

Response to reviewer #1 of “A new sub-grid surface mass balance and flux model for continental-scale ice sheet modelling: validation and last glacial cycle” by K. Le Morzadec et al.

July 28, 2015

1 General comments

I am really ashamed that I submitted the previous review before careful checks. Sorry to confusing. Here, I submit the revised review. Please forget about the first one. Thanks. This paper presents the potential impact of sub-grid scale processes such as surface mass balance and the ice transport to large-scale ice-sheet evolution. The method is an extension of previous work by Marshall et al (1993), with more topographic information and using two-way coupling between sub-grid and course grid model. The performance of the sub-grid model is evaluated using idealized and realistic regimes by a higher-order ice-sheet model ISSM. The sub-grid model is installed in a large-scale ice sheet model GSM and tested for simulation of the last glacial cycle.

I think this paper is fairly well written, but description of the model is lacked or left ambiguous. The point which were most unclear to me on first reading is the relation of and structure of SG, CG, ISSM and GSM. A CG cell is in a sense equivalent with a gridcell of GSM in the manuscript, not a model. CG model (e.g., p3049, L20) corresponds to GSM (but not explicit explanation). ISSM is just a reference model to be compared with the hypsometric flow-line model (SG model).

We clarify in the introduction that the GSM is our CG model: "the Glacial Systems Model (GSM, formerly the MUNGSM), our coarse grid model,..."

The abstract now states "We develop a new flowline SG model for embedding in coarse resolution models." In the introduction of section 2.3 we now state "In this section, we describe how the SG model is embedded in the GSM and the conditions applied to activate or deactivate the SG model in each CG cell."

Surface mass balance computation is performed with the same equation over all the three (SG, CG/GSM, ISSM) models. Such a rough picture may not easily be obtained. It might be better to extract the surface mass balance section 2.1.3 as a common aspect.

And the main text now states that this method is used in the three models at the end of section 2.1.3. "The GSM and ISSM compute the surface mass balance using the same PDD method."

Design of coupling between SG and GSM is also difficult to understand on first reading. Also as far as I understand, when perform coupling, the whole domain is computed by coarse grid (1 × 0.5 degree)

GSM. Some coarse gridcells (cell? synoptic grid? please unify the terms) are activated as SG mode when some condition is satisfied. Each gridcell SG activated has own (prescribed) hypsometric bins and other parameters. Thickness evolution of corresponding SG model is computed for each activated coarse grid cell. There are two way interaction between the activated coarse grid cell and corresponding SG model, where SG model information modifies corresponding coarse grid information. These rough structure is extracted by reading through section 2.4 in this manuscript. Rather, a flow chart or brief summary of the design may help.

A diagram (figure 2) has now been added depicting the relationship/coupling between CG and SG. "Synoptic grid" is changed to "CG" in the revised manuscript.

Detail methods are also bit hard to understand on first reading. Schematic figures to describe, for example, the redistribution of CG flux to SG levels and its opposite may also help.
as above, with the new diagram.

Next thing I am curious is that an extension to the alternative parameterization in Section 3.2. At an extreme end, we can compute the same computation as ISSM does for the same domain but with SIA model (e.g., GSM core) with the same flow parameters (in this case, rate factor at 0 degree). It corresponds to include all the topographic characteristics to the SG model. If it is not deviate from ISSM results, then an adaptive model with light SIA model, not heavy higher-order models may be practical for long-term simulations. It is beyond the scope of this paper, I do not require to include, but still happy to see.

This comparison would be worth investigating, but as it is beyond the scope of this paper, we now include this idea in the conclusion as ideas for future work: "Other alternatives to the hypsometric parameterization, such as running a high resolution SIA model in the region of rough topography, could be considered."

2 specific comments

Abstract, first sentence I would not write like this in the abstract. Although I agree that typical grid resolution at the moment is around 10 to 50km for long-term computation, this is not always a necessary condition. Rather, I would state simply that this resolution is a current typical configuration (instead of 'need to be run...').

"need to be run" was modified to "are typically run".

p3038, L26. better to delete 'coarse' (I feel it a bit subjective) as the same reason above. I would just state the fact simply, at this stage. The following sentences naturally drive us this resolution as 'coarse' one.

"coarse" has been removed here. But we have added it in quotations in the abstract to help define what we mean by coarse.

p3039, L6 'the mean surface elevation' of a coarse grid?

"the mean surface elevation" has been changed to "the mean surface elevation of a coarse grid cell".

p3039, L8, citing Abe-Ouchi et al.: The first part is somewhat misleading and confusing. Van den Berg et al explicitly discuss the sensitivity of ice-sheet evolution to the grid resolution, while Abe-Ouchi et

al. (I am the second author) do not explicitly discuss the errors due to a lower grid resolution, although one can lead such point from the paper. Dr. Abe-Ouchi and I both agree that the lower grid resolution in that paper leads to such errors as the author mentioned, but it seems to be an overstatement only by citing this paper. Instead I suggest to include, in addition, the paper Abe-Ouchi and Blatter (1993), *Ann. Glaciol.* 18, 203–207. which is relevant for this context.

This reference was added to the revised manuscript.

p3940 L10 ‘the size of these bins’ the total area of these bins?

"the size of these bins" was replaced by "the thickness of these bins".

p3940 L11. What the CG level means?

To avoid confusion the word level is not used anymore to refer to the hypsometric levels (bins is used instead in that context). SG and CG level and defined at their first occurrence in a footnote: " SG level represents the hypsometric curve while CG level correspond to a GSM cell." Figure 3, 5 and 8 had to be modified to change "level" with "bin" in the legend.

p3041 L17 ‘cubic dependence of ice flow on surface slope’ This statement requires the explanation of the shallow ice approximation under Glen’s flow law with exponent 3 beforehand, or at least refer equation 3 in advance and postpone the meaning of the cubic dependence etc.

This statement is now referred to eq.3.

p3041 L23 ‘from 1 to N’ better to write 10, or N(=10) instead of N, or define value of the N beforehand.

"divided into 10 bins (or bins)" has been replaced by "divided into N bins".

Equation 1. Please define which corresponds the lower level, 1 or N (I expect it is N).

This sentence has been changed using: "from 1 (highest) to N (lowest)."

p3041 L16 and after. This block is somewhat unclear to me and I am still puzzled what the authors do with the following equations. How to compute slope_k, the denominator of Eq. (1)? I read three or more times and finally I suppose that when ice starts to build up, there is no ice and the surface slope is the same as basal slope, which means slope_k is computed by GEBCO 1km DEM averaged over the same bin, and prescribed through the simulation. Is it correct? I suggest to reformulate this part to separate the definition of variables and their explanation. For example, The sentence ‘The effective length, L, ...’ may be ‘The effective length, L is computed for each level as: Eq (1). Using the effective length L, slope_t is updated as Eq.(2). As no information is’

This paragraph has been updated to take these suggestions into account.

p3042 L5. ‘To compute the slope at the lowest level...’ Is this same meaning with ‘ice cliffs boundary conditions’ (p3046, L10)?

This clarification has been added.

Equation (3) \bar{u} is computed at each SG levels? If so, better to write \bar{u}_k , H_k , hd_k etc, or mention to omit before the equation. And what is the relation of $\partial h d$ and the slope_k in ∂x Eq. (2)? The same quantity?

subscript k and superscript t have been added.

Equation (6) the same as Equation (3).

Eq.3 (ice velocity) has been removed as it is already defined in the description of the effective diffusivity term of Equation 6 (now Equation 3).

Equation (8) Please define Δx_k and Δy_k . I suppose Δx_k proportional L_k and Δy_k is the width defined in p3042.

Δx_k and Δy_k have been defined.

p3048 L9. I do not understand the method here. The condition is ‘Lowest hypsometric level surface elevation’ reaches the bedrock elevation of the highest level. To obtain surface of lowest hypsometric level, we need computation of thickness by SG model equations, which means the SG model is turned on. Is this surface elevation computed using CG level thickness and SG level bedrock? p3049 not p3048

This method is used to deactivate the SG model so the SG information at that stage is available. The above described added clarification of the usage of turned on/off and (de)activated should address this.

Section 2.4 about coupling. The coordinates of GSM (degree) and SG (Cartesian) are different. I am curious about the way how to convert the information from one to the other and/or the effective length computation.

The effective length is used only at the SG level and is computed using the high resolution data in km. Only ice volumes are exchanged between the CG and the SG cells. A clarification of how the Cartesian coordinates are converted to degrees is done in section 2.1.1 Hypsometric curves. " To select a region fitting the coarse resolution grid cell of the GSM (degrees), the GEBCO Cartesian coordinates are converted in degrees assuming the earth as a perfect sphere of radius 6370 km."

p3049 L26. Does it means that CG ice volume is replaced by sum of the volume of SG levels below the lowest unfilled level? On L20 above it is said that CG ice is added to the SG levels. I am afraid that this loop makes the SG ice volume infinite by this procedure.

CG ice is added to the SG bins only when the SG model switches from deactivated to activated. This has been clarified in the revised manuscript. "... when the SG model switches from deactivated to activated."

p3050 L15, adjacent CG flux into SG model. Is this procedure done after the computation of equation (6)?

We have now clarified that eq.6 is not used at the lowest bin of the sub-grid level and that instead, the CG fluxes are used to remove ice at the lowest bins. "When coupled to the GSM, the SG model does not compute flux out of the lowest bin through Eq.3."

p3051 comparison. I am curious how much is the difference in the computation time between SG and ISSM, just for information.

"The SG model computation time for 3000 years simulation, using 10 hypsometric bins, is about 0.02 seconds. At a resolution of 1 km and using 10 cpus, ISSM run time is about 2 to 5 hours (depending of the topographic region used). The sub-grid model adds 3 to 6 hours (depending of the parameter vector used) to the glacial cycle run-time over North America." This information has been added at the beginning of section 3.

Table 1. Caption, ‘At least half of the area’: ‘half of the area’ of what? coarse grid?

That sentence has been replaced by: "At least half of the CG basal elevation is above sea level".

Same, ‘HCG = Volume of lowest SG levels’: Confusing. Thickness of lowest SG levels? or Volume divided by the areas?

That sentence has been replaced by: " While SG is activated, H_{CG} is set to the $\frac{\text{totalicevolume}}{\text{totalarea}}$ of the filled SG bins at each CG timestep (the total SG ice volume is used during the deactivation timestep)".

Same, ‘HSG ’: difficult to understand what it means.

That sentence has been replaced by: "When SG switches to activated, the CG ice volume is redistributed over the SG bins using the mean between two methods: equal redistribution over all bins and redistribution of ice over the lowest bins"

3 technical corrections

Section 2.2. This section should be move to the end of section 2, or before 3.1.

This change was made to the revised manuscript.

Section 2.4 and after. The terms (De)activation and turn-on(off) are sometimes mixed up. In Fig.8 caption ‘turn on/off’ are used in terms of coupling/decoupling, while in section 2.4.1 are used in terms of activation/deactivation. I would keep them consistent.

In the revised manuscript, Turned on/off is kept for coupling/decoupling.

Section 3. ‘Sub-grid model performance’, or ‘Sub-grid surface mass balance and flux model performance’ is proper.

Section 3 title was modified to "Sub-grid model performance and tests".

Table 1. Rough topography Δhb ... Better to separate by some ways, e.g., Rough topography ($\Delta hb > 500m$).

This change was made to the revised manuscript.

(total volume when SG is turned off) Not necessary, because SG is not activated

The difference between turn off and deactivated was made clearer in a previous comment. "total volume when SG is turned off" was modified to "the total SG ice volume is used during the deactivation timestep".

Supplementary Figure S1. Define NHYPS. The lines of ISSM and NHYPS=5 are hardly distinguished. The five point line of NHYPS=5 may easily be regarded as ISSM line.

The line style was changed and "NHYPS=5" was replaced with "5 bins" to keep a consistent legend with the other plots.