

Interactive comment on “Simulating the growth of supra-glacial lakes at the western margin of the Greenland ice sheet” by A. A. Leeson et al.

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Dear Reviewer,

We thank you for your constructive comments on our manuscript and are pleased that you find the study presented within novel and interesting. We have attempted to provide further clarification where requested and we propose to revise the manuscript in order to address your comments by making the changes detailed below. We hope that you will approve of the measures we have taken to improve our submission. Reviewer comments are repeated in *italics* and our response follows in **bold**.

Kind Regards,

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Amber Leeson

Like the other reviewer I am concerned about the time-step dependence of the model results. It does not become clear from the model description where this dependence derives from, and why the sensitivity is so large. An effort should be made to explain this better. Also the choice for the final time step of 60 seconds as a trade-off between accuracy and computational expense should be better motivated, given the strong dependence of results on time step, and the fact that this works in a single direction.

(Repeated from response to reviewer 1) Model outputs for lake onset date, filling rate and location are not found to be time-step sensitive although we acknowledge that simulated lake area does show significant time-step sensitivity.

We have investigated this further since submission of the manuscript and are testing a fourth order Runge Kutta approximation with which to integrate the flow. We have also modified the method by which water is accumulated into lakes. Initial tests suggest that these measures act to reduce the time step sensitivity, although they do not completely remove it. We find that in some locations, because of the length scales involved, free surface gradients are such that even using the RK4 approximation, a proportion of cells experience water displacement greater than their water contents. The only way to reduce this error is to adopt a smaller timestep.

We chose to use the RK4 approximation over a full solution in order to retain the model's simplicity, which we believe to be a desirable attribute. In addition the water is now accumulated into lakes iteratively at each timestep; the water in a depression is accumulated until it is all incorporated into a lake,

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rather than on a cell-wise basis. As this is an early study, and one of the first attempts to model supra-glacial lake evolution, we feel that these actions adequately address the highlighted concern over timestep dependence, within the scope of this paper.

The revised manuscript will discuss model results obtained using an RK4 method of integration and a modified accumulation scheme. The method section in the revised manuscript will include details on this new approach and its implementation and we will discuss the limitations that the use of an RK4 over a full solution imposes on our results in our consideration of the study with particular reference to maximum lake covered area.

Another point of concern is that the model is driven by daily runoff rates from a regional climate model (RCM) at 25 km resolution. This lack of temporal and spatial resolution introduces two uncertainties. The first one is that in reality, summer runoff strongly peaks around noon, following the daily cycle in insolation. From the model description I derive that a constant runoff flux is prescribed over the day (page 1314, line 23).

This, in combination with the time-step dependence (see point above), could lead to significantly different results compared to the situation in which a daily cycle in runoff is be prescribed. Please comment.

Since our submission of the manuscript, we have obtained hourly MAR output for the melt seasons in 2003, 2005 and 2006 which we believe adequately captures the daily cycle you describe. We performed simulations of lake evolution using our model with an hourly time step forced with hourly MAR simulated runoff and also a constant runoff calculated by summing all the runoff generated in 24 hours and dividing it by 24. We see no difference at

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all between the output of each simulation (less than 0.001%) both in terms of spatial and temporal lake evolution. This suggests that in our experiments, the accumulation and routing of meltwater over the surface dampens out the diurnal signal of runoff production, with respect to the growth of supra-glacial lakes and that consequently they exhibit no diurnal variability in their evolution. This is of course, limited to our experiment and may not be the case for lakes which drain.

The revised manuscript will present this point in the discussion of model sensitivity to forcing data.

Secondly, the RCM only has about 26 data points in the selected domain. Because of the steep SMB gradients in this part of the ice sheet in summer (Van de Wal and others, 2005), this introduces large spatial discontinuities in prescribed runoff (Figure 1). Was an effort made to smooth these spatial runoff gradients when the RCM data were interpolated to the high-resolution grid?

This study is intended as an initial investigation into the effect of known parameters (i.e. runoff and elevation) on supra-glacial lake evolution. We generally have confidence in the ability of MAR to simulate surface mass balance with a reasonable degree of accuracy (Fettweis, Gallee et al. 2005) when run at 25 km resolution. However, we agree with your comments about the ability of MAR to resolve the steep SMB gradient close to the ice sheet margin. Franco et al (2012) perform simulations using MAR at 25 km and find, by comparison with observations taken along the K-transect (located within our study area), that a 25 km resolution simulation is not fine enough to resolve SMB very close to the margin. Because of this, in our study, we restrict our conclusions to be applicable only to that part of the ice sheet within our study area which lies above 1000 m; the closest point in this region to the ice sheet margin is 12 km away. We discuss this briefly in the manuscript (P1321, L10-12). We will

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extend this exclusion zone to 1100 m which renders the ice sheet margin 25 km (i.e. one grid cell) away. We feel that introducing processes at this stage, such as interpolating the MAR output with respect to e.g. surface topography, would introduce further uncertainty into our simulations and so is beyond the scope of this paper. We do, however, see the potential of such an exercise in improving our model and we will investigate this further with a view to inclusion in the next generation of the model. In the revised manuscript we will restrict our comments on model performance to that area which lies above 1100m a.s.l.

What is the effect of ignoring all modeled lakes smaller than nine grid boxes (page 1315, line 4)? Why was this threshold chosen and how does it impact results?

We mask out lakes smaller than nine grid cells (300 by 300 m) to enable comparison with MODIS imagery which has a resolution of 250 m. This exercise reduces the simulated daily lake covered area by 3-14% (and reduces the maximum cumulative lake covered area by 5%). This is interesting as Sundal et al (2009) estimate that they underestimate daily lake area by 12% due to the presence of lakes which are too small to be resolved by the MODIS instrument.

The revised manuscript will evaluate the model performance for lakes larger than 0.125 Km² only (See author response to first reviewer) which are resolved by the MODIS instrument, and so there will be no need to apply a mask.

I suggest to combine sections 5 ('Discussion') and 6 ('Conclusions') into a single section (Discussion and Conclusions) and remove all overlap to arrive at a more concise paper.

The revised manuscript will be edited to be more concise.

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References

- Fettweis, X., H. Gallee, et al. (2005). "Greenland surface mass balance simulated by a regional climate model and comparison with satellite-derived data in 1990-1991." *Climate Dynamics* 24(6): 623-640.
- Franco, B., X. Fettweis, et al. (2012). "Impact of spatial resolution on the modelling of the Greenland ice sheet surface mass balance between 1990–2010, using the regional climate model MAR." *The Cryosphere Discuss.* 6(1): 635-672.
- Sundal, A. V., A. Shepherd, et al. (2009). "Evolution of supra-glacial lakes across the Greenland Ice Sheet." *Remote Sensing of Environment* 113(10): 2164-2171.

Interactive comment on The Cryosphere Discuss., 6, 1307, 2012.

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