In the reply, the referee's comments are in *italics*, our response is in normal text, quotes and modifications from the manuscript are in blue.

Anonymous Referee #1

This paper presents a modelling study of Jakobshavn Isbrae using the ice flow model BISICLES. The model is initialised and calibrated to fit the observed front retreat and annual velocities between 2004 and 2013. Three parametrisations are used to control the position of the front:

- *basal melting (Eq. 11),*
- *calving based on a crevasse depth criteria (Eq. 10),*
- *and a parametrisation meant to represent the buttressing of the ice melange in the front and that affect the driving stress (Eqs. 8-9) near the front.*

Because it is a target for the calibration, the total observed front retreat is well reproduced by the model. The timing of the front variations with winter advance and summer retreat is captured by the model, however the seasonal variability is overestimated at the end of the period because the model does not reproduce the winter calving. Finally, the model is used to estimate the evolution during the 21st century. The results during the calibration are convincing and well discussed. However, I found that few points are missing for the description of the model and set-up, the initialization and calibration is relatively hard to follow as it involves many steps that have been implemented manually and the discussion mainly concentrates on what the model has and forget to include what is missing. I give more details below.

My main remark concerns the parametrisation of the buttressing by the ice melange. The boundary condition for the front is not mentioned in the model description but should be the difference between the force exerted by the ice and the back stress from the sea water.

Reply: Sorry. We added boundary conditions into text:

Reflection boundary conditions were applied at the edge of each domain:

$$\boldsymbol{u} \cdot \boldsymbol{n} = 0, \qquad \boldsymbol{t} \cdot \nabla \boldsymbol{u} \cdot \boldsymbol{n} = 0, \qquad \nabla h \cdot \boldsymbol{n} = 0, \quad (8)$$

where $\boldsymbol{n}$ is normal to a boundary and $\boldsymbol{t}$ is parallel to it. Normal stress across the calving front is equal to the hydrostatic water pressure there:

$$\boldsymbol{n} \cdot [\phi h \bar{\mu}(2\dot{\boldsymbol{\epsilon}} + 2\mathrm{tr}(\dot{\boldsymbol{\epsilon}})\mathbf{I})] - \boldsymbol{\tau}^b = \frac{1}{2}\rho_i g \left(1 - \frac{\rho_i}{\rho_w}\right) h^2 \boldsymbol{n}. \quad (9)$$

It would seem natural to implement the effect of the ice melange as an additional back stress. The parametrisation implemented here modifies the driving stress near the front. More justification for this implementation is really required.

Reply: Our parameterization of ice mélange buttressing is similar to Nick et al., (2013, Eq. S5) that alters the stress balance at calving front.

Is this process really needed to reproduce the front variations? What appends if there is only the calving parametrisation?

Reply: Mélange buttressing effects play a decisive role in the recent retreating and evolving of Jakobshavn (Joughin et al., 2004; Joughin et al., 2008; Vieli et al., 2011). Ice mélange buttressing does affect calving by altering the stress field that contributes to crevasse penetration depth (Eq. 12).

Moreover, the effect is proportional to the fjord temperature and is thus continuously increasing in the future simulations. However, as the temperature increases, we may expect some kind of threshold where the ice melange disappears and its effects become negligible?

Reply: Yes. There might be such a threshold. So far the physics of ice mélange is poorly understood, where no much clues can really help to speculate such a threshold.

Few important informations are missing for the model description: What is the temperature field for the initialisation? Is the model thermo-mechanically coupled? What is the mesh resolution?

Reply: Our model is not thermo-mechanically coupled with a fixed temperature field -10 °C. Our finest resolution is 500 m which cover the whole fast-flow-area (Fig. S1).

The description of the initialisation is very hard to follow. For example for the step 2, we don't know what is the target to adjust β. In step 3, it is said that β from step 2 is used but that there is no calving, however β controls the calving criteria.

Reply: Agreed, the statement was imprecise. The section 2.3 has been rewritten:

1) We solved the inverse problem for basal conditions (Eq. 7) and stiffening factor using 2010 velocities (Joughin et al., 2010) and 2009 geometry (Gogineni et al., 2012), following Cornford et al. (2015). Our friction coefficient and stiffening factor fields are shown in Fig. 3. Fig. S2 shows the discrepancy between observed velocity field (Joughin et al., 2010) and the velocity derived from the inversion.
2) Starting from the inversion of step 1, we let the model glacier evolve freely without calving and with zero SMB and with sub-shelf melting (γ=0.0238) forced by repeating the observed 2004 ocean temperature for 11 years until its surface elevation profile reached a state shown in Fig. S3.
3) We carried out several 10-year simulations each with different β values estimated. These simulations were forced by repeatedly applying the 2004 seasonal climate forcing so that the glacier approaches a steady state. From these, we selected the β that provided a calving front position closest to that observed in 2004. The best β here is 0.034. This is our best guess for the 2004 state. The annual minimum extent of Jakobshavn retreats ~ 2 km from 2004 to 2005 following the loss of melange butressing, but then stabilizes until 2007 (Joughin et al. 2010). Annual maximum extents are stable over the 2004-2007 period. Front velocities increase slowly from 2004-2007 (~5.9% a^{-1} Joughin et al. 2010), and the model simulated velocities increase by about 3% a^{-1}. This period of relative stability also makes 2004 a good time from which to start transient simulations.

Basal friction coefficient values downstream of the 2010 grounding line were set equal to that in the nearest 2010 grounded location. This was necessary because steps 2 and 3 involved grounding line advance beyond the region for which basal friction coefficients had been inferred. The geometry after this spin up procedure, and the friction coefficient and stiffening factor distribution from the inversion in step 1 were used as the initial condition for model calibration.

It is said that γ = 1, however in page 9, Eq. 11, it is said that γ was derived from the 1985 *observed submarine melt rate.*

Reply: *We rewrote this paragraph:*

The parameters in the model, α, β and γ representing mélange buttressing, crevasse depth sensitivity to surface runoff, and shelf melt sensitivity to ocean temperatures need to be estimated. The measured relationship between ocean temperatures and sub-shelf melt rate (Motyka et al., 2011) gives the value of γ to be 0.238. We tune parameters α and β manually to best reproduce Jakobshavn Isbræ's calving front position and surface velocity evolution for the 10 year period 2004-2013. Reproducing the total retreat distance and the temporary stable state after 2012 were secondary desirable features to match. The best set of parameters are α_1=0.82, α_2=0.111, β=0.0638. Since these values come from a manual search we do not claim them to be the best in all parameter space. We assess model sensitivity to the parameter values next.

The discussion mainly focuses on the effect of the shear margins and the fact that due to the non linearity in the ice flow law the effective viscosity decreases as the strain-rates increase. This mechanism is described as a positive feedback, however I'm not sure that this is the right term, as both the velocities and the strain-rates are the results of the force balance equation, so that the velocities and the effective viscosity depends on the model parameters and boundary conditions. But is it difficult to describe this as a feedback as they both are solution of the same equation.

Reply: Vertically varying effective viscosity μ is solved by Eq. 6, instead of the stress balance equation (Eq. 3).

However, the results are certainly dependent of the ice flow law and the value of the stress exponent, and we certainly may expect that the results would be different with a linear flow relation, or, as discussed, a flow band model that would parametrised the lateral drag.

Reply: Yes. Our chosen stress exponent is quite common.

The mesh resolution might also influence the results as the resolution should be sufficient to properly capture the steep velocity gradients to represent this effect.

Reply: Our finest resolution of 500 m well covers the main trunk and shear margins (Fig. S1).

In addition, the comparison with Bondzio et al. (2017) might be a bit confusing as Bondzio et al. include the thermo-mechanical coupling (which is absent here?), and they report that the warming from shear heating accounts for 20 to 30% of the decrease in effective viscosity. There is also several mechanisms that could affect the viscosity of the shear margins with potential feedbacks, this includes damage, cryo-hydrologic warming, anisotropy etc... This could be discussed also.

Reply: Our model is not thermo-mechanical coupled. The periods for viscosity drop calculations are not quite overlapped. Here we only attempt to roughly verify our results by cross model comparison. We add more discussion in section 4:

Several absent processes in our model could affect ice viscosity. Crevasses saturated by surface melt water within the shear margins of Jakobshavn occurred and last in summer that is visible on satellite images (Lampkin et al., 2013). These melt water can transfer heat throughout the ice column through discharge within crevasses and moulins thus soften the ice (Phillips et al., 2010). Consideration a continuum damage model in BISICLES would further exaggerate the shear margin weakening as it rise the non-linear dependence of strain rates to stress fields (Sun et al., 2017).

Finally it would be also interesting to see or at least discuss how the model results are sensitive to other uncertainties in the model; this includes the description of the bedrock and the basal friction law, especially the linear assumption that is used here.

Reply: Lines added in Model improvements:

Ice thickness and basal topography with resolution of 150 m became available for main outlet glaciers of Greenland (Morlighem et al., 2017) recently. This allows finer mesh resolution in modeling works which would be expected to reveal more details of ice-stream especially on perpendicular-to-flow direction, including more precise shear-margin-weakening and single calving near side walls. Other than our simple assumption of basal drag (Eq. 7), implementing a physics-based basal sliding law (Schoof, 2010; Gagliardini et al., 2014; Tsai et al., 2015) would produce more speedup and retreats in model results as dynamic thinning constantly reduce the effective pressure which leads to lower basal shear stress.