discussion on the role of calving:
The experiments with different values of the calving parameter are discussed, and the effect of small-scale variations in the bed toppography is put into perspective:

> Calving has a significant effect on the total mass budget of Monacobreen, but different values of the calving parameter do not change the qualitative evolution of the glacier during the Holocene very much. The range over which Monacobreen fluctuates is somewhat smaller for a larger calving parameter (the green curve in Fig. 9). This is understandable for a bed profile that slopes downward along the flowline, because the front of a growing glacier comes into deeper water and the mass loss by calving increases.
> It has been observed that on shorter time scales details of the bathymetry may have significant effects on the calving rate and thereby on the position of the glacier front (e.g. Vieli et al., 2002). According to the measured bathymetry in the Liefdefjorden, these variations with an amplitude of 10 - 50 m are irregularly spaced and consist mainly of deposited moraines. It is unlikely that a similar bed would currently be present under Monacobreen with its very smooth surface, or existed in the fjord before the glacier started to advance in late Holocene times. Therefore it does not seem meaningful to include a map of the present-day bathymetry of the Liefdefjorden in one way or another. Probably, the smaller features of the bed profile do not matter too much for the glacier evolution on longer time scales, unless there are very marked jumps in bed or side geometry that could serve a pinning points. However, this does not seem to be the case.

References added:

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