Non-linear retreat of Jakobshavn Isbræ since the Little Ice Age controlled by geometry

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Abstract. Rapid retreat of Greenland's marine-terminating glaciers coincides with ~~the recent observed warming trend, which has~~ regional warming trends, which have broadly been used to explain these rapid changes. However, ~~Greenland~~ outlet glaciers within similar climate regimes experience widely contrasting retreat patterns, suggesting that the local fjord geometry could be ~~important~~an important additional factor. To assess the relative role of climate and fjord geometry, we use the retreat history of Jakobshavn Isbræ, West Greenland, since the Little Ice Age maximum in 1850 as a baseline for the parametrization of a width-depth integrated ice flow model. The impact of fjord geometry is isolated by using a ~~linearly increasing~~ linearly-increasing climate forcing and testing a range of simplified geometries.

We find that the ~~strength of the~~ total rate of retreat is determined by external factors—such as hydrofracturing, submarine melt and buttressing by sea ice—whereas the retreat pattern is governed by the fjord geometry. Narrow and shallow areas provide stabilization points and cause delayed but rapid retreat after decades of grounding line stabilization without additional climate warming. We suggest that these geometric pinning points may be used ~~as a proxy for moraine build-up~~ to locate potential sites for moraine formation and to predict the long term response of the glacier. As a consequence, to assess the impact of climate on the retreat history of a glacier, each system has to be analyzed with knowledge of its historic retreat and the local fjord geometry.

1 Introduction

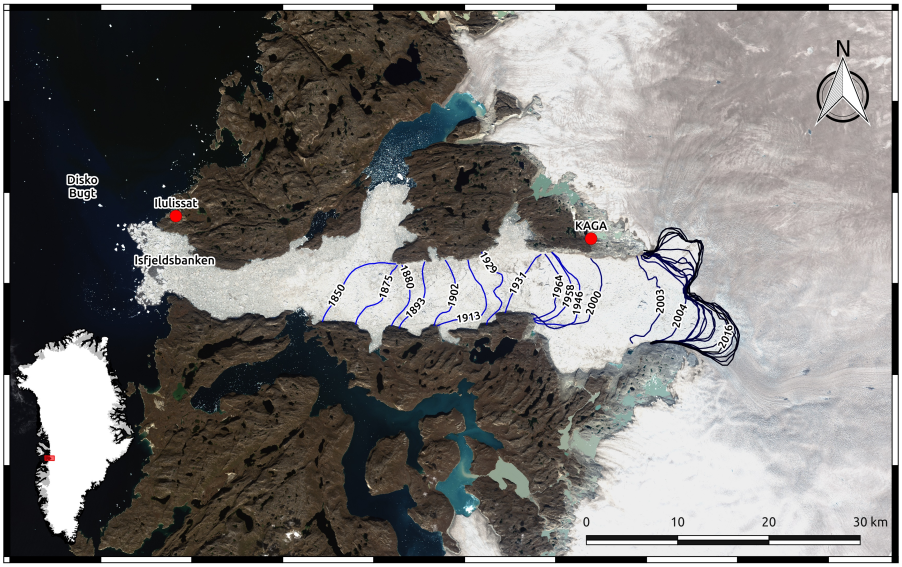
Marine-terminating glaciers export ice from the interior of the Greenland Ice Sheet (GrIS) through deep ~~troughs~~ valleys terminating in fjords (Joughin et al., 2017). ~~Ice discharge accounts for about~~ Mass loss from the GrIS has increased significantly during the last two decades, contributing increasingly to sea-level rise (Rignot et al., 2011). The observed increase in mass loss has broadly been associated with large-scale atmospheric and oceanic warming (Holland et al., 2008a; Lloyd et al., 2011; Vieli and Nick, 20 About half of the current ~~GrIS mass loss (Khan et al., 2015) and~~ mass loss from the GrIS is due to dynamic ice discharge (Khan et al., 2015), which is impacted by several processes partly linked to air and ocean temperatures~~, of which most are poorly understood as well as spatially and temporally heavily undersampled (e.g. Straneo et al., 2013; Straneo and Cenedese, 2015)~~. A warmer atmosphere enhances surface runoff, which may ~~change the rheology and might~~ cause crevasses to penetrate deeper through hydrofracturing, which in turn, can promote iceberg calving (Benn et al., 2007; van der Veen, 2007; Cook et al., 2012, 2014; Pollard et al., 2015). A warmer ocean strengthens submarine melt below ice shelves and floating tongues (Holland et al., 2008a, b; Motyka et al., 2011), which can potentially destabilize the glacier ~~through~~ via longitudinal dynamic coupling and upstream propagation of thinning (Nick et al., 2009; Felikson et al., 2017). Increased air and fjord temperatures can additionally weaken sea ice and ice mélange in fjords, affecting calving through altering the stress balance at the glacier front (Amundson et al., 2010; Robel, 2017). Most of these processes are still poorly understood as well as heavily spatially and temporally undersampled (e.g. Straneo et al., 2013; Straneo and Cenedese, 2015).

~~Although observed~~ Despite widespread acceleration and retreat around the GrIS~~is broadly associated with large-scale atmospheric and oceanic warming (e.g. Carr et al., 2013; Straneo et al., 2013), inland mass loss can be restricted by glacier geometry (Felikson et al., 2017). Despite widespread acceleration~~, individual glaciers correlate poorly with regional trends ~~(Moon et al., 2012; Csatho et al., 2014): only four glaciers~~ (Warren, 1991; Moon et al., 2012; Csatho et al., 2014). For example, four glaciers alone have accounted for 50 % of the total dynamic mass loss since 2000~~, where~~ ; Jakobshavn Isbræ (JI) in West Greenland ~~has been~~ is the largest contributor (Enderlin et al., 2014). ~~These heterogeneous patterns are poorly understood, inhibiting~~ Even if exposed to the same climate, individual glaciers can respond differently, because inland mass loss can be regulated by individual glacier geometry (Felikson et al., 2017). It is well-known that grounding line stability and ice discharge is highly dependent on trough geometry, with retrograde glacier beds potentially causing unstable, irreversible retreat (e.g. Schoof, 2007; Jamieson et al., 2012; Gudmundsson et al., 2012). The impact of glacier width, however, is less studied. Lateral buttressing (Gudmundsson et al., 2012; Schoof et al., 2017) and topographic bottlenecks (Jamieson et al., 2012; Enderlin et al., 201 been suggested to stabilize grounding lines on reverse bedrock slopes. Despite these studies showing the importance of geometry, limited knowledge still exists regarding the interplay between bedrock geometry, channel-width variations and external controls on glacier retreat. A poor understanding of the heterogeneous response of individual glaciers inhibits robust projections of ~~sea level rise from marine ice sheet loss. Attribution of observed changes also remains challenging because the relatively short period of observational records inhibits the understanding of the response of marine-terminating glaciers to external forcing. Here~~sea-level rise due to mass loss from ice sheets. So far, there has been a strong emphasis on the role of ice-ocean interactions as a key control on the retreat of marine-terminating glaciers, disregarding the influence of trough geometry (e.g. Holland et al., 2008a; Joughin et al., 2012; Straneo and Heimbach, 2013; Fürst et al., 2015; Cook et al., 2016). Also, studies that focus on the control of geometry so far only model synthetic glaciers (e.g. Schoof, 2007; Enderlin et al., 2013b), prohibiting validation and justification of model parameters. In this paper, we therefore use ~~an expanded data set of climatic conditions reaching from the Little Ice Age (LIA) maximum in 1850 to present-day.~~ a real-world glacier geometry to study the geometric controls on glacier retreat.

~~Compared to previous studies , our focus on a longer time period provides context for recent observed changes on JI in West Greenland~~Several attempts to model JI have been made to understand the dynamics behind the observed acceleration and retreat (Vieli and Nick, 2011; Joughin et al., 2012; Nick et al., 2013; Muresan et al., 2016; Bondzio et al., 2017). These studies focus on the time period past 1985 and partly into the future. However, our understanding and model capacity should span long (centennial) timescales given the current exceptional rapid changes if we are to predict changes into the future. JI has a history of step-wise and non-linear retreat, that we aim to understand by comparing modeling results with observations since the LIA from 1850 into the present. Since the deglaciation of Disko Bugt between 10.5–10.0 thousand years before present (kyr BP) (Ingólfsson et al., 1990; Long et al., 2003), JI has experienced ~~an alteration between~~ alternating periods of fast retreat and ~~periods of stabilization , that formed~~ stabilization with the formation of large moraine systems (e.g. at Isfjeldsbanken, Fig. 1; Weidick and Bennike, 2007). Most observations exist after the Little Ice Age (LIA) maximum in 1850 (Fig. 1), when the glacier started retreating again ~~and~~ after a period of frontal advance. From 2001 until May 2003 it accelerated significantly after the disintegration of its 15 km long floating tongue ~~from 2001 until May 2003 (Thomas et al., 2003; Joughin et al., 2004; Luckman and Murray, 2005; M~~ ~~It is now~~ (Thomas et al., 2003; Joughin et al., 2004; Luckman and Murray, 2005; Motyka et al., 2011). Today, it is the fastest glacier ~~on~~ in Greenland (Rignot and Mouginot, 2012) with a maximum velocity of $18\,\mathrm{km\,yr^{-1}}$ (measured in summer 2012; Joughin et al., 2014) and ice discharge rates of about $27–50\,\mathrm{km^3\,yr^{-1}}$ (Joughin et al., 2004; Rignot and Kanagaratnam, 2006; Howat et al., 2011; Cassotto et al., 2015). ~~JI alone contributed to~~ With a contribution of 4 % ~~of the global sea level~~ to global sea-level rise in the 20th century (IPCC, 2001)~~and is the glacier in Greenland with the largest contribution to sea level rise~~ , JI is the largest contributor in Greenland (Enderlin et al., 2014). It is also one of the most vulnerable glaciers ~~in Greenland~~of the GrIS, with recent thinning potentially propagating as far inland as one third of the distance across the entire ice sheet (Felikson et al., 2017). Combining these centennial observations with dynamic flow modeling is crucial for putting the recent dramatic changes into a long-term perspective, but also for interpreting palaeo records and for future projections.

~~The recent rapid retreat of JI and other marine-terminating glaciers has been explained by regional warming (Holland et al., 2008a; Lloyd~~ ~~However, the dependence of ice discharge and marine ice sheet stability on the bed topography implies different responses of individual glaciers, even if exposed to the same climate (Warren, 1991; Moon et al., 2012). It is well-known that grounding line stability is highly dependent on trough geometry, with retrograde glacier beds potentially causing unstable, irreversible retreat (e.g. Schoof, 2007). The impact of glacier width is less studied, but lateral buttressing (Gudmundsson et al., 2012; Schoof et al., 2017) and topographic bottlenecks (Jamieson et al., 2012; Enderlin et al., 2013b; Jamieson et al., 2014) are suggested to stabilize grounding lines on reverse bedrock slopes. Despite these studies showing the importance of geometry, limited knowledge still exists regarding the interplay between bedrock geometry, channel-width variations and external controls on a real glacier. Most of the above mentioned studies on the control of geometry only focus on synthetic glaciers, prohibiting a model validation and justification of parameters choice. Also, there is still a strong emphasis in the community on the role of ice-ocean interactions as a key control on the retreat of marine-terminating glaciers (e.g. Holland et al., 2008a; Joughin et al., 2012; Straneo and Heimbach, 2013; Fi~~

The aim of this study is to investigate the external, glaciological and geometric controls on JI in response to a linear forcing on a ~~long time scale~~centennial timescale. We use a simple numerical ice flow model ~~(e.g. Vieli et al., 2001; Nick et al., 2010)~~ (e.g. Vieli and Pa a fully-dynamic treatment of the calving front to assess the relative impact of geometry and climate forcing on the retreat of JI from the LIA maximum to present-day. Geometric controls are isolated (a) using a linear forcing to avoid complex responses and (b) artificially straightening the trough width and depth. The study extends to a centennial ~~time scale~~ timescale to account for internal glacier adjustment. The application of the model on a real glacier ~~provides a model validation against~~ enables a



~~Glacier front positions of JI from Khan et al. (2015) (1850–1985) and CCI products derived from ERS, Sentinel-1 and LANDSAT data by ENVO (1990–2016). The background map is a LANDSAT-8 image from 16 August 2016 (from the U.S. Geological Survey). Location names that occur in the text are marked. The inset shows the location of JI on Greenland.~~

Figure 1. Glacier front positions of JI from Khan et al. (2015) (1850–1985) and CCI products derived from ERS, Sentinel-1 and LANDSAT data by ENVO (1990–2016). The background map is a LANDSAT-8 image from 16 August 2016 (from the U.S. Geological Survey). Location names that occur in the text are marked. The inset shows the location of JI in Greenland.

comparison of model results with long-term observed velocities and front positions, but also ensures the use of ~~right~~ realistic dimensions for the width-depth ratio, velocities, and model parameters.

In Sect. 2 of this paper, the numerical ice flow model is described, followed by Sect. 3 which describes the specific setup used for the simulations. In Sect. 4, the results of the forcing and geometry experiments are presented. Section 5 discusses the limitations of the model and stresses the ~~importance of the geometry compared to climate and discusses the resulting implication for geomorphology and the limitations of the model~~importance of trough width versus depth as well as the implications for understanding the past.

2 Modelling approach

A simple width and depth integrated flowline model (Nick et al., 2010) is used for this study. ~~It~~ Despite many assumptions made, it is well suited to study the general long-term (centennial) retreat pattern of an outlet glacier with high-basal motion (such as JI). It is based on continuity and a balance between driving stress, longitudinal stress gradient and basal and lateral drag. The model benefits from a robust treatment of the grounding line ~~, an explicit physical representation of the calving front, and~~ (Pattyn et al., 2012) that is consistent with Schoof (2007) and a fully dynamic marine boundary (Nick et al., 2010). Also, it is more efficient than complex models (Muresan et al., 2016; Bondzio et al., 2016), which enables many model runs and the coverage of a centennial ~~time scale~~timescale. The used physical calving law has been successfully tested on several outlet glaciers against observations (Nick et al., 2013) and has the advantage of allowing for a dynamic and free migration of the glacier terminus given changes in climate forcing. The climate forcing is implemented as a slow linear change in surface mass balance, crevasse water depth, submarine melt and buttressing by sea ~~ice—parameters that are linked to~~ ice—model parameters that represent impacts by temperature. In this section, the physical approach, parameterizations and the implementation of climate forcing are described.

2.1 Numerical ice flow model

The ~~here used~~ width and depth integrated numerical ice flow model is constructed for marine-terminating glaciers (Vieli et al., 2001; Vieli and Payne, 2005; Nick et al., 2009, 2010). Ice thickness variations with time are calculated from the along-flow ice flux and mass balance, using a width- and depth integrated continuity equation ~~(Eq. 1).~~

$$\frac{\partial H}{\partial t} = -\frac{1}{W}\frac{\partial (HUW)}{\partial x} + \dot{B}. \qquad (1)$$

H is ~~thereby~~ the ice thickness, W the width, U the velocity and x the along-flow component. The mass balance $\dot{B}$ includes the surface mass balance (SMB) and submarine melt below the floating tongue described in Sect. 2.3.

The ice flux is controlled by a balance of lateral and basal resistance, along-flow longitudinal stress gradient and driving stress~~(Eq. 2)~~. Lateral resistance is parametrized using a width-integrated horizontal shear stress (van der Veen and Whillans, 1996) and we use a Weertman-type basal sliding law based on effective pressure (Fowler, 2010). The longitudinal stress gradient is dependent on the effective viscosity ν, which is non-linearly dependent on the ~~strain rate~~ longitudinal strain rate $\dot{\epsilon}_{xx}$ and the rate factor ~~(Nick et al., 2010).~~ A (Nick et al., 2010). The stress balance is calculated as

$$2\frac{\partial}{\partial x}\left(H\nu\frac{\partial U}{\partial x}\right) - A_s\left[\left(H - \frac{\rho_w}{\rho_i}\frac{\rho_s}{\rho_i}D\right)U\right]^{1/m} - \frac{2H}{W}\left(\frac{5U}{E_{lat}AW}\frac{5U}{EAW}\right)^{1/n} = \rho_i g H\frac{\partial s}{\partial x}, \qquad (2)$$

where s is the surface elevation, g the gravitational acceleration, D is the depth of the glacier below ~~sea level,~~ sea-level and ρ_i and ~~ρ_w~~ ρ_s are the densities of ice and ocean water, respectively. ~~A is the rate factor and~~ n and m are the exponents for Glen's flow law and sliding relations, respectively. The lateral enhancement factor ~~E_{lat} is used to tune the~~ E for reducing lateral resistance and the basal sliding parameter A_s ~~tunes the resistance from the bed~~are model parameters that are adjusted to roughly match the observed flow and ice thickness for the present geometry. Both parameters are constant along the flowline and in time. The dependency of the basal resistance on effective pressure is accounted for through the term $H - \frac{\rho_s}{\rho_i}D$.

The grounding line position is calculated with a flotation criterion based on hydrostatic balance (van der Veen, 1996). Its treatment relies on a moving grid that adjusts freely to the new glacier length at each time step, continuously keeping a node at the calving front (Vieli and Payne, 2005; Nick et al., 2009, 2010). This allows for a precise simulation of the glacier front and grounding line position using high grid resolution. The grid size is ~~set to~~ Δx = ~~300~~ 302 m initially ~~, which decreases further as the glacier retreats and the length decreases~~and reduces to Δx = 292 m at the present day position due to the use of a stretched grid. At the marine terminus, a dynamic crevasse-depth calving criterion is used and further explained in Sect. 2.2.

2.2 Calving law

The here used fully-dynamic crevasse-depth criterion calculates calving where the sum of surface and basal crevasse depth (~~d_{sc} and d_{bc}~~d_s and d_b, respectively) penetrate the whole glacier thickness (Nick et al., 2010). The depth of ~~basal crevasses is calculated from tensile deviatoric stresses (R_{xx}) and the height above buoyancy. The depth of~~ surface crevasses is ~~caused by~~ given by

$$d_s = \frac{R_{xx}}{\rho_i g} + \frac{\rho_w}{\rho_i} d_w, \text{ with } R_{xx} = 2\left(\frac{\dot{\epsilon}_{xx}}{A}\right)^{1/n}. \tag{3}$$

as the sum of tensile deviatoric stresses ~~and enhanced by~~ R_{xx} and additional water pressure from melt water filling up ~~crevasses due to the additional water pressure (Eq. 3; Nye, 1957; Nick et al., 2013). The~~ the crevasses (Nye, 1957; Nick et al., 2010). Note that the water depth in crevasses ~~(d_{cw})~~ d_w is not a physical quantity, but a forcing parameter within the calving model that links calving rates to climate~~and is in our experiments used as a perturbation parameter.~~

$$\cancel{d_{sc} = \frac{R_{xx}}{\rho_i g} + \frac{\rho_{fw}}{\rho_i} d_{cw}, \text{ with } R_{xx} = 2\left(\frac{\dot{\epsilon}_{xx}}{A}\right)^{1/n},}$$

~~where ρ_{fw} is the densities~~. ρ_w is the density of freshwater. The tensile deviatoric stress ~~R_{xx}~~ is the difference between tensile stresses that ~~pulls~~ pull a fracture open and the ice overburden pressure. It is calculated ~~from the longitudinal strain rate $\dot{\epsilon}_{xx}$ through~~ via Glen's flow law ~~(Eq. 4).~~

~~Buttressing by sea ice is implemented as~~ from the longitudinal stretching rate $\dot{\epsilon}_{xx}$, which is responsible for the opening of crevasses by

$$\dot{\epsilon}_{xx} = \frac{\partial U}{\partial x} = f_i A \left[\frac{\rho_i g}{4}\left(H - \frac{\rho_s}{\rho_i}\frac{D^2}{H}\right)\right]^n \tag{4}$$

in dependency of a sea ice factor ~~(f_{si}), which can be reduced accounting for~~ f_i, which accounts for reduced buttressing due to weakening of ice mélange~~by increasing the strain rate. The strain rate (Eq. 4) is responsible for the opening and downward-penetration of crevasses at the glacier terminus, consequently increasing calving rates.~~. The depth of basal crevasses is calculated from tensile deviatoric stresses and the height above buoyancy (Nick et al., 2010).

$$\cancel{{}_{xx} = \frac{\partial U}{\partial x}} d_b = \cancel{f_{si} A \frac{\rho_i g}{4}} \frac{\rho_i}{\rho_s - \rho_i}\left(\cancel{H}\frac{R_{xx}}{\rho_i g} - \cancel{\frac{\rho_w}{\rho_i}\frac{D^2}{H}}(H - \frac{\rho_s}{\rho_i} D)\right)^{\cancel{n}} \tag{5}$$

~~The model uses separate parameters for water~~

Table 1. List of variables, physical parameters and constants used in the model. ~~Values for the~~ The forcing parameters with their initial (LIA) ~~forcing parameters~~ values are given in the lower part. Parameter values used for the glacier retreat experiments are listed in Table 2.

Symbol	Definition	Value	Unit
H	glacier thickness		m
t	time		yr
W	glacier width		m
x	along-glacier coordinate		m
U	velocity		$\mathrm{m\,yr^{-1}}$
B	mass balance		$\mathrm{m\,yr^{-1}}$
ν	viscosity		Pa yr
D	depth below sea-level		m
s	surface elevation		m
d_b	depth of basal crevasses		m
d_s	depth of surface crevasses		m
R_{xx}	tensile deviatoric stress		Pa
$\dot{\epsilon}_{xx}$	longitudinal strain rate		$\mathrm{m\,yr^{-2}}$
Q_L	lateral ice flux		$\mathrm{m\,yr^{-1}}$
a	surface mass balance (SMB)		$\mathrm{m\,yr^{-1}}$
s_0	transition height for SMB	1600	m
g	gravitational acceleration	9.8	$\mathrm{m\,yr^{-1}}$
ρ_i	ice density	900	$\mathrm{kg\,m^{-3}}$
ρ_s	ocean water density	1028	$\mathrm{kg\,m^{-3}}$
ρ_w	fresh water density	1000	$\mathrm{kg\,m^{-3}}$
m	sliding exponent	3	
n	Glen's flow law exponent	3	
A	rate factor taken from Cuffey and Paterson (2010)	A(-20°C) – A(-5°C)	$\mathrm{yr^{-1}\,Pa^{-3}}$
A_s	basal resistance parameter	120	$\mathrm{Pa\,m^{-2/m}\,s^{-1/m}}$
E	lateral enhancement	10	
dx	grid size	250–300	m
dt	time step	0.005	yr
Perturbation parameters with their initial LIA values			
m	submarine melt rate	175	$\mathrm{m\,yr^{-1}}$
d_w	crevasse water depth	160	m
G_l	lower SMB gradient	0.0011	$\mathrm{m\,yr^{-1}}$
G_u	upper SMB gradient	-0.002	$\mathrm{m\,yr^{-1}}$
a_0	maximal SMB	0.64	$\mathrm{m\,w.e.\,yr^{-1}}$
f_i	sea ice buttressing factor	1	

Water in crevasses and sea ice buttressing ~~, although they both~~ are both model parameters that impact the glacier response ~~similarly~~ by changing the calving rate. ~~This separation is done because the two~~ Because the parameters are linked to different processes~~and can hence be forced separately~~, they are kept separate in the model to enable a distinct forcing.

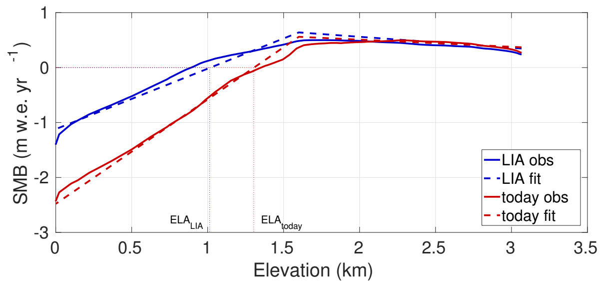


Figure 2. SMB profiles along JI's main flowline at the LIA (1840–1850 average) and present-day (2002–2012 average) from observations by Box (2013) and the linear fit used in the model. Thin dotted lines show position of the equilibrium line altitude (ELA) for the present day and LIA fit.

2.3 Atmospheric and ocean forcing

The model SMB~~(~~, a~~)~~, is derived from observed monthly mean SMB data at JI (Box, 2013) ~~. Our implementation~~ which are based on a combination of meteorological station records, ice cores, regional climate model output and a positive-degree day model. Its implementation in our model consists of a piecewise linear function of ~~the~~ surface elevation separated ~~in two regions~~by a transition height s_0: the steep lower part ~~below the transition height s_0~~ where the SMB increases with elevation and the ~~higher surface elevations with~~ flat upper part of low precipitation where the SMB decreases with elevation (Eq. 6).

$$a(x) = \left(a_0 - \frac{da}{dx} \cdot s_0\right) + \frac{da}{dx} \cdot s(x);\ \text{with}\ \frac{da}{dx} = \begin{cases} G_l & \text{for } s(x) \leq s_0 \\ G_u & \text{for } s(x) > s_0 \end{cases} \tag{6}$$

~~Table 1 provides the LIA values~~ Figure 2 shows the observed and linearly approached SMB profiles for the LIA period (1840–1850 average) and for present-day. The corresponding values for the vertical gradients ~~G_{a1} and G_{a2}~~ G_l and G_u as well as the SMB a_0 at the height s_0 are given in Tables 1 and 2.

Submarine melt is implemented in the model as a vertical melt rate that ~~reduces the ice thickness of the floating tongue. In this model , an along-tongue variation of submarine melt shows similar results to a constant submarine melt along the whole tongue, so that a spatially~~ decreases the glacier thickness seaward of the grounding line and is assumed to be spatially uniform. The thereby induced artificial step decrease in ice thickness is smoothed out in the model by a grounding line flux an order of magnitude larger than the submarine melt rates and a sufficiently small time step. Sensitivity analysis with along-flow variations (Motyka et al., 2011) in submarine melt show similar results as long as the constant value is ~~used here.~~ comparable with the along-flow averaged submarine melt rate.

2.4 Lateral ice flow

~~Additionally to the SMB, the glacier is fed by tributary glaciers mainly adding mass in the lowermost 80~~The model domain covers the full drainage basin towards the ice divide at about 520 km upstream of the present-day position. For the lowermost

77 km~~. The formulation of those tributary ice flow is inspired by Lea et al. (2014) and based on mass conservation. The lateral influx Q_L~~, we restrict the model width to the pronounced narrow channel seen in bed topography data to realistically account for lateral and basal stresses. Lateral ice flow into this narrow channel from the surrounding ice sheet and tributary glaciers is here implemented as an additional SMB similar to previous studies (Nick et al., 2013; Jamieson et al., 2014; Lea et al., 2014) to get a realistic mass flux into the lower channel. This lateral influx $Q_{L,0}$ is initially calculated ~~at each grid point~~ as the sum of the northern and southern lateral fluxes given by observed velocity ~~($U_{L,0}$) and thickness (~~and thickness $H_{L,0}$ ~~)~~ ~~(Rignot and Mouginot, 2012; Morlighem et al., 2014) weighted with~~ (Rignot and Mouginot, 2012; Morlighem et al., 2014) at each grid point along the lateral boundary of the narrow main channel divided by the width of the main trough W_{JI} (Eq. 7). ~~This influx~~ The strength of the initial influx is indicated by the arrows in Fig. 3 and locally accounts to about 100 times the SMB, with a maximum of 120 m yr^{-1} ~~(Fig. 3). Throughout the simulations,~~ .

We assume that the relative contribution of the lateral flux ~~is parametrized to show the same evolution than the one of the main trunk and keep its relative contribution to~~ to the overall flux is constant in time; therefore, we scale it with the change in the overall flux with time (Eq. 8).

$$Q_{L,0}(x) = \frac{U_{L,0}(x) \cdot H_{L,0}(x)}{W_{JI}(x)} \tag{7}$$

$$Q_{L,t}(x) = Q_{L,0}(x) \cdot \frac{Q_{JI,t}(x)}{Q_{JI,0}(x)} \tag{8}$$

$Q_{JI,0}$ and $Q_{JI,t}$ are thereby the initial overall flux through the main trunk and the flux after time t, respectively. Note that the constant relative contribution by side fluxes is a rough approximation, because a thinning of the main trunk could initiate a speed up in the tributary glaciers due to the increased surface slope.

3 Model setup

Despite the general focus of this study on the external versus geometric controls ~~of~~ on glacier retreat, we apply the model to JI—a real glacier. The ~~intension thereby is the use of~~ intention is to use a realistic along-glacier geometry ~~and forcing. In addition, the total retreat of JI since the LIA is used for model tuning. For the initialization, observed trough geometry data are used (Boghosian et al., 2015) as well as the glacier extent during the LIA maximum (1850) (Khan et al., 2015). Observed velocities, ice thickness~~ to compare modeled thickness, length and velocity with observations. Observations of velocities, calving front positions, ice thickness, and ice discharge (Joughin et al., 2004, 2014; Howat et al., 2014; Khan et al., 2015) are used to tune ~~parameters (Joughin et al., 2014; Howat et al., 2014; Joughin et al., 2004)~~model parameters. In the following, we distinguish between constant parameters (basal sliding parameter, rate factor and lateral enhancement factor) and climate-related perturbation parameters (SMB, submarine melt rate, crevasse water depth and sea ice buttressing). For the model experiments, ~~climate-related parameters are perturbed linearly to simulate~~ the perturbation parameters are changed linearly from their LIA values to simulate generally increasing temperatures. ~~During the retreat~~Importantly, the calving front and grounding line evolve freely ~~with a total retreatrate depending on the forcing~~during retreat. Only those combinations of forcing parameters~~are considered, where the total glacier retreat corresponds to the observed~~ , that simulate a total retreat rate matching the observed retreat of about 43 km from the LIA to ~~2015.~~ 2015, are considered. In the following, the ~~initial parameters and their~~ choice of tuning parameters and the perturbations are elucidated together with related observations.

3.1 Model ~~initialization~~glacier geometry

~~We use a~~ JI expands 520 km inland towards the ice divide and is mainly distinct from the surrounding ice sheet by its high velocities along the deep trough. The geometry of the model glacier consists of a narrow (in average about 5.4 km wide) and deep (1.3 km at the deepest) trough; further upstream, it widens gradually with a relatively flat and shallow bottom. The fjord width in the today's ice free area is obtained from satellite images (Fig. 1) and the channel width in the fast flowing part (77 km upstream of the 2015 position) is defined as the trough width at the present-day sea-level from topography data by Morlighem et al. (2014). Further upstream, where the catchment widens gradually, the width is defined following Nick et al. (2013). For the one-dimensional ~~along-flow bed topography profile~~ glacier depth in the deep trough and fjord, we use the along-flow bed topography profile as it is presented in Boghosian et al. (2015). The fjord bathymetry is ~~thereby~~ therein obtained from Operation IceBridge gravity data and ~~for~~ the subglacial trough ~~the~~ profile from high-sensitivity radar data by Gogineni et al. (2014)~~are used here~~. For the bed ~~upstream of the deep trough (77 km from the 2015 front position)~~in the wider catchment area, 150 m resolution data by Morlighem et al. (2014) are averaged over the glacier width. ~~The glacier width is defined as the trough width at the~~

3.2 Constant parameters

Most observations only exist for present-day~~sea level from topography data (Morlighem et al., 2014) and satellite images in the ice-free fjord (Fig. 1) . JI's catchment widens gradually over the upper 445 km up to the ice divide, and the width is defined accordingly following Nick et al. (2013)~~. Parameters that are constant in time (basal resistance parameter, lateral enhancement factor and rate factor) are therefore tuned with those observations to obtain a steady-state glacier that corresponds to the observed present-day glacier geometry. Climate-related perturbation parameters are set to values corresponding to present-day. After tuning the constant parameters, the climate-related perturbation parameters are reduced to colder temperatures to achieve a steady-state at observed LIA front position that is used as initial setup. For the LIA steady-state, the only constraints are given by the LIA front position (Khan et al., 2015) and the height of the LIA trimline found at the Global Positioning System (GPS) station KAGA (Fig. 1; Jeffries, 2014) by Csatho et al. (2008).

Basal sliding—as implemented in the ~~model—changes~~ model—influences ice flow and hence the surface slope and ~~hence the ice thicknessat the ice divide~~thickness. The basal sliding parameter $A_s = 120\,\mathrm{Pa\,m^{-2/3}\,s^{-1/m}}$ is ~~therefore chosen for the LIA~~ chosen to achieve an observed present-day thickness of 3065 m at the ice divide (Howat et al., 2014); the present-day thickness in the interior ~~can be used~~ is also valid for the LIA initialization because the ice sheet is assumed to be in steady-state above 2000 m of elevation ~~(Krabill, 2000). Also the height of the trimline found at the GPS station KAGA (Fig. 1; Jeffries, 2014) by Csatho et al. (2008) is used as a reference height. The~~ within this time period (Krabill, 2000). We keep the basal sliding parameter constant in time, because the impact of increased melt on basal sliding on interannual ~~time scales~~ timescales is still unclear (Sole et al., 2011; Tedstone et al., 2015)~~, so that the basal sliding parameter is kept constant in time and space in our~~

~~model simulations. The strength~~. Also, the model takes into account the dependency of basal sliding on the effective pressure, which is calculated explicitly. The actual degree of basal resistance at the bed of JI is highly debated with some studies explaining high surface velocities ~~with~~ as reflecting a slippery bed ~~(Lüthi et al., 2002; Shapero et al., 2016; Bondzio et al., 2017)~~(Lüthi et al., 2002 whereas other studies use weakened shear margins as main explanation for high velocities (e.g. van der Veen et al., 2011) or an interplay of both processes (Bondzio et al., 2017).

The ~~glacier surface is~~ surface profile and velocity are in addition determined by the lateral resistance and the rate factor. A ~~constant~~ uniform lateral enhancement factor ~~of $E_{lat} = 10$~~ is applied along the ~~glacier that~~ whole glacier and controls the strength of the transmission of lateral drag to the sides~~to achieve~~. A value of $E = 10$ achieves best a present-day surface corresponding to observations (Howat et al., 2014). The rate factor for Glen's flow law is in a first approximation a function of ice temperature and here set to values corresponding to temperatures of -20°C at the ice divide linearly increasing to -5°C at the terminus (Cuffey and Paterson, 2010), which provides present day glacier surface and velocities closest to observations (Howat et al., 2014; Joughin et al., 2014). The rate factor is here kept ~~temporally constant~~ constant in time.

~~The depth of water filling crevasses has not been measured yet, but the chosen value of 160 m for the~~

3.3 Forcing experiments and perturbation parameters

The climate-related perturbation parameters are tuned for the LIA steady-state ~~achieves~~ to simulate the observed glacier length and ~~a calving rate of 34 in 1985, which is in the same order of magnitude as the observed calving rate of 26.5 in 1985 (Joughin et al., 2004) and values obtained from other studies (24–50 $\mathrm{km^3\,yr^{-1}}$; Rignot and Kanagaratnam, 2006; Howat et al., 2011; Casso~~ ~~The crevasse water depth may be exaggerated, as no submarine melt is applied at the vertical glacier front in the model and mass has to be removed.~~

3.4 ~~Forcing experiments~~

velocities or ice discharge. A retreat of the initial LIA glacier is then forced with simultaneous linear changes in SMB, crevasse water depth, submarine melt rate and sea ice buttressing. The parameter perturbations are ~~thereby~~ combined to force a total retreat of 43 km from 1850 to 2015, corresponding to the observed retreat. Nine different combinations ~~are presented here that~~ that satisfy the observations and cover a wide range of perturbations ~~for each parameter. The SMB is well known (Box, 2013), and all runs are therefore forced with the same gradual change in the SMB profiles~~are presented here. Table 2 shows the values that each parameter reaches in 2015 for the nine different model runs.

~~Sea ice buttressing can be assumed to decrease with increasing air and ocean temperatures, largely influencing iceberg calving (e.g. Sohn et al., 1998; Reeh et al., 2001). However, the correlation is poorly known~~ SMB is the only purely physical and well known parameter both for LIA and today (Box, 2013). The piecewise-linear function presented in Section 2.3 is a good approximation to the observed profiles (Figure 2) and ~~a temperature increase may only impact seasonal frontal migration, leaving annual fluxes unaffected (Amundson et al., 2010; Cassotto et al., 2015). We conduct experiments with unchanged sea ice buttressing ($f_{si} = 1$) as well as decreased buttressing by a factor two and three compared to the LIA value in 2015.~~

~~Nine combinations of the perturbation parameters used in this study. Values shown here are those reached in 2015 after a linear perturbation from their LIA value shown in Table 1. Values for the SMB are perturbed to the same 2015-values for all model runs:~~ ~~$G_{a1} = 0.0019\,\mathrm{yr}^{-1}$, $G_{a2} = -0.00013\,\mathrm{yr}^{-1}$, $a_0 = 0.64\,\mathrm{m\,w.e.\,yr}^{-1}$~~. ~~Run 5 (in bold) is presented in more detail in the paper. run ID~~ ~~f_{si} m c_{cw} $\mathrm{m\,yr}^{-1}$~~~~m1 1 180 395 2 1 260 370 3 1 340 340 4 2 180 295 6 2 340 255 7 3 180 225 8 3 260 210 9 3 340 185~~

~~10 2 260 250~~ is therefore used here. All model experiments use the same gradual changes of the SMB gradients and maximal SMB from the LIA values to present day values (Table 2).

Submarine melt is influenced by ocean temperatures, which have increased from about 1.5 °C in 1980 to 3 °C in 2010 ~~outside JI~~ in Disko Bugt (Lloyd et al., 2011) with a 1 °C warming ~~only~~ in 1997 (Holland et al., 2008a; Hansen et al., 2012). Jenkins (2011) estimates about a doubling of melt rates underneath the tongue of JI (depending on initial conditions and the way in which melting is applied), when considering a 1 °C warming and steepening of the glacier front. Submarine melt rates may additionally be enhanced by increased subglacial ice discharge (Jenkins, 2011; Xu et al., 2012, 2013; Sciascia et al., 2013), although this may be a local effect and negligible when with-averaged (Cowton et al., 2015). Observations of submarine melt rates beneath JI's floating tongue suggest an annual melt rate of 228±49 $\mathrm{m\,yr}^{-1}$ between 1984 and 1985 (Motyka et al., 2011) and 2.98 $\mathrm{m\,d}^{-1}$ (1087 $\mathrm{m\,yr}^{-1}$) averaged over the melt seasons in 2002 and 2003 (Enderlin and Howat, 2013). Since submarine melt rate is ~~poorly constrained~~ otherwise poorly constrained, especially further back in time, we conduct a large range of linear forcing, from no increase, to a ~~two fold~~ two-fold increase of the LIA value ~~reaching then~~ of 175 $\mathrm{m\,yr}^{-1}$ to 340 $\mathrm{m\,yr}^{-1}$ in 2015.

Note that the model neglects submarine melt at the vertical calving front.

The crevasse-water depth has not been measured and is here a non-physical model parameter that regulates discharge fluxes. It is therefore likely exaggerated to account for the lack of submarine melt at the vertical glacier front in the model. For the LIA steady-state, the crevasse water depth is set to 160 m, which produces the observed glacier length and a calving rate of 34 $\mathrm{km}^3\,\mathrm{yr}^{-1}$ in 1985, which is in the same order of magnitude as the observed calving rate of 26.5 $\mathrm{km}^3\,\mathrm{yr}^{-1}$ in 1985 (Joughin et al., 2004) and more recent values obtained from other studies (24–50 $\mathrm{km}^3\,\mathrm{yr}^{-1}$; Rignot and Kanagaratnam, 2006; Howat et al., The increase in crevasse water depth with time is unknown, but may be ~~comparable~~ related to the increase in runoff, which has increased by 63 % since the LIA (Box, 2013). To account for such a large range, we increase the crevasse water depth from its LIA value depths to values between 185 m and 395 m in 2015. It is thereby tuned depending on the combination of sea ice buttressing and submarine melt rate to reach the observed retreat (Table 2).

Ice mélange in the fjord can apply a buttressing stress to the calving front of about 30-60 kPa or one tenth of the driving stress (Walter et al., 2012). With increasing air and ocean temperatures, ice mélange can weaken or break-up, largely influencing iceberg calving (e.g. Sohn et al., 1998; Reeh et al., 2001). However, the correlation is poorly known and break-up of ice mélange is thought to impact frontal migration on a daily to seasonal timescale, leaving annual fluxes unaffected (Amundson et al., 2010; Walter et al We conduct experiments with unchanged sea ice buttressing ($f_s = 1$; also used for the LIA steady-state) as well as decreased buttressing by a factor two and three compared to the LIA value in 2015.

In order to reach the ~~same total retreat~~ observed retreat position in 2015 in all combinations presented in Table 2, the 2015-values for each parameter depend on the values for the other parameters. This means e.g. that a ~~high~~ low submarine melt rate is

Table 2. Nine combinations of the perturbation parameters used in this study. Values shown here are those reached in 2015 after a linear perturbation from their LIA value shown in Table 1. Values for the SMB are perturbed to the same 2015-values for all model runs: $G_l = 0.0019\,\mathrm{yr}^{-1}$, $G_u = -0.00013\,\mathrm{yr}^{-1}$, $a_0 = 0.64\,\mathrm{m\,w.e.\,yr}^{-1}$. Run 5 (in bold) is presented in more detail in the paper.

run ID	f_s	m [$\mathrm{m\,yr}^{-1}$]	d_w [m]
initial steady-state values in year 1850			
0	1	175	160
linear forcing: values reached in 2015			
1	1	180	395
2	1	260	370
3	1	340	340
4	2	180	295
5	**2**	**260**	**275**
6	2	340	255
7	3	180	225
8	3	260	210
9	3	340	185
step forcing: values applied in 1850			
10	2	260	250

needed in case of reduced sea ice buttressing and a small crevasse water depth or that the crevasse water depth has to be large when sea ice buttressing is not reduced and the submarine melt rate small.

In addition to experiments with linearly increased parameters, we also conduct one experiment with a step increase in the ~~three~~ four parameters after the LIA maximum. The values for sea ice buttressing, submarine melt rate, water depth in crevasses and SMB applied in 1850 for the step increase are comparable to those reached in year 2015 in run 5, with slightly different values to reach the right front position in 2015. All experiments shown in Table 2 are run until 2100 to expand the temporal and spatial dimensions to show the importance of the geometry.

Despite a relatively high ~~amount~~ number of frontal observations since the LIA (Fig. 1), only the observed calving front positions in 1850 and 2015 are used here to tune the parameters; in between, the forcing parameters increase linearly and the glacier length evolves freely. ~~Nevertheless, we~~ We present the time evolution of the simulated front positions together with observations. To obtain one-dimensional observed front positions, we ~~first calculate a centerline as a smoothed line following~~ assume the trough to be approximately east-west oriented. We calculate the mean latitudinal ~~position~~ coordinate of each observed ~~glacier~~ calving front (Fig. 1) ~~. The front positions are then chosen where the observed calving fronts intersect with the model centerline; the~~ with the corresponding longitudinal position at that latitude. The positions of the resulting one-dimensional front positions lie approximately in the center of the trough. The uncertainty of the front positions is calculated as the maximal spread of each front in cross-trough direction.

3.4 Geometric experiments

In addition to the effect of forcing, we also ~~test the impact~~ try to investigate the effect of fjord geometry ~~on glacier retreat~~and the relative importance of bed topography versus channel width. We design experiments with a smoothed width and depth in the deep and narrow trough. Four different geometry combinations are constructed and shown in Fig. 3.

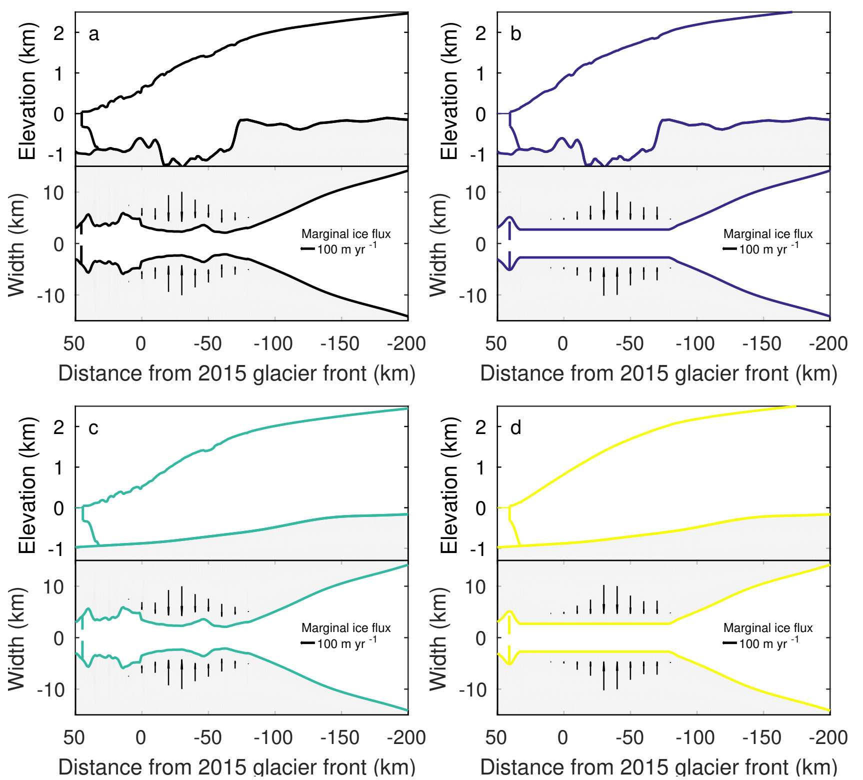


Figure 3. Different model geometries used to investigate the impact of topography on ice dynamics. (a) Original geometry, (b) straight width, (c) straight bed and (d) straight width and bed. Arrows indicate the tributary ice flux, with their length representative for the influx volume.

- **a** Original geometry: Observed width and depth of the trough as described in Sect. ~~??~~3.1.
- **b** Straight width: The width until 80 km inland of today's front is set to a constant value of 5.4 km. Only at the LIA front position, a wide section is kept in order to reach a steady-state with the same parameters. The depth is kept as in **a**.
- **c** Straight bed: The bed of the deep trough to 120 km inland of today's front is smoothed to get an almost straight bed, linearly rising inland. The width is kept as in **a**.

d Straight width and bed: Both, the width and the bed are straightened here.

The runs with simplified geometry start from steady-state at the LIA front position with the same parameters and forcing as for the original model setup (Table 2). Due to the changed topographies, the glacier surfaces and velocities differ from the original geometry and the LIA front position is slightly changed.

4 Results

In this section, we present the steady-state glacier at the LIA maximum extent and the glacier retreat simulated with run 5 (Table 2) as an example. In addition, the response to different forcing parameter combinations, more simplified geometries and a step forcing is presented.

4.1 Jakobshavn Isbræ at the LIA maximum

The initial steady-state glacier as shown in Fig. 3a and 5a is reached with the parameters in Table 2. It has an uneven surface that reflects the trough geometry, which is common for fast flowing ice streams (Gudmundsson, 2003). At the position of KAGA, the surface elevation ~~is~~ reaches about 400 m compared to the 300 m of the LIA-trimline height ~~Csatho et al. (2008)~~(Figure 4a; Csatho et al., 200 however, the side margins are expected to be lower than the centerline and the model glacier has a—probably overestimated—surface bump at that position. The LIA glacier terminates with a 9 ~~km long~~ km-long floating tongue, where it has a velocity of 5 $\mathrm{km\,yr^{-1}}$ and a grounding line flux of 35 $\mathrm{km\,yr^{-1}}$. The ~~modelled~~ modeled width-averaged basal shear stress for the LIA is about 128 kPa at 40 km inland of the present-day front position and the driving stress is 290 kPa at that location, when applying a 3 km moving average to smooth the surface bumps. ~~Compared to this, ice flow simulations suggest low basal resistance (Joughin et al., 2012; ?)~~ In comparison, other modeling studies obtain lower basal resistance (Joughin et al., 2012; Habermann et al., 2013) data assimilation methods imply basal stresses at the bed of the deep trough of about 65 kPa at 50 km upstream of the calving front, equivalent to only 20 % of the driving stress (Shapero et al., 2016). However, these estimates are from present day and it is unknown how much the relative contribution of the stresses have changed over the time period. During the speed up, the basal shear stress might have reduced in the lowermost 7 km and not changed further upstream (Habermann et al., 2013). Note also that the stresses provided by the model are width-averaged.

4.2 Non-linear glacier response to linear forcing

Figures 4 a,b show that the modelled front position retreats non-linearly in response to the linear external forcing (shown here is run 5 in Table 2). It retreats 21 km during the first 163 years, after which a 16 km long floating tongue forms. During the break-off of the tongue in 2013 to 2014, the front retreats a further 23 km. Throughout the retreat, the glacier terminus configuration alternates between a floating tongue and a grounded front. The front velocities (Fig. 4c) only increase by 3 $\mathrm{km\,yr^{-1}}$ during the first 163 years and more than double from 8 $\mathrm{km\,yr^{-1}}$ to 19 $\mathrm{km\,yr^{-1}}$ when the floating tongue breaks off. This acceleration is overestimated, as the simulated tongue breaks off faster than observed. However, velocity observations ~~by~~

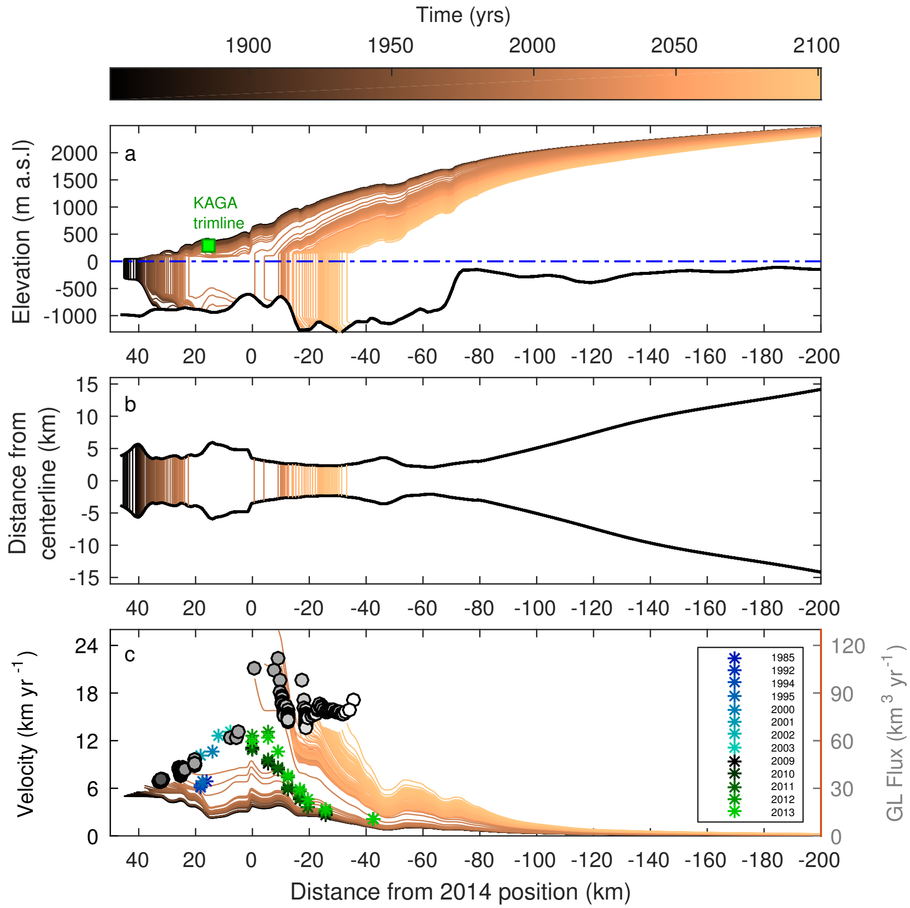


Figure 4. Modeled retreat of JI in response to a gradual change of the forcing parameters (run 5 in Table 2). Yearly profiles are shown for (a) the along-flow glacier profile and the elevation of the KAGA LIA trimline (Csatho et al., 2008) in green, (b) the front positions in a top-view and (c) the along-glacier annual velocities including the yearly grounding line (GL) flux (grey circles from dark to light with time)~~and observed~~. Observed yearly velocities are plotted at the calving front from 1985 to 2003 (Joughin et al., 2004) and at seven different points upstream from the glacier front from 2009 to 2013 (Joughin et al., 2014).

~~Joughin et al. (2014)~~Joughin et al. (2004, 2014), shown in Fig. 4c, are smaller than the simulated in the early 1990s, but are in-between the simulated velocities before and after the break-off. The model simulations show that the acceleration continues until the retreat of the front slows down. The grounding line flux, calculated as the grounding line velocity times the grounding line gate area, increases from 35 km^3 yr^{-1} to 65 km^3 yr^{-1} from the LIA until ~~2015.~~ 2015 compared to observed values of about 32-50 km^3 yr^{-1} between 2005 and 2012 (Rignot and Kanagaratnam, 2006; Howat et al., 2011; Cassotto et al., 2015). Beyond 2015 it increases to 100 km^3 yr^{-1} and finally ~~stabilizes~~ stagnates with 77 km^3 yr^{-1}.

Various parameter combinations presented in Table 2—and many more that are ~~approximately an interpolation of~~ in-between those presented here—force the observed total retreat since the LIA. Figure 5 shows the retreat of the glacier front and grounding line with time for the applied nine parameter combinations. The simulated ~~evolution of the frontal position~~ temporal retreat pattern of the glacier front is similar for all experiments and shows the strong non-linearity of the frontal retreat—despite the linear forcing (Fig. 5a). The response to the different forcing experiments differs mainly in the timing of ~~each further~~ the phases of rapid retreat, especially the final retreat just after 2050. All model runs show a very abrupt retreat of at least 23 km within a few years, which corresponds to the observed retreat of 19 km after year 2000. The simulated frontal positions ~~from the observations, but~~ differ from those observed, which is expected due to the ~~simplicity of the model and the forcing, the~~ strong simplification of the forcing. The aim is here to study the geometric controls on rapid retreat rather than tuning the model until the simulated retreat fits the observations. The reasons for the deviation of the simulations from the observations is discussed in Sect. 5.

The grounding line retreats more step-wise (Fig. 5b) compared to the glacier front. Before 2015, it stabilizes at distances of 32 km, 25 km and 20 km from the 2015 frontal position for all experiments. It retreats more gradually beyond 2015 with short stabilizations at 8 km, 12 km and 18 km upstream of the present-day position. The forcing parameter combination thereby ~~only determines~~ determine the timing of the grounding line displacement.

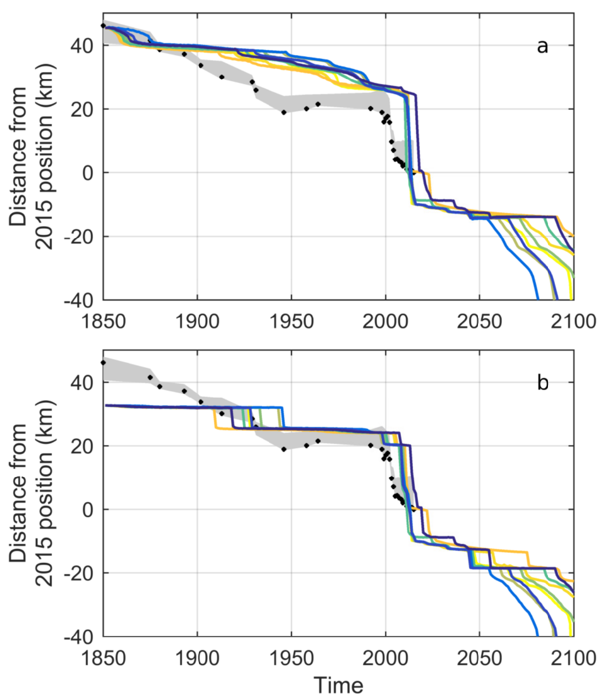


Figure 5. Simulated position of (a) the front and (b) the grounding line for nine different gradual forcing combinations presented in Table 2. The colors for the different model runs are random. Black dots show the observed front positions at the centreline with a spread (grey shading) corresponding to the across-fjord variation of each front position (Fig. 1).

4.3 Control of fjord geometry on front and grounding line retreat

The ~~stability~~ residence time of the grounding line is analyzed here for the different geometries introduced in Fig. 3. ~~Stability~~ Residence time is thereby quantified by the ~~time~~ amount of time that the grounding line rests ~~at one position~~within a distance of 1 km. Figure 6a shows the original geometry with the most pronounced pinning points at distances of 32 km, 25 km, -10 km and -13 km from the 2015 position. Only the length of ~~stabilization~~ grounding line still-stand thereby varies among the nine different model runs (Table 2), whereas the ~~stabilization~~ pinning point locations coincide (also seen in Fig. 5b). Artificially straightening the width removes the pinning points at 25 km and those beyond the 2015 position (Fig. 6b). Instead, the glacier ~~stabilizes~~ rests at the present-day position. The geometry with the straightened bed causes a similar response to the linear forcing as with the original geometry, only with a wider spread of ~~stabilization~~ pinning points (Fig. 6c). Straightening the bed and the width removes all pinning points (Fig. 6d) and leads to a linear retreat. Note that all geometries have an initial pinning ~~points~~ point at the LIA position to allow a steady-state at the LIA position. Generally, a reduction in the complexity of the fjord geometry, e.g. straightening the bed and/or width reduces the number of pinning points.

4.4 Delayed abrupt glacier response

In addition to the linear increase in climate forcing, the response to a step forcing (Table 2) is presented in Fig. 7. With the step forcing, the glacier front remains ~~stable~~ at a distance of 22 km for 60 years, before it retreats rapidly to its new ~~stable positions~~pinning point. This unprovoked rapid retreat—after centuries of constant forcing—demonstrates the long response time of the glacier ~~(Nye, 1960; Jóhannesson et al., 1989; Bamber et al., 2007)~~(Nye, 1960; Jóhannesson et al., 1989; Bamber et al., 2007; E The long response time is caused by a slow adjustment of the glacier volume to external changes. The corresponding accumulated volume loss also shown in Fig. 7 adjusts steadily to the initial changes in forcing, despite the ~~stable grounding line~~ constant grounding line position. During the rapid ~~front~~ frontal retreat, the volume decreases by 300 Gt and continues even after the grounding line ~~stabilizes. This emphasized that a stable grounding line~~ reaches a still-stand. This emphasizes that a constant grounding line position does not imply a steady-state. Similarly, an observed rapid retreat of a marine-terminating glacier might be the delayed response to previous temperature changes.

5 Discussion

~~Our~~ For the example of JI, our results show the importance of lateral and basal topography and ~~its~~ their implications for the evolution of glacier retreat in fjords. ~~JI on Greenland studied here is only one example. This challenges our~~ This knowledge can be used for a better understanding of the recent observed retreat history~~and makes it~~ ; however, it is hard to isolate the relative impact of changes in ocean forcing, SMB and internal factors including the fjord geometry. Here, we discuss the impact of fjord geometry on glacier front retreat and compare the simulated glacier response to the recorded long term glacier retreat history~~, as well as~~ . In addition, we explore the implications of our results for the future response of JI to changes in climate.

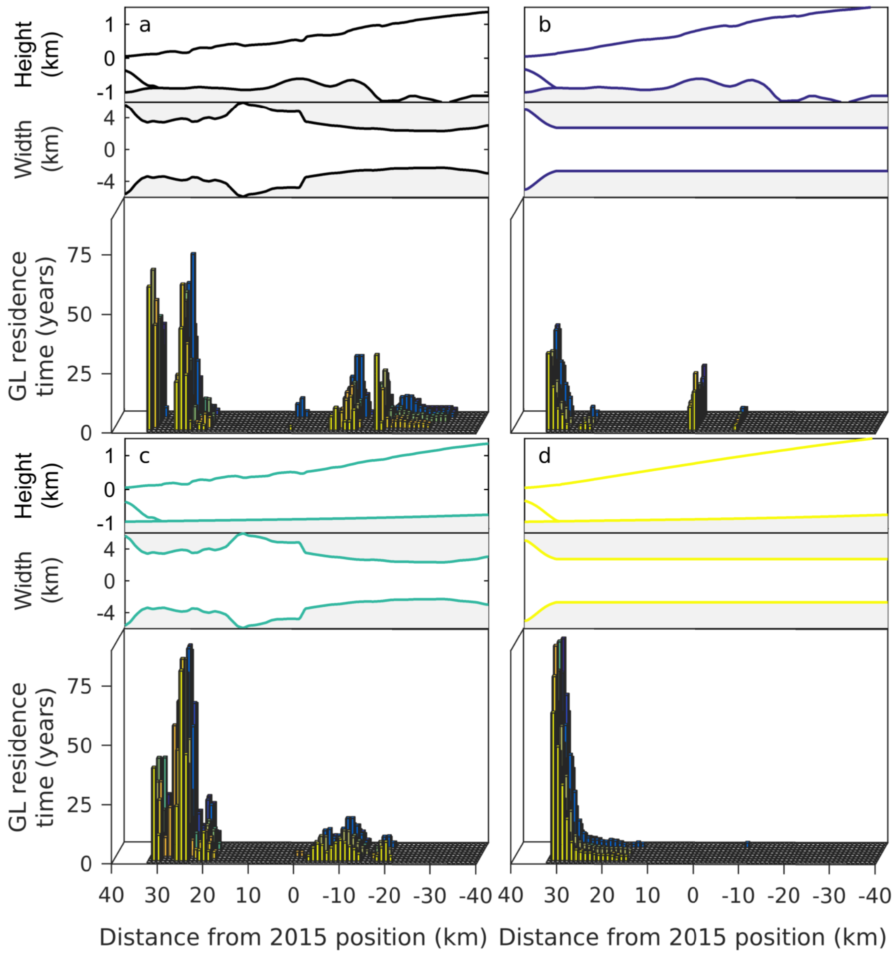


Figure 6. ~~Stabilization~~ Residence time of the grounding line (GL) for the different geometries presented in Sect. 3.4: (a) the original geometry, (b) straightened width, (c) straightened bed and (d) straightened width and bed. The bars represent the time that the grounding line rests within 1 km (in years), and the colours correspond to the model runs in Table 2. Only ~~stable periods~~ residence times of more than two years are included.

We argue that fjord geometry and fjord width in particular to a large ~~extent controls the retreat~~ degree control the retreat pattern history of marine-terminating glaciers. Nevertheless, changes to the external forcing of the glacier are important ~~as their magnitude times the onset of the retreat and determines its strength~~ because their magnitude controls the onset and overall rate of the retreat (Fig. 5).

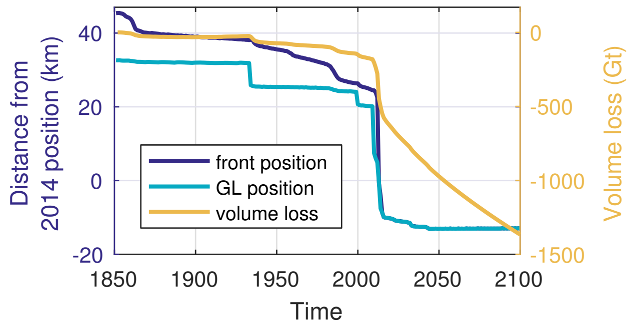


Figure 7. Simulated front ~~positions~~ and grounding line (GL) positions with accumulated volume loss for the step forcing (Table 2).

5.1 Geometric control on glacier stability

Our simulations show that once a glacier retreat is triggered through changes at the marine boundary or at the glacier surface, a non-linear response unfolds due to variations in the fjord geometry with a complexity given by the bed topography and the trough width.

For a retrograde bed, ~~in a one-dimensional model, variations in the underlying bed topography influence the~~ an increasing water depth as the glacier retreats increases ice discharge, leading to ~~an~~ further unstable glacial retreat in the case of non-changing lateral stresses (Weertman, 1974; Schoof, 2007). Previous studies ~~also~~ show that changes in the width of a glaciated fjord impact the lateral resistance as well as the ice flow, thereby stabilizing the glacier ~~in narrow sections (Gudmundsson et al., 2012; Jamieson et al., 20~~ narrow sections occur (Gudmundsson et al., 2012; Jamieson et al., 2012, 2014; Enderlin et al., 2013b; Morlighem et al., 2016; Åkesson et These findings are corroborated in our study. However, most of these studies use synthetic glaciers that do not allow for a validation of the model, ~~they use a shorter time period~~ shorter time periods that disregards long term adjustments or ~~they use~~ a realistic forcing that makes the role of the geometry nontransparent. Figure 7 shows that the ~~time scale~~ timescale of glacier adjustment can be several decades~~long~~. However, in reality temperature ~~does not change step-wise and it changes less than shown here. It still shows that the~~ changes are likely smaller and less abrupt than we have imposed. Nevertheless, our study highlights that observed recent retreat can ~~be the consequence of a warming that set in much earlier~~have been triggered and sustained by a warming event further back in time. This finding is consistent with Jamieson et al. (2014), who studied Antarctic ice stream retreat on millennial timescales. Depending on the local geometry of the underlying bed, individual glaciers have different response times and spacial extensions of dynamic thinning (Felikson et al., 2017).

~~In Figure 6 ,~~ The geometry experiments in Figure 6 assess the relative role of glacier width versus glacier length on JI~~is assessed. A flat glacier bed is less effective in reducing the non-linearity compared to straight~~. The width seems to be the leading factor for grounding line still-stand as artificially straightening the lateral boundaries removes most of the pinning points that cause slow-down in grounding line retreat. Straightening the bed topography is less efficient in linearizing the grounding line retreat compared to straightening the lateral boundaries. It has to be considered that the glacier trough is an order of magnitude wider than it is deep with larger variations in the width compared to the bed, resulting in a larger importance of the glacier width. ~~Whether this is the case in reality has to be studied further~~ Future studies will add further detail to these findings.

5.2 Relative role of forcing parameters

Only certain parameter combinations simulate the observed total retreat of JI since the LIA (Table 2). If the submarine melt rate is increased, the crevasse water depth has to be reduced and/or the sea ice buttressing increased. Similarly, if the sea ice buttressing is reduced, the crevasse water depth and submarine melt rate have to be smaller (Table 2). Importantly, none of the forcing parameters can trigger the retreat alone, ~~given that they are perturbed within a reasonable range~~unless they are changed unreasonably much relative to their LIA values. Only changed individually, the submarine melt rate would have to reach 650 $\mathrm{m.yr}^{-1}$ in 2015—an increase by 370 % from the LIA, the crevasse water depth has to increase to 400 m (250 % ~~of~~ larger than the LIA value), and the sea ice buttressing factor has to be more than quadrupled (value 4.2 relative to LIA factor of 1) in 2015 to force a strong enough retreat. Absolute values for the parameters have to be taken with caution, because they do not necessarily correspond to physical variables. For example, to reach the observed grounding line flux, the value for the crevasse water depth is likely too high in our study. This is ~~due to the lack of vertical submarine melt at~~ because it is a model parameter for calving that has to balance the neglected submarine melt along the calving front in the model. The change in parameters required to trigger the retreat is also dependent on the initial parameter choices and what forcing is needed to unpin the grounding line from the initial pinning point. As shown by Enderlin et al. (2013a), non-unique parameter combinations can exist for the same front positions~~, implying~~ . This implies that real-world observations are vital to reduce uncertainty in transient model simulations.

Note that the SMB ~~has an insignificant contribution~~ contributed insignificantly to the frontal retreat, even if the ~~frontal gradient~~ lower SMB gradient G_l is doubled and the SMB curve is lowered by 50 %, which together gives a SMB of -6 $\mathrm{m\,w.e.\,yr}^{-1}$ at the terminus compared to -1.1 $\mathrm{m\,w.e.\,yr}^{-1}$ during LIA ~~. In the model and for this glacier, changes~~ (cf. Fig. 2). In our model of JI, variations in air temperatures ~~therefore~~ contribute mainly through runoff and the filling of crevasses with water, rather than directly through surface ablation. For the specific geometry of JI, that the influx of ice at the lateral boundaries is a factor 100 larger than the ~~SMB and~~ local SMB could be important for the sensitivity of the glacier to changes in climate forcing. However, the lateral influx is an order of magnitude smaller than the flux through the main trough and a sensitivity study shows that the lateral flux has a minor impact on the retreat ~~rate, and if~~ pattern (not shown here). If all other parameters are kept fixed, the lateral influx has to be decreased by nearly 70 % ~~to match the observed retreat, which is deemed unrealistic.~~ from its LIA profile to simulate the observed overall retreat.

5.3 ~~Model limitations~~

~~Although the model captures the observed rapid retreat after the disintegration of the floating tongue, neither the step forcing nor the linear forcing reproduce all the details of~~

5.3 Model limitations and comparison to observations

In order to isolate the effect of geometry on glacier retreat, a relatively simple—but physically based—model is forced here with a linearly changing external forcing. Notwithstanding a number of assumptions, the model used is well suited as it is computationally inexpensive and allows for a large range of ensemble simulations starting from the LIA in 1850. The use of this long time period is vital in order to capture internal glacier adjustment to changes in external forcing beyond the last few decades. Unfortunately, few observations exist for such a long time period to validate the model with, which supports our chosen idealized model setup. The model parameters are calibrated with the few observations that exist and the modeled retreat of JI is compared to the observed retreat~~history since the LIA~~ .

Both modeled and observed calving front positions show a highly non-linear retreat and the rapid disintegration of a several km long floating tongue (Fig. 5~~and Fig. 7~~). The ~~magnitude of the rapid retreat is also exaggerated, which leads to an overestimation of the velocities, giving higher ice discharge compared to observations. However~~model results show a robust dependency of this non-linear retreat on the trough geometry, especially the trough width. However, the modeled glacier front retreats more slowly in general (deviation to up to 13 km from the observations) and exaggerates the break-off of the floating tongue. For the dynamic interpretation of the non-linear retreat, a perfect ~~match is not expected from a simple ice flow model as is used here, in particular given the linear forcing applied and the difficulty in measuring bed topography and bathymetry in this area (Boghosian et al., 2015). Due to the importance of the trough geometry, a small inaccuracy in the geometry would cause a different retreat~~agreement is not essential, especially given the one-dimensionality of the model and the uncertainties in the width averaged observed front positions.

~~If the objective is to accurately predict or reconstruct the time evolution of glacier retreat (e.g. Nick et al., 2013; Muresan et al., 2016; Bor a more sophisticated model has to be used accounting for the following shortcomings in the one-dimensional model :~~

~~Bed topography is averaged over the width, which removes bumps in~~ For the interpretation of the model results, the assumptions made in the model have to be considered. The most obvious assumption is the ~~trough that partly~~ one-dimensionality that does not account for across and vertical variation in geometry. The residence time of the grounding line at pinning points may be partly overestimated due to this width- and depth integration. Local bedrock highs that have been observed to ground the floating ~~part as it was observed by Thomas et al. (2003). The glacier width becomes symmetric due to the width-averaging, although in realitythe trough can be widening on one side and narrowing on the other . This asymmetry causes an uneven frontal retreat as seen in~~ tongue (Thomas et al., 2003) are not properly represented in a width-averaged setting and the width is regarded as symmetric around the central flowline. In reality, one lateral margin might narrow down and pin the grounding line while the other lateral margin widens up, causing an asymmetric calving front retreat (see Fig. 1~~. The bed and the lateral walls are treated as flat, which causes a stronger stabilization at pinning points.~~). Here, we only focus on the large-scale dynamics; lateral and vertical variations in the ice flow are seen as second order processes considering the high basal motion and high velocities in the deep and narrow channel at the lowermost 100 km of the model domain. As the glacier retreats further upstream "into" the ice sheet, the lateral ice flux becomes more significant so that the whole drainage area should explicitly be modeled, suggesting the use of a three dimensional model for future projections.

The depth and width integration also applies to internal glacier properties; ice temperatures are in reality high at the bottom (Lüthi et al., 2002), so that most deformation happens there, whereas the model assumes a vertically constant shearing and a constant rate factor. Along the ~~glacier margins~~ margins of a real glacier, ice viscosity drops significantly in response to acceleration and calving front migration (Bondzio et al., 2017) and marginal crevasses can form, which ~~is disregarded. The lateral inflow from the surrounding ice is here changed with time depending on the ice flux in the main trough. This allows for a dynamic response of the lateral influxes, but to be more realistic, the whole catchment area should be included. In addition, calving and submarine melt rates could be included in a different way, although these processes are still poorly understood and a different submarine melt rate implementation barely contributes to the glacier behaviour as modelled here. Also, the model only outputs annual values for velocity, front position and calving fluxes, which should all be regarded interannually to account for seasonal changes that may have an impact on annual changes~~are here disregarded. However, lateral drag and weakened margins mostly affect the timing but not the style of retreat, which has been tested in an idealized setting with the same model (Åkesson et al., 2018). Ice viscosity is rather a response to dynamic changes rather an a cause and is therefore not expected to change the retreat pattern significantly, although it may alter the timing and residence time of the grounding line slightly.

Several parameterizations of physical processes are used in the model, such as submarine melt and buttressing by ice mélange. This complicates direct model validation with observed values. However, these processes are still crudely implemented, if at all represented. For example, many models prescribe the position of calving front (e.g. Bondzio et al., 2017) or only focus on grounding line migration, whereas our model uses a physical calving law. Also, few observations exist on submarine melt rate, calving rates and basal sliding, especially over the long time period studied here. The impact of plume dynamics on submarine melt could be implemented in our model (Jenkins, 2011) or an along-flow variation in submarine melt rates (Motyka et al., 2003); however, the number of observations on ocean temperatures is sparse and the model results are similar when using along-flow variations in submarine melt compared to a constant value along the floating part (not shown here). Also an interannual variability of calving rates due to submarine melt, runoff and ice mélange is neglected here and not considered as important when looking at centennial timescales. Although many of the model parameters are only indirectly linked to observations, existing observations such as velocities, ice discharge and thickness are used to tune the parameters and to reproduce the glacier behavior as close as possible. Note that the needed change in forcing parameters to dislodge the grounding line from its stable LIA position might be overestimated due to strong variations in bed topography and width. Also, many parameter combinations can simulate the same stable position but lead to different glacier retreat (Enderlin et al., 2013a). We therefore include a large range of parameter perturbations, which lead to different residence times for the grounding line, but do not influence the importance of the geometry in defining locations of intermittent slow down in the overall grounding line retreat.

The choice of the model is dependent on the questions raised; if the objective is to accurately predict or reconstruct the time evolution of glacier retreat (e.g. Nick et al., 2013; Muresan et al., 2016), a more sophisticated model has to be used. Note that also the observations contain uncertainties~~, as the~~. The front position can vary by several kilometers seasonally (e.g. Amundson et al., 2010) and ~~the~~ this position varies by several kilometers across the trough (Fig. 1). For the calculation of the one-dimensional front position, we assume a west-east orientation of the trough, which gives an offset at the most recent calving fronts; however, the deviation is only a few km and within the spread of the across variation of the calving front. Most importantly, the bed topography—especially in the densely ice covered fjord and a sediment rich subglacial bed (Boghosian et al., 2015)—is challenging to obtain. Due to the strong control of the fjord geometry on the glacier retreat, small uncertainties in the trough geometry cause a highly different retreat pattern. This highlights the importance of detailed knowledge on the underlying bed topography (e.g. Durand et al., 2011).

5.4 Glacier front reconstructions based on trough width

5.5 ~~Predicting moraine positions~~

Figure 6 illustrates the potential in using the model simulations in a geomorphological context. Marine-terminating glaciers continuously erode their beds and deposit sediments, forming submarine landforms such as moraines. The rate of sediment deposition and resulting proglacial landforms are functions of climatic, geological and glaciological variables, though these functions remain poorly quantified due to sparse observational constraints. Proglacial transverse ridges tend to form during gradual grounded calving front retreat, whereas more pronounced grounding zone wedges are associated with episodic grounding line retreat (Dowdeswell et al., 2016).

The abundance of ice mélange in front of JI renders studies of submarine geomorphology difficult. Studies of this kind are lacking in the fjord, though evidence of the style of deglacial ice sheet retreat in Disko Bugt do exist (Streuff et al., 2017). Our study raises generic questions about the links between trough geometry and moraine positions. We suggest that ~~moraine positions to a first order~~ likely locations for moraine formation can be predicted from the glacier width, which here largely determines the position of grounding line stabilization. ~~In this context, numerical models can be used to calculated the position and duration of stabilization from the glacier width as in~~ The finding of very robust influence of width on the retreat patterns (Fig. 6~~, which then can be used as proxy for moraine build-up.~~) means that looking at fjord geometry allows us to locate positions of expected slow-downs or step changes (Åkesson et al., 2018; Small et al., 2018). This is extremely useful for reconstructions and interpreting paleo-records, for example from adjacent land-records e.g. moraines and reconstructions based on proglacial lake sediments.

~~Thereby, stable (moraine) positions are independent of model parameters, supporting geometric controls of moraine formation. This hypothesis remains to be tested with a model including sediment dynamics and constrained by a number of well-studied, diverse glaciological and climatic environments. While not a substitute for in-situ investigations, potential sites for more detailed (and costly) submarine studies could also be identified based on geometric information, using airborne or remotely sensed platforms.~~ To this end, our study clearly highlights the potential of ~~combing~~ combining long-term modelling studies with geomorphological and sedimentary evidence to understand the non-linear response of marine ice sheet margins. This needs to be considered when inferring ~~information on the climate by looking at~~ climate information based on glacier retreat reconstructions.

6 Conclusions

The rapid retreat of many of Greenland's outlet glaciers during the last decades has been ~~correlated~~ related with increased oceanic and atmospheric temperatures, though glaciers display diverse behavior. ~~We use the fjord geometry of JI as case study with a realistic setup of a numerical model~~ As an example of a rapidly retreating glacier, we study the retreat of JI from its Little Ice Age maximum to its present-day position. The numerical model is forced with a linear increase in SMB, submarine melt rate, crevasse water depth and reduction in sea ice buttressing to isolate the importance of geometry for temporary grounding line stability. The following conclusions can be drawn:

- The glacier response to a linear climate forcing is highly non-linear ~~.~~ due to its characteristic trough geometry. The importance of the trough geometry is a robust feature in our study and the modeled non-linear frontal retreat is consistent with longterm (century scale) observations.

- ~~A change in climate forcing determines the strength~~ External changes at the glacier terminus determine the degree and the timing of the glacier retreat~~; for our model glacier, SMB plays a negligible role and climate-related processes such as~~ : calving and submarine melt act together to ~~cause~~ trigger the observed total retreat of JI. SMB plays a negligible role in forcing the glacier retreat.

- ~~Fjord geometrydetermines the position of temporary grounding line stability;~~ The fjord geometry, and in particular trough width, determines where the grounding line retreat slows down during the overall retreat. Artificially straightening the trough ~~topography~~ geometry in the model reduces the non-linearity of the glacier ~~'s~~ retreat.

- Grounding line stabilization on pinning points can cause delayed rapid retreat due to a long dynamic adjustment to past changes in external forcing. We show this for the case of JI which might be transferable to similar marine-terminating glaciers in Greenland and other regions with glaciated fjord landscapes.

~~We argue~~ Our findings suggest that the retreat history of Jakobshavn Isbræ since the LIA has largely been controlled by ~~changes in the~~ variations in trough width and ~~depth~~ bedrock bathymetry and that future retreat will be governed by similar factors. Since grounding line stability is fundamentally controlled by the geometry, we also postulate that geometry—notably trough ~~width—can be used to infer sites of moraine formation~~width—is a vital source of information for when interpreting paleo-records of marine-terminating glaciers.

Code and data availability. The model code is available through Faezeh M. Nick (faezeh.nick@gmail.com). The model output and other datasets can be obtained upon request from the corresponding author.

Author contributions. Nadine Steiger, Kerim H. Nisancioglu and Henning Åkesson designed the research, Nadine Steiger performed the model runs and created the figures with significant input from Kerim H. Nisancioglu, Henning Åkesson and Basile de Fleurian. Faezeh Nick provided the model and technical support. Nadine Steiger wrote the paper, with substantial contributions from all authors.

Competing interests. The authors declare that they have no conflict of interest.

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Comments on N. Steiger et al., “Non-linear
retreat of Jakobshavn Isbræ. . . ”
https://doi.org/10.5194/tc-2017-151
J. H. Bondzio
April 3, 2018

1 General Comments

1.1 **Summary**

N. Steiger et al. set up a 1D flowline glacier model of Jakobshavn Isbræ (JI) and perform a sensitivity analysis on various climatic and geometric model input parameters for the glacier's evolution from the Little Ice Age to today and into the future (until 2100). The authors conclude that the fjord and trough geometry are the main controls on the glacier's retreat history. They argue to be able to infer points of grounding line stabilization – and hence moraine formation – from the trough geometry using an ice flow model.

1.2 **Novelty**

The study has two main threads:
The first is the “non-linear” dynamic response of the glacier, controlled by the bed topography, once the calving front retreat has been triggered. The idea that bed topography controls the calving front retreat is not new (cf. e.g. Enderlin et al., 2013; Morlighem et al., 2016), and the study does not provide substantially more information beyond this statement. The thread in its current form should therefore be dropped. It would be worthwhile to quantify and analyze the degree of non-linearity of the glacier response, but this is difficult with the irregular real-world glacier geometry used here. An idea would be to use an artificial bed topography and to quantify exactly how the bed topography translates into a front retreat rate. When using this approach, it would need to be discus sed how much of the response is due to model physics and how much due to model parametrizations. The second thread is the argument to infer stable grounding line positions by combining an ice flow model with geomorphological information, i.o. to infer potential sites for moraine formation. This thread is novel (to my knowledge).
Two comments on this: First, I'd suggest to motivate more clearly why it is important to identify these sites for readers that are not familiar with the subject. Second, I have reservations about the practicability of the method, cf. Section 1.3.

We thank the reviewer for his many comments and suggestions.

We agree that the importance of bed topography on the calving front retreat is not new. This is pointed out several times in the manuscript and we refer to studies that show the importance of water depth on grounding line stability. However, the novelty here is that the trough width is the leading control on the retreat pattern and determines positions of grounding line slow-down. This is very useful when interpreting reconstructions as it can provide valuable information to the possible locations of moraines.

The first thread relating to bed topography, as the reviewer points out, is well covered in existing studies. However, the dominance of trough width on groundling line movement is not as well known and has not been assessed for glacier such as Jakobshavn over timescales longer than a few decades. We have edited the text to make this point clear to the reader.

The second thread on using the model to locate potential sites for marine formation is as stated by the reviewer novel and we agree with the reviewer that the value of this approach should be better described in the manuscript. This has been taken into account in the revised version.

Another clearly novel thread of the paper not listed by the reviewer is the long term (centennial) timescale over which the non-linear retreat of JI is assessed in the manuscript. This has not been done before. Our results show that studying glaciers such as JI on longer than decadal timescales is critical, as the glacier responds slowly to changes in forcing and can respond abruptly to climate changes occuring decades to centuries earlier. Therefore, the long term history of a given glacier must be considered when projecting future retreat (or advance).

We elaborate further on these three points in the revised manuscript. See also response to reviews 3 and 4.

1.3 **Inferring Stable Grounding Line Positions Using an Ice Flow Model**

The second thread of the paper assumes that it is possible to determine the exact grounding line position over time from an ice sheet model only. I question this assumption for the following reasons:

- First, there is a large spread in the grounding line position across different ice flow models – and even for different mesh resolutions within the same model – for otherwise equal model setups (cf. e.g. Pattyn et al., 2013).
- Second, observational errors in bed topography and ocean melting rate near the grounding line are large. However, ice flow models are highly sensitive to small errors in exactly these model input parameters.

Hence, the likelihood of predicting the 'correct' grounding line position using only one model is small. The likelihood decreases further with the duration of the simulation, as errors add up and are amplified by dynamic englacial non-linear processes.

Instead of determining the exact grounding line position, we suggest that ice flow models, such as the one applied here, can simulate periods where the movement of the grounding line is much reduced. These relatively stable positions of the grounding line help identify potential locations of moraines and can help interpret past records of glacier activity. We have reformulated this section to make this clear and have focused more on the importance of fjord width to identify likely positions of moraines and periods of relatively stable ground lines positions.

We are aware of the challenges relating to differences between models and mesh resolution applied and have updated the manuscript to better explain the difference between simulated and observed glacier retreat including the impact of errors in bed topography and ocean melt data. However, given these caveats we argue that the model is a valuable tool in assessing the impact of fjord width on grounding line stability and can be used to predict the approximate locations of moraines given the simulated long residence time of the grounding line at certain locations.

1.4 **Model Fitness**

I have concerns that the 1D flowline model used here is not able to accurately capture the "correct" stable grounding line positions, as important physical processes for grounding line stabilization such as lateral stabilization (cf. e.g. Gudmundsson et al., 2012) are missing or parameterized at best. The study would have to show that the setup presented here is able to match the grounding lines obtained with 2D or 3D ice flow models. If the authors choose to only present the idea of the second thread here, I'd suggest to discuss which models would be better suited to capture the grounding line in future work. My current understanding on numerical modelling of JI and other isbræ-type outlet glaciers is that lateral physical effects (stress transfer, mass influx) have to be explicitly modeled due to their high importance for the glacier dynamics and their capacity for rapid, non-linear change themselves (Truffer and Echelmeyer, 2003; Joughin et al., 2012; Shapero et al., 2016; Bondzio et al., 2017). The model results obtained from using a 1D flowline model as used here have therefore to be interpreted with care, especially since some of the model parameters used here are unphysical (cf. specific comment 2.2).

We agree on that the model is simplified. However, as stated by reviewer 3, it contains all the "essential ingredients" needed for the study. It includes a physical parameterization of lateral and basal drag and is able to simulate stable grounding line positions on a reversed bed. Simple models, such as the one used here, have the advantage of focusing on 1st order processes. Further, they are extremely efficient, making it possible to perform large ensembles of simulations covering long (centennial) time scales, which is crucial for understanding the retreat pattern of glaciers such as JI, as discussed in our study. The model, despite being width and depth averaged, includes the main physics such as stress balance, fully dynamic calving and a robust grounding line treatment. Although some of the model parameters are "non physical", they are linked to physical processes (such as basal drag or calving) and can be tuned to match observations covering long timescales (not only the last decade). However, it should be noted that there are very few observations on fjord glaciers such as JI making it very hard to assess models, including complex 3D models with many tunable parameters.

Therefore, we disagree with the reviewer that the model is not suited for this study. In the revised manuscript, we discuss this in more detail and assess both the weaknesses and advantages of simple flowline models for studies of fjord glaciers on long timescales. We have also improved the model description in order to avoid any misunderstanding and better document the physical processes included in the model.

2 Specific Comments

2.1
p2, l10:"Compared to previous studies [..]": A review of modelling studies and their findings that treat the same problem (JI) is lacking. A few studies that you might want to discuss are Truffer and Echelmeyer (2003); Vieli and Nick (2011); Joughin et al. (2012); Enderlin et al. (2013); Muresan et al. (2016); Shapero et al. (2016); Bondzio et al. (2017). In particular, the main differences to Enderlin et al. (2013) have to be pointed out.

Thanks for the list of important papers. We have included those investigating the dynamics of JI with a dynamical ice flow model, including Bondzio et al. (2017) which was not published at the time of submission of our paper.

2.2
p5, Table 1: The model uses unphysical model parameters. Crevasse water depths of up to 395 m are higher than observed, and submarine melting rates of only 175 m/a are lower than observed (Motyka et al., 2011). Moreover, these two model parameters tend to influence calving in the same way (higher respective values lead to higher calving rates). Why have they thus not been chosen in the range of observed values? Please motivate your model parameter choice.

We clearly state throughout the revised manuscript that some of the parameters are not directly linked to physical processes. Specifically, the crevasse water depth is a model parameter used to tune the grounding line fluxes to match observations. The calving fluxes are overestimated as they have to account for the neglected submarine melt along the vertical calving front. However, the parameters are guided by observations, which are unfortunately sparse and only exist for very recent past. Regarding the submarine melt rate, Motyka et al., 2011 present melt rates for the year 1985, whereas 175 m/yr is for the LIA. Due to our applied linear increase in submarine melt rates, the LIA values are chosen to be small inititally. Applying a linear increase in submarine melt rate, the values reach 244 m/yr in 1985 for the reference model run 5. Because there is little knowledge on submarine melt rates and also other factors (no estimates on sea ice buttressing), the ensemble of model runs cover a large range of parameter values. The choice of the model parameters is explained in more detail in the revised manuscript.

2.3
p7, Eq.5: What are Q JI,0 and Q JI,t ? Please discuss that this scaling of the lateral ice influx allows only for small perturbations in mass flux, as geometric changes will alter the lateral influx along the ice stream over time. If, for example, the ice flow velocity of JI doubles, your lateral influx will double as well, which is contrary to what happens when you model the lateral physics explicitly: then, a thinning ice stream thins the surroundings of an ice stream, which (initially) reduces the mass flux into the ice stream. Your parametrization of lateral influx therefore potentially “overfeeds” the ice stream in comparison. The motivation and discussion of this parametrization is important, as the lateral mass influx affects the grounding line position directly.

We specified in the revised manuscript that Q_JI,0 and Q_JI,t are the initial overall flux through the main trunk and the flux after time t, respectively. We discuss that this parametrization is based on mass conservation assuming that the mass flux in the main ice stream is changing synchoneously with the flux of the side glaciers. This parameterization may initially overestimate the lateral flux in a situation with ice stream thinning, which may thereby alter the initial modelled grounding line response. However we expect this effect to be small on the time scales considered in here, since we expect resulting increased surface slope, driving stress and resulting speedup will compensate on the longer time scales considered here. We additionally tested the sensitivity of the model results to changes of the side fluxes and found that the results are little sensitive to the absolute strength of the side flux as that flux is of an order of magnitude smaller than the flux in the main channel.

2.4
p9, l14,15: It is not clear to me why you use the “mean latitudinal position” of each calving front? Moreover, if you mean the latitudinal coordinate of each calving front position, the please explain how you deal with the fact that the glacier trough is bent: fronts along a North-South oriented section of the trough would then receive the same “latitudinal position”.

We used the mean latitudinal coordinate, assuming that the trough is almost west-east oriented. This gives some small errors in the most recent front positions that are smaller than the across-trough spread of the calving front. This is discussed in the paper.
The calculation of 1d front positions is ellaborated in the revised manuscript.

2.5
p15, l20-22: The idea presented here is not new, cf. e.g. Vieli and Nick (2011).

We added references (Felikson et al., 2017, Jamieson et al., 2012) in the revised manuscript to support our finding of a long adjustment time of the glacier in response to climate changes.

3 **Minor Corrections**

1. p2, l32: “still”: This is either a typo or it suggests that you do not agree with the hypothesis that the ocean has an influence on the glacier. Please clarify.

The ocean does have an influence on the glacier, but we believe that there has so far been a too strong focus on the ocean as a key control alone, disregarding geometric controls on the retreat. The sentence is reformulated in the revised manuscript for better clearity.

2. p5, table 1: The dot on # xx is misplaced.

Thanks, this is corrected in the revised version.

3. p3, l2: “long timescale”: Please be more specific. A centennial or decadal time scale?

We clearified in the new manuscript that a centennial time scale is meant.

4. p6, Eq. 3: The equation interrupts the text flow. Section 2.2 needs to be restructured for text flow.

The whole Section 2.2 is restructured for a better understanding of the model setup, also taken into account the comments from the other reviewers.

5. p6, Eq. 4: Due to hydrostatic equilibrium, D = ρ i /ρ w H. Hence, Eq. 4 can be simplified to the form of Eq. 6 in Enderlin et al. (2013).

Note that this is only true for the floating part of the glacier; we therefore kept the equation in its more general form as is has been formulated so far. The same applies for the calculation of basal crevasses, which becomes only dependent on the tensile stresses Rxx where the ice is floating.

6. p6, l14: The model variable SMB, a, is usually put between two commata.

Thanks, we corrected this for clearity.

7. p7, l8: “The intention”. This sentence is incomplete. The intention is to use a realistic geometry to do what exactly?

This is corrected to: The intension is the use of a realistic along-glacier geometry to compare modeled thickness, length and velocity with observations.

8. p7, l17: “bed topography profile”: This is a repetition of p7, l9.

We removed the mentioning of the used topography data in the introductory sentences of section 3 to avoid repetition.

9. p8, l1: Bondzio et al. (2017) showed that the study attributes the glacier's high flow velocities to the interplay of both the slippery bed and the dynamically weakening shear margins, not just a slippery bed.

Thanks, we changed the formulation to clearify that both processes are used in Bondzio et al. (2017) to explain high flow velocities.

10. p8, l2: There is a question mark at the location of the citation in the text.

The citation was included here in the revised manuscript.

11. p8, l26: "outside JI". Please clarify.

We changed it to Disko Bugt.

12. p9, l4: The sea-ice buttressing in the model is an enhancement factor for the calving rate (Eq. 4). High sea ice buttressing occurs for low values of f si and vice versa. Therefore, I assume it is a typo when you state that high submarine melting would be necessary for low sea ice buttressing and vice versa?

Thanks for pointing out that typo. You are right, that a low submarine melting would be necessary for low sea ice buttressing.

13. p9, l8: "The values": Please specify which values you mean.

We specified that these are the values for the step increase of the four parameters (submarine melt rate, sea ice buttressing, water in crevasses and SMB) applied in 1850.

14. p11, l30: The glacier's total SMB is about 30 to 40 Gt, which is half of the modelled grounding line flux past 2015. I would therefore use a word other than "stabilizing".

In the revised manuscript, stabilizing and stability is renamed as slow down of grounding line or residence time or similar.

15. p15, l2-9: This introductory paragraph is hard to follow. Please rephrase.

The introductory paragraph is rephrased in the revised manuscript.

16. p17, l18: This is a one-sentence paragraph.

Following the suggestion by reviewer 3, section 5.3 is rewritten in the new version to better point out the suitability of the model for the question posed here, also revealing the caveats of the model.

Review of “Non-linear retreat of Jakobshavn Isbræ since the Little Ice Age controlled by geometry” by Stieger et al., submitted to The Cryosphere

Summary: The authors use a width- and depth-integrated flowline model that includes a parameterization to account for lateral ice fluxes to test the sensitivity of Jakobshavn Isbræ’s long-term retreat to variations in geometry under a variety of environmental forcing scenarios. The model results suggest that the non-linear retreat of the glacier is likely due to along-flow variations in fjord width and basal topography. The time series of grounding line and terminus retreat deviate from the observations for all the prescribed climate change scenarios, likely indicating that the simple linear climate forcings used here do not capture the complexities of the actual climate change during the observation period. However, the focus of the manuscript is on the importance of geometry in modulating the response to climate change and I think the paper clearly demonstrates that geometry exerts a strong first-order control on the timing and magnitude of dynamic change.

Specific Comments:
There are a few points that I feel should be slightly expanded on in the text for the sake of clarity and transparency in methodology.

We would like to thank the reviewer for the comments that we have now improved in the manuscript. A reply to each comment is given in the following.

1) It would be helpful to include an equation to clearly show how the height of basal crevasses is estimated from tensile deviatoric stresses and the height above buoyancy. There is presently no reference provided and it is up to the reader to search for an appropriate reference and equation therein that would relate these variables.

Both, the equation and the corresponding reference (Nick et al., 2010) are included in the new manuscript.

2) The transition height for the SMB parameterization is not listed in Table 1.

Thanks for pointing this out. We have now added the transition height to Table 1.

3) I do not see how it is possible that the ice thickness can be uniformly decreased due to submarine melting seaward of the grounding line without introducing an artificial step decrease in ice thickness across the grounding line. Is the time step sufficiently short that the step reduction in thickness at any given time is minimized? Or is submarine melting applied orthogonal to the floating ice so that it essentially ablates ice horizontally at the grounding line?

You are right that submarine melt is applied as a reduction in ice thickness, which induces a step at the grounding line. However, the submarine melt rate is an order of magnitude smaller than grounding line fluxes and the time step is sufficiently small that the model can smoothen out the artificial step. The way of treating submarine melt in the model is described more detailed in the revised version.

Both Motyka et al., J. Geophys. Res. doi:10.1029/2009JF001632, 2011 and Enderlin et al., J. Glaciol., doi: 10.3189/2013JoG12J049, 2013 provide modern estimates of submarine melting beneath Jakobshavn's floating tongue. How do your melt rates compare? This should be stated in the text.

We included in section 3.3 how the chosen submarine melt rate value of 175 m/yr for the LIA and up to 340 m/yr in 2015 compare to observed values of 228 m/yr in 1984-1985 (Motyka et al., 2011) and 2.98 m/d during the melt seasons in 2002 and 2003 (Enderlin et al., 2013).

4) Where is the lateral influx prescribed? Is it evenly added along the lowermost 80km or is the flux weighted so that it increases or decreases in the along-flow direction? What velocity data are used for the initial parameterization? Is the average annual velocity at each grid point bordering the main trunk used to estimate lateral flux variability along flow? Please elaborate.

The lateral influx is added on top of the smb and it varies along the lowermost 80km depending on the velocity and depth along the margins of the main trough (Fig. 3 in the new version). Annual velocity data by Rignot and Mouginot (2012) and depth at each grid point bordering the main trunk are taken to calculated the lateral flux. This is now clearified in the new manuscript.

5) You state that a crevasse water depth of 160m during the LIA may be exaggerated but I think you should at least say it is "likely" exaggerated because it is highly unlikely that crevasse water depths are anywhere close to that deep, especially given that there is no visible water in crevasses immediately inland of the modern terminus.

It is true that real crevasse water depths would not reach that high values. We clearified in the manuscript that the parameter is rather a model parameter than a physical parameter and that it is tuned by ice discharge rate and flacier length as there are no observations on crevasse water depth existing. Also, the crevasse water depth has to be exaggerated to reach the observed ice discharge, as submarine melt along the vertical calving front is not implemented into the model.

6) At the bottom of page 14 you state that geometry can delay the response of glaciers to climate change. The influence of geometry on the timing and magnitude of dynamicchange was also discussed in Enderlin et al., The Cryosphere, doi:10.5194/tc-7-1007-2013, 2013 and should be cited here as support for the importance of geometry on dynamic change (albeit using simple, synthetic glacier geometries).

Thanks for providing a supportive reference. We added the citation to the paragraph about the delayed response of glaciers to cliamte change in the revised version.

Introductory note
Note that this is a review on the revised version of the manuscript only. Note also, that I have not previously reviewed the initial submission but I have read the two reviews (ref1 and ref2) of the initial submission and the author response as well as the re-review of the revised manuscript of one of the previous reviewers (ref1).
However, I first tried to judge this revised manuscript on its own, but I could not get around relating here or there to the earlier very critical reviews, in particular with regard to novelty and value of the paper and the choice and limitations of the model.

General assessment
In my view, this is an interesting manuscript that investigates the dynamic retreat behaviour of Jakobshavn Isbrae in Greenland since the little ice age (LIA) using a simple flow model with a fully dynamic treatment of the calving front (ocean boundary) and importantly compares it to the observed retreat behaviour.
While several attempts of modelling the flow and dynamic changes of Jakobshavb Isbrae have been undertaken (including an early study with a similar model by myself), these earlier works focussed on the time period after 1990 and partly into the future and they did not all use a fully dynamic calving model (partly prescribed retreat to study upstream propagation of thinning/velocity).
The novelty of this study here clearly lies with the longer time perspective considered in which it attempts to explain (through flow modelling) to determine the essential controls of the observed step-wise and non-linear retreat behaviour from the LIA (1850) into the present.
While I agree with the earlier reviewers that the found sensitivity to fjord geometry (mainly water depth) has long been proposed and investigated, comparing detailed observed retreat behaviour with a fully dynamic flow model (moving calving front) over century time scales is still lacking (apart from Lea et al 2014, JG, but with much coarser data and on a much smaller glacier). The understanding and model capability of dynamic retreat over century time scales is however crucial given the current rapid changes and that predictions into the future typically should span a century or two and
Further, the modelling also goes beyond the argument of water depth as a control for non-linear retreat and demonstrates that the width of the fjord is for the retreat since the LIA the more dominant control for the retreat pattern, which has not been explicitly investigated before.
The strongly simplified forcing (slow linear changing forcing) in the modelling still produces very robustly (extensive sensitivity study) the highly non-linear retreat pattern which highlights the potential importance of long-term transient effects (inherent) in addition the response to the current rapid warming.

Thus, I have no doubt that this study is, although using a relatively simple flow model (but with all essential ingredients), clearly novel and a first in combining longer-term (centuries) observations successfully with dynamic flow modelling of marine outlet glacier behaviour.
This is not only crucial for understanding and putting current dramatic dynamic changes into a longer-term perspective but also highly valuable for interpreting the palaeo record (reconstructions).

There are a couple of points that one can criticise (as done in the other reviews) which I comment on below in more detail, and some of them should be addressed, but in my view they do not substantially affect the main conclusions of the paper and therefore I have the strong view that this is a valuable contribution for TC and of wider interest (modellers, contemporary glaciology, palaeo-reconstruction community).
Andreas Vieli

We would like to thank the reviewer for his constructive suggestions for the TC manuscript that are addressed in the revised manuscript together with the comments of the other reviewers. In the following, we outline how we addressed concerns and suggestions in the revised manuscript.

1) typos/editing/use of language:
In general here and there are some editing issues, typos or inaccurate use of language (see minor points below) which is somewhat unfortunate for a revised version but maybe just a result of the major rewriting in the revisions. Thus, the manuscript should be carefully proof-read again (ideally from native English speaker).

Thanks for correcting editing/ typos and language errors in the minor points. The revised version was indeed largely rewritten, which might be the reason for the errors. The new manuscript has now been proof-read by a native English speaker.

2) The model used here:
both earlier reviewers to some degree criticise the used flow-model as not fully appropriate, as too simple for such a complex outlet glacier. I agree that the model is relatively 'simple' and reduced and clearly has some limitations, but in my view such a model does not necessarily have to be inappropriate. It just depends on the question one asks and what processes are expected to be included. For a reduced question (of less complexity: e.g. a simple channel, only retreat pattern…) and simpler model may be appropriate.
In this case, I think one just has to be clear about the assumptions made (which could be improved a bit). Basically, the flowline model sees a channel, with variable width though, it includes longitudinal stress gradients and lateral drag from the side (given a width) as well as a fully dynamic marine boundary (calving criterion and capable to form a floating tongue, (which has been tested on several contemporary outlets against data)). Yes, all is vertically and width averaged but for the outer fjord channel (LIA position to recent terminus position) and given the high basal motion this seems to me a valid approach. Also note that with buttressing from a floating tongue or a narrowing channel it is perfectly capable of producing stable positions in retrograde slopes (consistent with Gudmundsson et al (2012) and unlike stated by reviewer1 (which to me seems from the comments in the review, not really to understand the used model here)).
Of course one should then not expect to reproduce details related to complex lateral topography variations… and not really interpret the continuation of the modelling runs into the future (as the stream retreats back into the ice sheet, a fair point of the earlier reviewers).

For addressing the question of what the effect of fjord geometry (bed AND width) are on the longer-term retreat pattern since the LIA, to me the model seems perfectly adequate, if the assumptions (what is in the model) are made clear. Simpler models sometimes also make it easier to tease out the essential things (zero-order) rather than hangup on details (2nd ortder).
Perhaps the authors could clarify this point a bit and make clearer somewhere that: 'assuming these and these stresses/processes are important and included in the model we test whether we can reproduce the general pattern of retreat as observed'.
Also the assumptions and a general statement about what terms/processes in the model could maybe at the beginning of the methods be clarified. In the moment it is a bit spread out and one has almost to already 'know' the model to know what is roughly in there.

Yes, I agree with the other reviewers that future work should start to use improved models, likely 3d and with additional processes in (e.g. shear softening, which I actually explored for JAKO already in an

adhoc way in the 2011 paper with a similar flowline model) and in particular for future projections. The authors already addressed this latter issue well in the revisions.
One should also note that more complex models (3d, more processes) also need better/more input data to constrain parameters or geometry, which for example for the ice-fjord channel here is simply not there. Further, for example the groundingline issue related to the sliding formulation (hinted on be re-review 1) does not go away when using more complexe models. On that note, the grounding line migration of the used model is actually pretty robust and fully consistent with schoof (2007) (successful in the MISMIP 1-d comparison exercise).

Thanks for discussing the suitability of the model for the question posed here and pointing out how to better clearify the abilities and caveats of the model in the manuscript. We largely expanded section 5.3 on the model limitations in the revised version and elaborated the suitability of the model. The general shortcomings of the model are now discussed together with their impact on the results of our study. The model description is improved for clearification and to stess that it contains all essential physics needed to address the research question.

Model calibration/experiment setup
A further point related to the model is the calibration of the parameters and experiment setup. As mentioned by reviewer 2 as well, I somewhat struggled a bit how the parameters have been chosen. I think most is there but it could structured and formulated a bit better (see detailed comments below). Regarding the waterdepth parameter (mentioned in the re-review 1) I am also a bit puzzled about the very high values used, in earlier papers they are usually below 100m for the calving model using surface and bottom crevasses (which is still high). Anyway, what is more important here is to make clear that this is not necessarily a 'real' water depth but rather a model parameter in the calving relation that can be used to perturb/force the model (calving) (with some relation to the surface e melt), see Nick et al 2010. This should be clarified.
The issue of calibration to the observations (see reviewer 2) has mostly been addressed well by making clear that only start and end position are used as constraints and the retreat in between is free to evolve.

Many if the parameters are indeed to be seen as non-physical model parameters. For some of them there are no corresponding observations at all (e.g. water depth in crevasses) so that related variables (e.g. ice discharge) are used for calibration. Most existing observations are used to constrain the model parameters. The total retreat from LIA to present day is the most important observation. The choice of parameters in relation to observations is better explained now in the revised manuscript. Including a wide range of perturbations in the sensitivity study shows that the main conclusion is independent of the choise of parameters and makes the results robust.

Model limitations
I agree that one should be clear about model limitations but in the moment this section is more like a description what the model can not do with little justification why this is still ok and does not affect the main conclusions.
It would be useful to explain why the authors think the results are still ok for their conclusions/question and to defend what their simple model can do and that this is ok for the given question. Again, just needs some reformulations and justifications (see some suggestions in comments below).

In the revised manuscript, we largely expanded on section 5.3 about the model limitations and justified the used of the model despite its simplicity. The assumptions and parametrizations used in the model are elaborated with a discussion on how/ if they impact our results. Sensitivity studies on the *parametrizations of the lateral influx and a submarine melt rate varying along the floating tongue show both little impact on the retreat pattern, which is discussed in the new version. A more detailed comparison of the simulated grounding line retreat to observations is included and the impact of the one-dimensionality of the model on the results is discussed.*

Moraine build up proxy
I partly agree with re-review 1 that the conclusion of using the model to locate potential moraine build up locations is not that useful. I agree that such retreat slow downs will likely be coincident with submarine moraines but I do not think they replace bathymetric or radar surveys. I would phrase the thread of conclusion just slightly different. The found very robust influence of width on the retreat patterns means that looking at fjord geometry, and in the case of Jako in particular fjord width, allows to pin down locations of expected slow-downs or step changes in retreat which is extremely useful for interpreting paleo records, for example from adjacent land-records (moraines) etc. this will be useful for reconstructions and pale-record interpretations.
So basically, this study is very helpful of interpreting the past changes and paleo-record, but also for interpreting current high spatial and temporal variability in outlet glacier retreat/mass loss. But this could maybe made clearer/be highlighted a bit.

Thanks for the suggestions on how to improve this section. Instead of determining the exact grounding line position, we suggest that ice flow models, such as the one applied here, can simulate periods where the movement of the grounding line is much reduced. These positions of grounding line retreat slowdown help to identify potential locations of moraines and can help interpret past records of glacier activity. We have reformulated this section to make this clear and have focused more on the importance of fjord width to identify likely positions of moraines and periods of relatively stable ground lines positions.

Discussion of terminus versus grline (and floating tongue):
In general, in the discussion of the results, a slightly more differentiated discussion of the influence of the dominance of width over the bed (in this case) maybe useful and add value to the study. Or am I wrong in this interpretation.
Further the formation of the floating tongue before the rapid step retreat (or lack of a floating tongue in the phase before compared to observations, see fig 4) should in my view be commented a bit more, as the shown run in fig 4 differs the observations somewhat (extensive floating tongue in 1980-90s). It may well be an issue of underestimated water depth in the fjord…? Or is it simply because you crevasse depth perturbations are so high that hardly any floating tongue is able to form. Maybe your extensive forcing sensitivity study gives an answer on this (from fig 4 it seems that some runs seem to form a floating tongue well before the rapid retreat (similar as observed.
Another point related to maybe discuss a bit more (or have I missed it?) is that the more stepped and pronounced 'resting' points of the grounding line compared to the terminus (see fig. 4 and as described in section 4.3 maybe indicates that the groundingline retreat pattern is a bit stronger related to the bed topography whereas the terminus (at most times floating) rather reflects the width variations (narrowings/widening…). and the floatng tongue makes the difference between the terminus and grline retreat pattern.
Maybe this differential behavuiour needs a little be more anaylsis or thought, but some more differentiated discussion/analysis of the effect of width and bed topography maybe useful and mare this study more valuable (to counteract the mentioned 'lack of novelty by the earlier reviewers ('we know the bed is important').

In the revised manuscript, we are more specific on the importance of width versus depth. Also the difference between grounding line and calving front retreat is discribed in more detail.

More detailed specific comments.

The specific comments are implemented in the revised manuscript together with the more general comments above. We reply to those comments that need some extra clarification, otherwise if there is no reply, the suggestion is accepted and implemented as it is.

Introduction p. 2, bottom paragraph: I would emphasise here so far missing longer-term perspective constraint by observations (century scale).

We largely restructured the introduction to emphasise the novel arguments in the paper and to point to missing aspects in earlier studies.

p. 3 line 2: I think this should be Vieli et al. 2005 (as in the 2001 paper I used a full stokes model!!!).
p. 3 lines 5-7: rephrase this a bit, I am not sure the 'validation' is fully appropriate here. Yes application to real world is important but also that compared to longer-term retreat…

p. 3 line 13-14: could refer to Pattyn et al (2012, TC) paper on the statement of the robust grline treatment

p. 4 line 12: '…submarine melt below the floating tongue described…'

p. 4 lines 21 and 22: the formulation of '…to tune the…' is a bit awkward, as you would have to say to what constraints you tune the model.
Maybe just say they are model parameters (basal sliding coefficient, lateral enhancement factor to reduce lateral resistance…) that adjusted to roughly match the observed flow for the present geometry.

Yes, it is true that the parameters are to be seen as model parameters instead of physical parameters. Some of the parameters are rather used to implement the changes in temperature with time into the model. Also, some parameters have no corresponding observations (e.g. water depth in crevasses) and are indirectly tuned through other observations (e.g. calving rates or glacier length). The link of the parameters to the corresponding observations is improved in the revised manuscript. The absolute values are, however, less important and the focus is more on the changes with time relative to the initial value. This is clearified and stressed in the revised manuscript.

Is a constant every where or is there also some water pressure (peff) dependency built in? faezeh used this in here nature paper as far as I remember.

*The effective water pressure is part of the basal drag term in equation 2 (H – rho_s/rho_i*D), but the basal sliding coefficient itself is constant in time and space.*

p. 4 line 26: '…300m initially, and due to using a stretched grid, it reduces to ???m when retreat to the present position.

It reduces from 302m initially to 292m at the present position.

p. 4 line 31: '(dsc and dbe, respectively)

p. 5 line 1: '…crevasses is dependent on the tensile…'

p. 6 top half: this is maybe more of a personal preference, but I would avoid double letter subscripts (e.g. d_cw, d_sc, rho_fw,…).
Similar within the text (also on page before) I think you do not need the brackets around the variables (line 1, 6 ,..) at least be consistent everywhere.

Yes, we renamed the parameters with double letter subscripts for better readability and the brackets around the variables are removed.

p. 6 line 1: maybe clarify that water depth in crevasses not necessarily a 'real' quantity but rather a forcing parameter within the calving model.

Yes, this is clearified throughout the manuscript, see our reply to comment on p.4/l.21

p. 6 line 1/before eqn. the variable 'd_sc' is not 'named' yet. Maybe add before eqn text: 'The crevasse depth d_sc is given by…'

Thanks, we made sure that all variables are mentioned before the occur in equations.

p. 6 lines 3-8: I find this explanation a bit confusing, maybe rewrite and restructure this explanation of the horizontal stretching rate. Maybe first explain the important stresses/terms and then the forcing parameters.

The whole paragraph 2.2 about the calving law is restructured for better readability and a better understanding.

p. 6 line 6 and 7: the sentence explaining the factor f_si should be moved to after the eqn starting with e_xx.

p. 6 line 14: add what the basis for the SMB of Box 2013 is (meteo station records?

We added that the SMB data are based on a combination of meteorological station records, ice cores, regional climate model output and a positive-degree day model.

p. 6 paragraph on atmospheric forcing: I find this explanation and variation in forcing rather difficult to understand. Am I right you actually change the mass balance gradient in the ablation area? Maybe a figure illustrating the SMB along x (before and after change) would be useful (maybe in appendix). And what is s_o? the ELA? or did I miss this? add s_o to to table 1. And again why use a 2 letter subscript for the vertical gradien 'G_a1'?

A figure with observed and linearly approched SMB for LIA and present day is included in the revised manuscript.

p. 6 line 21: '…as a vertical melt rate at the base of the floating tongue and that is assumed to be spatially uniform. Sensitivity analysis with along-flow variations in submarine melt showed similar results.'

p. 6 line 25: clarify the that you do this to get a 'realistic mass flux in the lower channel'. Note that Nick et al 2013, Jamieson et al (2014) and Nick et al (2013) did something similar.

The discription of the parametrization of the lateral influx is improved and descriped more clearly, following the comments of reviewer 2. Also references to similar parametrizations are added.

p. 7 line 8: '..and realistic FORCING', is this really so, you strongly simplify/modify the forcing to linear! Maybe rephrase and clarify.

True, the forcing is not realistic. We rather meant the use of real observations to constrain parameters, which we clearified in the revised manuscript.

p. 7 line 10-11 and next paragraph (3.1): I would be more specific how you do this tuning and which parameters you tuned.

Section 3 on the model setup is restructured into 3 subsections to easier describe alle parameters that have been tuned without having to mention parameters twice.
- *Model glacier geometry*
- *Constant parameters*
- *Forcing experiments and perturbation parameters*
- *Geometric experiments*

Also more observations are included and related to the corresponding parameters.

p. 7 line13: IMPORTANTLY, during the retreat the calving front…'

p. 7 line 14: exactly 43 km? or approximately?

Approximately. We corrected this.

p. 7/8 section 3.1 Model initialization in general: in particular last paragraph on p. 7 and two pragraphs on p. 8 should be clarified and maybe structured and explained more logically. I struggled to follow (see some more specific points below). E.g. make clearer that LIA extent and trimline used as constraint for initial LIA geometry and present extent, surface and velocity for geometry and basal sliding coefficient.

Section 3 on the model setup is restructured in the revised manuscript (see above). Each tuned parameter is now described in detail how it is constrained and linked to observations (if existant).

p. 7 line 24: basal sliding changes - the surface slope and hence ice thickness? Do you mean the choice of the basal sliding coefficient influences flow, and hence surface slope and divide thickness?

Yes, exactly. This is clearified in the revised manuscript.

p. 7 line 28: 'reference height'??? do you mean 'is used as elevation constraint for the LIA surface'?

Yes, thanks.

p. 7 line 30: again is the sliding parameter independent ofg peff (effective pressure/water pressure)

Yes it is. The sliding parameter is constant in time and space and only used to adjust the initial surface slope. Effective pressure is a separate included in the basal drag term (see above).

p. 8: line 3-4: maybe rephrase by saying: 'The steady state surface profile is …. A uniform lateral…'. Question, did you apply it up to the divide? Or just in the fjord part? May need some explanation. This also rises the question of what with you used upstream…? The cahnnel or the catchment width?

It is applied along the whole along-flow profile up to the ice divide. In the lowermost 77km inland of the present day position, the channel is used as it is very distinct in the bed topography. Further upstream, the width widens up to the catchment width. As the width is much larger in the catchment area, the enhancement factor playes a nigligible role there and is mainly effective in the channel.

p. 8 line 9 and line 12-13: again the crevasse water depth is rather a calving parameter than a 'real' quantity.

We stressed this throughout the whole manuscript.

p. 8 line 15-19: explain better how you vary SMB 'linearly'. At what rate, how? Before and further down you say you use Box dataset, but then you perturb it here??? But always the same way? Maybe show the SMB profiles in the appendix.

A figure with the observed and linearly approximated SMB profiles for the LIA and present day is included, also showing the ELA for both time periods. It clearifies the SMB parametrization.

p. 8 line 20-24: maybe check and refer to these referneces who also considered ice-melang buttressing (walter et al 2012 Ann Glaciol, Todd 2014 TC, Todd 2018 JGR,…)

Thanks for profiding further relevant literature. The papers are cited in the revised manuscript.

p. 8. Line 33: '…may be related…' (comparable would mean water deoth and runoff have same units!)

table 2: I would add and clearly label the unperturbed steady state parameters as well, so one can see the step change applied.

The steady-state LIA parameters are added to Table 2 to directly show the applied changes.

p. 9: '…to reach observed retreat position in 2015'

p. 9 line 11: awkward phrasiung 'high amount of observations', better: 'high NUMBER of …'

p. 9 line 13: delete 'Nevertheless' is not needed

p. 9 line 15: I can not foillow this 'mean latitudinal' ? do you mean you define a centreline along flow and then take the front perpendicular to it? 'latutudinal' refers to geographix coordinates.

Yes, we did use the mean latitudinal (geographical) coordinate, assuming that the trough is almost west-east oriented. This gives some small errors in the most recent front positions that are smaller than the across-trough spread of the calving front. This is discussed in the paper.
The calculation of 1d front positions is ellaborated in the revised manuscript.

p. 10 line 4: you could be more specific here: '…we also try to investigate the effect of fjord geometry and the relative importance of bed topography versus channel width….'

p. 11 line 12: '…reaches about 400m compared to 300m…'.; and refer to Fig. 3a here.

p. 11 are these values (stresses) from LIA or today?

From LIA, which is clearified now.

p. 11 line 17: 'In comparison, other modelling studies obtained lower basal resistance (joughin…)' and but they are from present??

Yes, they are from present. But they are the only observations/ estimates that exist. We assume that the ice discharge has increased since the LIA and try to start off with parameters that reach those observed values after the linear increase.

p. 11 line 23: '…retreats a further…'

p. 11 line 29: how do the 65 km^3 compare to todays observed flux?

It is a bit overestimated (todays observed flux is between 32-50 km^3). The observed values are added here.

p. 12 line 1: '…that are approximately an interpolation of those…' awkward formulation, rephrase ('are inbetween?').

p. 12 line 3: '…the simulated temporal retreat patternof the glacier front…'

p. 12 line 5: '…in the timing of the phases of rapid retreat…'?

p. 12 line 7: what do you mean with 'the simulated frontal positions from the observations???'

Sorry, this is a typo and should mean: 'the simulated frontal positions differ from the observations'.

p. 12, fig 3: this figure clearly shows that it is not just BED TOPO that is important for retreat pattern but that width (widening/narrowing)m seems here even more dominant influence. Should be mentioned and discussed later.

We put more focus on the importance of the trough width compared to bed.

Figure 3: how does it fit with earls 1990s velocity data, pre-rapid acceleration (joughin 2003)?

Velocities at the calving front from Joughin 2003 are added to Figure 3 and compared to the simulated velocities in the revised manuscript.

p. 13 line 3: 'The forcing parameter combinations thereby determine the …'

p. 13 line 5: this section is not just on grline but also on front retreat, so adjust title to: 'Control….on front and groundingline retreat'

p. 13 whole bottom paragraph: maybe 'stability' and 'stabilization' are not quite the right terms here as these are mathematically not fully stable, but rather slow downs in retreat.

We exchanged the words stability and stabilization by residual time and slow-downs or still-stands through the manuscript.

I am somewhat surprised that the grline position doe not change when the front is retreating. Do you measure here how long the front is within the same 'bin' (grid size)?

We added the grounding line position in Figure 7, where the retreat of the grounding line and the calving front can now be directly compared. It shows that they mainly retreat synchoneously and only the length of the floating tongue changes.

Clarify how you measure stability.

"Residence time is thereby quantified by the numbers of years that the grouding line rests within a distance of 1km."

Also in caption of fig 5: maybe 'residence time' or 'still stand time' is more appropriate as '0stabilization'.

It is changed in the figure and in the caption.

p. 13 line 10 : add a 'space' between 'position' and '(Fig., 5b)'

p. 13 line 12: '…forcing as with the original…'

p. 13 caption fig 4: add in caption what grey shaded line is.

We clearified that it is the maximal spread of the grounding line position.

p. 14 whole paragraph. Maybe the jamieson (2012) paper is relevant here.

p. 15, fig 6: maybe adding the grline positions as well (as in Fig 4) would be useful here.

Good suggestion. We added the grounding line position in Figure 7 which enables a direct comparison of the retreat of the grounding line and the front position.

p. 15/16 Improve/differentiate discussion of terminus versus grline: see main comments

We differentiated between the grounding line and terminus change with time in the revised version.

p. 15 line 2: 'At the example of JI, our results show.…and THEIR implications…' and delete first sentence on line 3.

p. 15 line 7: '…fjord geometry and fjord width in particular to a large degree controls the retreat pattern history…'

p. 15 line 8: '…magnitude controls the onset…'

p. 15 line 5: these references refer to large scale ice sheets/shelves and in the case of Schoof without a floating tongue. I would add some tidewater calving example as well

In our opinion, Schoof is the most important reference for explaining unstable retreat as the grounding line retreats into deeper waters. Most papers on tidewater calving stress the importance of the glacier width, whereas we here only want to point out the importance of water depth for the irreversible retreat. Papers for tidewater glaciers are given just after, where we also include the importance of the width.

p. 15 line 16: width not just affects lateral drag but also the flux cross section (narrowing leads to a jamming of ice flux and thus along flow thicknening/steeoeninG).

p. 15 line 13-14: 'they use shorter time periods' or ' use a short short time pertiod'
p. 15 line 21-22: the jamieson (2014) paper maybe relevant here.

Jamieson 2014 is definitely a relevant paper and we cited it here as well as on many other places.

p. 16 first paragraph: maybe one could highlight importance of width here (in comparison to bed topo).

The leading importance of the glacier width compared to glacier bed is highlighted better throughout the revised manuscript.

p. 16 line 9: 'reasonable' range? 340m of water depth in crevasses seems not necessarily 'reasonable to me.

We stressed that only the relative changes are of importance. The absolute values are very much dependent on the intial configuration, how hard it is to trigger any retreat etc...

p. 16 line 14: related to comment just above, yes, water depth in crevasses is not necessarily a 'real' quantity, but a model parameter. I am still puzzled why you had to use such big values, was it so hard to push/force it of the LIA position?

It was mainly tuned to reach approximately observed ice discharge raters and here, submarine melt at the vertical front plus calving are combined in the calving rates. But yes, it was also hard to force it from the LIA position.

p. 16: line 14: 'vertical'? do you mean 'horizontal submarine melt'? at the vertical calving face?

Yes, I mean horizontal submarine melt at the vertical calving face. This whole section is rewritten.

p. 16 line 18-20: again would be useful to see this SMB profile (add figure maybe in appendix)

We added the figure into the main manuscript and refer to it here.

p. 16 line 22: '…than the local SMB…'

p. 16/17 model limitations: I would mention the 'comparison to observations' as well in the subtitle and maybe say a bit more there how it matches or not matches the observed geometry change (forming of floating tongues …). Basically a little bit more on the 'details' mentioned on line 27. But keep it positive, meaning first say in the things it does well and what it still captures and not only a list of what it does not do. And regarding the limitations some more justification why these limitations are not crucial for the main conclusion/question of the study would be useful. (see main comments).

The section on the model limitations is rewritten and details of the simulated retreat compared to obervations is included.

p. 17 line 2: note that Bondzio actually did prescribe the front position over time…

Yes, that's right and it is formulated in a more clear way.

p. 17 line 6: 'This asymmetry causes in reality…'

p. 17 line 8: 'treated as STRAIGHT…' (rather than flat)
most would agree that SSA is a reasonable approximation for flow.

p. 17 line 7-9: depends on the question but for here I think

p. 17 line 10: yes ice viscisity evolution may change with acceleration but this is unlikely to affect the stepped retreat pattern as it is a response to the rapid dynamic changes rather than a cause (it may change the timing and average retreat rate later a bit though).

Thanks for the clearification. This is considered in the discussion of the model limitations.

p. 17 lines 12-13: did you test the sensitivity to this effect out, if so this may help to support your case. I think we did that in the jamieson et al (2012/2014) papers and did not see much effect on the stepped retreat pattern.

We tested the sensitivity of the model to different magnitudes of the lateral influx, where we kept the spatial pattern as it is and multiplied it by different factors. It only influenced the glacier surface when that factor was big (piling up of mass or producing a small depression), but it didn't seem to effect the retreat pattern significantly.

p. 17 line 15: 'outputs annual'? you mean you do not consider seasonal variations? Maybe clarify, but again including seasonal changes is unlikely to change your retreat pattern/main conclusions.

We clearified that there is no seasonal variability included in the model, but that it would not change the main conclusion.

p.17 line 18-19: with regard to data uncertainties I would also mention the relatively poorly constrained bathymetry data in the fjord.

Yes, that is true! We pointed out the importance of using an accurate bathymetry and bed topography, which is very difficult to obtain in an ice-covered fjord like JI and a sediment rich bed.

p. 17 section 5.4: see my main comment in general comments.
I would not focus too much on 'predicting moraine positions' (and hence change title) but rather towards how it helps for interpretation of palaeo records and to do reconstruction (e.g. looking at the fjord width tells you an awful lot)

We removed the suggestion of using a model to predict moraine positions and rather focused on the importance of trough width to pin down locations of retreat slow-down and to interpret palaeo records. The title is changed accordingly.

p. 18 line 7: '…has been RELATED to increased…' ('correlation' is a statistical technique and would require a coefficient and significance….)

p. 18 in the conclusions I would say a bit more what comes out/what it means at the end (fjord topo crucial and very robust for longer.-term retreat pattern) rather than what you did. For example the relative importance of the width and grline for the retreat pattern would be useful.

The importance of the width is stressed more in the revised manuscript.

p. 18 line 12: '…is highly non-linear …which is a robust feature of the modelling sensitivity study and consistent with longer-term (century scale) observations'