# Response to Referee #2

Yuzhe Wang

We would like to thank Martin Lüthi for giving insightful and constructive comments on our paper; they were very helpful to improve our manuscript. Our responsees to all the comments are given below. The original comments of the reviewer are given in italic, and our responses are given directly below in regular.

## Specific comments

*Leave away colons (:) before equations, this is not usual in The Cryosphere.*

We have deleted colons before equations and have reformulated the sentences if necessary.

*You should decide on one version of English. Now there are "modeled" and "modelled" in the same sentence.*

We now use "modeled" and "modeling" in the manuscript.

*p1,1 "see" could be omitted*

Changed. We have also removed "see" appeared in other similar case.

*p3,11 also give the slope angle in degrees, i.e. 4.6°.*

Changed.

*p3,12 L is often used for the glacier length, y would be more common for a transverse coordinate.*

We have changed the equation to $z = aW(z)^b$.

*p3,19 also indicate distance from terminus, or along-profile*

We have added the distance information. The sentence now reads:

"All stakes were located in the distance between km 0.6 – 7.9 along the CL (Fig. 3), spanning an elevation range of 4355 – 4990 m.a.s.l. (Fig. 1)."

*p5,13 omit ":", maybe writing "following Flowers et al. (2011)"*

The sentence has been reformulated to "we parameterize the lateral drag, $\sigma'_{xy}$, as a function of the flow-band half width, $W$, following Flowers et al. (2011)".

*p5,16 "horizontal diffusion is parametrized by glacier width" is quite opaque. Please explain what you are doing, since this is not standard. This seems to be middle term in the parentheses, but it is not clear where this comes from. Does this somehow parametrize lateral diffusion (along the y-Axis)? But then, why would the longitudinal velocity gradient $dT/dx$ play a role? Please explain this in detail (maybe in an appendix).*
*Overall, it seems advantageous to ignore heat flow in y-direction (i.e. leave away the problematic term in Equation (6), since nothing is known about the boundary conditions there.*

We directly use the parameterization of heat diffusion in $y$ from Pattyn (2002) (Equation (16)) therein). It's just a rough assumption. We didn't check with F. Pattyn for the details of the mathematical derivation. The thoughts behind it, by our understanding, are from (1) assuming $\partial T/\partial x$ has a linear relationship with $\partial T/\partial y$, $\partial T/\partial y = \partial W/\partial x \times \partial T/\partial x$; (2) assuming $\partial^2 T/\partial y^2 = 1/W \times \partial T/\partial y$.

As suggested by the reviewer, we now have removed the diffusion term in $y$. As shown below, this diffusion along $y$ (E-yDiffu) has very limited impact on the model results, compared with the case without it (E-ref). Thus, we can indeed ignore this term in the 2D ice temperature model.

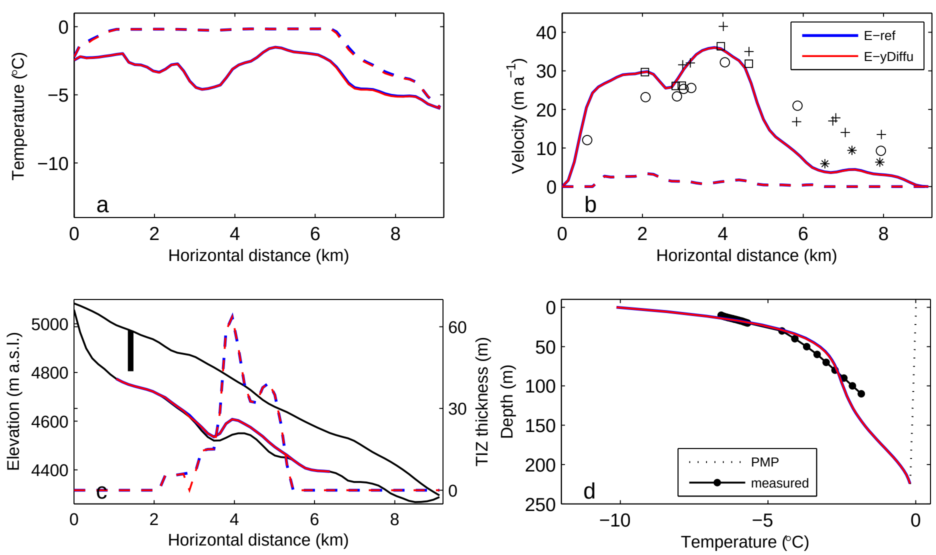


Figure 1: Modeled ice temperatures and velocities for experiments E-ref (blue line, without diffusion in y-axis) and E-yDiffu (red line, with parameterized diffusion in y-axis)

*p5,26 What happens with water produced by dissipation? Does this stay in the ice, or does it drain at a certain volume ratio? Is a balance equation for the water content, or the enthalpy, solved?*

We thank the reviewer for these very good questions! Sorry to admit that we've not considered those problems so far yet. We assume a constant water content in the temperate ice layer. But we haven't yet included a thermo-hydrological model. An enthalpy scheme for the polythermal glacier with a balance equation is under development.

*p6,3 Even if the model is described elsewhere in detail, the main characteristics should be given here: solution method (finite difference, finite element, ...), discretization (element type, mesh size), solution method (solver, time-stepping, CFL condition) etc., and maybe some implementation details (solver libraries used, maybe Matlab, etc...).*

The numerical implementations are the same as described in Zhang et al. (2013). We now have added a sub-section introducing the main features of the numerical solutions in p7–line19-25.

*p6,7 Parentheses should be adapted using \left( and \right)*

Corrected.

*p6,11 Strictly, this should be $\sigma_n - P_w$ using the normal stress on the bed, which might be quite different from the overburden calculated with the local vertical ice thickness. In which direction is $H$ measured, vertically (along $z$), or perpendicular to the ice surface?*

Here $H$ is vertical to the ice-bed interface (along $z$). The effective pressure used in the friction law is defined as the ice overburden pressure (see Gagliardini et al. (2007)), not the normal stress.

*p6,30 This boundary condition is valid for cold ice, but what is used in temperate ice? There, any geothermal heat will contribute to melting.*

If there is a temperate layer at the glacier base, two cases must be distinguished. For the melting case where cold ice flows into the temperate ice, we assume a negligible water content, and the ice temperature gradient at the CTS equals to the Clausius-Clapeyron gradient ($\beta$). For the freezing case where temperate ice flows into the cold ice, the latent heat released due to refreezing must be taken into account. We assume an ice temperature gradient at the CTS following Funk et al. (1994):

$$\frac{\partial T}{\partial z} = -\frac{Q_r}{k} + \beta. \tag{1}$$

The above description has been illustrated in the section 3.2.

*p7,2 I assume that the G-term is not very important for the model results. In mountain topography, the geothermal heat flux can vary a lot on short spatial scales, so the importance of this should be at least discussed.*

We now discuss the impacts of geothermal heat flux in our discussion section.

"Another uncertainty could be from the spatially uniform geothermal heat flux that we assume in the model, as it may have a great spatial variation due to the mountain topography (Lüthi and Funk, 2001)."

*p7,22 So, the water content is assumed constant throughout the temperate ice? This* *is problematic and will obviously introduce some inaccuracies.*

It's true that a constant water content may bring uncertainties in our results. Further efforts of including the water content computation and drainage system are still under development. We now have add a sentence for this in the discussion section.

"In addition, we can also improve our model ability by linking the water content in the temperate ice layer to a physical thermo-hydrological process in the future."

*p8,3 "compare to"*

Corrected.

*p8,6 The omission of convergent flow is only one possible (and likely) explanation, but there might be others, e.g. basal motion. This statement should be made more carefully.*

It's correct that our explanation is one of many possible reasons. The underes-

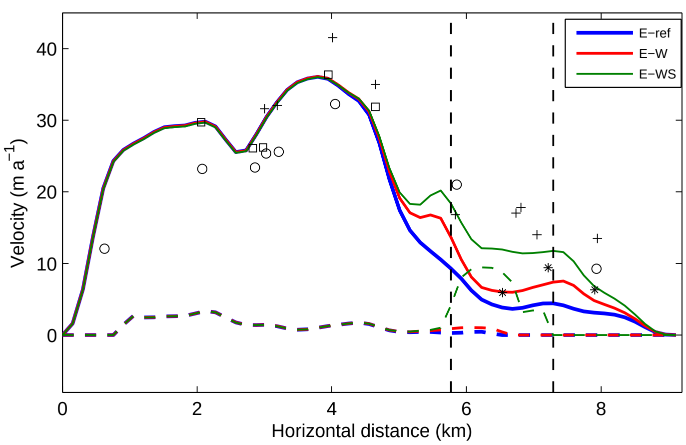


Figure 2: Modeled ice velocities for experiments E-ref (blue line), E-W (red line), and E-WS (green line). The glacier widths in the zone bounded by the vertical dashed lines are uniformly increased by 450 m.

timation of the ice surface velocities may possibly result from the neglect of the convergent flow from the west branch and an enhanced basal sliding which is not captured by our model in the confluence area. To verify this hypothesis, we conduct two other experiments, E-W and E-WS. In E-W the glacier widths are increased by 450 m at km 5.8 – 7.3 as a proxy of including the impact of the convergent flow from the west branch (Fig. 2). In E-WS, except for the same glacier width increase as in E-W, we also increase $\lambda_{\max}$ by 200% and decrease $m_{\max}$ by 60% for accelerating the basal sliding at km 5.8 – 7.3 (Fig. 2). We can clearly find that while both factors have a non-negligible contribution to the model results, the basal sliding may play a bit more important role in the confluence area. This indicates a need of considering glacier flow branches and spatially variable sliding law parameters in real glacier modeling studies. See p9–line3-10.

*p8,7 Here you should qualify "the modeled basal sliding velocities", IIUC. The reality, again, could be that basal sliding is much higher there. This could be elaborated upon in the Discussion.*

Yes, we discuss the modeled basal sliding velocities here. As suggested by the reviewer, we have conducted two other experiments in which the glacier widths are increased and the sliding law parameters are spatially tuned in the confluence area (see the above response). Then we discussed the impacts of convergent effects of the west branch and basal sliding (see p9–line8-10).

*p8,8 "observed": this is confusing, as you talk about model results. Better say: "the model predicts"*

We now use "The model predicts a TIZ overlain by cold ice over a horizontal distance of km 1.1 – 6.5".

*p8,9 add space between "110m"*

Fixed.

*p8,10 "ice fluxes" (not "ice flows")*

Corrected.

*p8,13 More important than matching temperatures would be a discussion of the heat fluxes. While the measurements show constant fluxes below 50 m depth below the surface, the model shows zones of warming and cooling (bends in the temperature profile). It would be important to understand the reason for these excursions from a straight line, is the shape of this profile due to advection, dissipation, or due the temperature history?*
*Closer to the surface (above 50 m depth) the measured gradient is much higher, which might reflect the thermal properties of the firn in a steady state (lower conductivity k). Since ice conductivity is assumed everywhere in the model, this might explain the difference there (cf. Fig. 5 in Luthi and Funk (2001) for a theoretical temperature profile with firn).*

This is a good question. To account for the thermal properties of the firn as suggested by the reviewer, we lower the conductity ($k = 0.17$ W m$^{-1}$ K$^{-1}$) of the surface layer in the accumulation zone (experiment E-FC). Compared with the reference experiment (E-ref), E-FC results in higher temperature gradient above 60 m depth (Fig. 3a). Nevertheless, this cannot explain the deviation of the modeled temperature profile from a nearly straight line below 30 m depth. We also conduct other experiments to investigate the possible factors affecting the shape of the modeled temperature profile by adjusting the parameters, i.e., ELA, firn temperature and horizontal grid resolution. We find that the bend of the modeled temperature profile at the borehole is strongly influenced by the discontinuous thermal surface boundary condition accross the accumulation and ablation zones. The borehole is located in the upper ablation area (4971 m a.s.l.), and is close to the snow line (around 4980 m a.s.l.). Therefore, the modeled temperature at the borehole can be influenced by the horizontal advection of relatively warm ice due to released latent heat from the accumulation zone. The higher temperature gradient in the upper part of the modeled profile demonstrates the impacts of horizontal heat advection from the upstream. We also compare the modeled temperature profiles below the borehole, which show little impacts from the upstream heat advection (Figure 3b).

In 2011, we observed that the ice drilled below the depth of 166 m was wet, indicating the temperate ice layer there was possibly thicker than our model prediction (around 5.6 m). As our 2D flow-band model assumes a simple parameterization of the surface thermal boundary conditions, and neglects the convergent flow from the other cirques, it cannot capture the complex heat flow at the deep borehole site. In the future, we may perhaps try a 3D Stokes model and see if there would be something different.

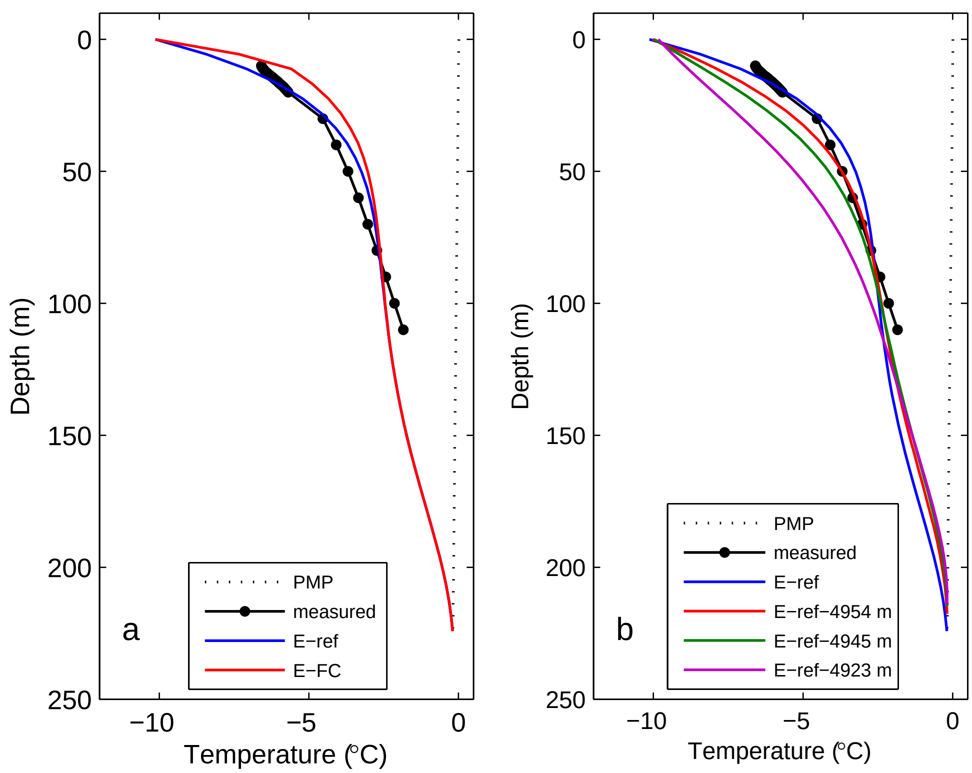


Figure 3: (a) Comparison of modeled temperature profiles at the borehole site. Blue line shows the modeled temperature in the reference experiment, while red line shows the result of experiment E-FC in which the firn conductivity is taken into account. (b) Comparison of modeled temperature profiles in the reference experiment. Blue line shows the modeled temperature at the deep borehole (4971 m a.s.l.). The red, green and purple lines show the modeled temperature profiles at 4954 m a.s.l., 4945 m a.s.l. and 4923 m a.s.l., respectively. Measured borehole temperatures are shown in dots. The pressure-melting point is shown by the dotted line.

*p8,27 It would be helpful to also show a graph of TIZ thickness (a second panel in Fig. 8c). It appears that the bed is temperate almost everywhere in the blue and* *green model runs, but with very small TIZ.*

Good suggestions. We have shown the TIZ thicknesses in the double-Y-axis graphs, i.e. Fig. 10c, 11c and 12c. It's correct that a large region of the bed is temperate as predicted by the experiments E-ref and E-20m. Thick temperate basal ice appears in km 2 – 6, while temperate ice in other places is only one layer.

*p8,31 "above" (leave away "in")*

We now delete "in".

*p9,11 ff instead of "drop" and "remove" you could consistently use "neglect" or "leave away"*

Thanks. We now use "neglect" and "leave away".

*p9,25 qualify basal sliding by modeled*

Corrected.

*p9,28 leave away "higher-order"*

Changed.

*p10,2 "physically" should be "physical"*

Corrected.

*p10,9 consolidate the two citations*

Corrected.

*p10,11 Past changes can have a very important impact (see for example Luthi et al. (2015)), as are warming processes in the firn (e.g. Machguth et al. (2016))*

The corresponding sentences have been reformulated as "The assumption of steady state neglects the transient effects of past climate and glacier changes, which can have a very important impact on the shape of temperature profile (Lüthi et al., 2015; Gilbert et al., 2015).".

*p11,16 Replace "e.g." with "of" (these are not just examples, but an exhaustive list of measurements used in the study).*

Fixed.

*p11,21 No need to show the symbol "(u)" here again (leave away).*

We now delete "(u)".

*Fig 1 A nice overview photograph would help setting the scene for this remote glacier that most readers wont know.*

Good suggestion. We now use a Landsat 8 satellite image of LHG12 Glacier.

*Fig 2 same labels on the horizontal axis of Figs. 3 and 4 would ease of comparison.*

Fixed.

*Fig 8d Caption: modeled and measured (lines vs symbols) should be interchanged.*

Corrected.

## References

Funk, M., Echelmeyer, K. A., and Iken, A.: Mechanisms of fast flow in Jakobshavn Isbræ, West Greenland: Part II. Modeling of englacial temperatures, Journal of Glaciology, 40, 569–585, 1994.

Gagliardini, O., Cohen, D., Råback, P., and Zwinger, T.: Finite-element modeling of subglacial cavities and related friction law, Journal of Geophysical Research, 112, F02 027, 2007.

Pattyn, F.: Transient glacier response with a higher-order numerical ice-flow model, Journal of Glaciology, 48, 467–477, 2002.

Zhang, T., Xiao, C., Colgan, W., Qin, X., Du, W., Sun, W., Liu, Y., and Ding, M.: Observed and modelled ice temperature and velocity along the main flowline of East Rongbuk Glacier, Qomolangma (Mount Everest), Himalaya, Journal of Glaciology, 59, 438–448, 2013.