Reviewer 1:

General This paper presents estimates of the surface mass balance (SMB) of the Laurentide ice sheet (LIS) through its last deglaciation (21-12 ka ago). A benchmark is provided by the glacial isostatic adjustment (GIA) from ICE-6G, which puts thresholds on mass loss rates. An important discrepancy is found, which cannot be explained by the non-consideration of ice dynamics because the SMB model overestimates mass loss. Various potential reasons and sensitivities are discussed. The paper is interesting, well written and the figures are clear. The analysis is generally meaningful, but important information is lacking to get a clear picture of potential sources of error, see below.

Thank you for the summary of the work. We found your comments very helpful and have revised accordingly. Specially, we added a ground heat flux term into our energy balance, and this indeed made a significant difference on the resulting SMB. We also switched to a monthly melt analysis as suggested (the zero net surface energy balance when no melting occurs meant that this did not affect the SMB, but using annually-averaged values in the breaking of the SEB to different terms was indeed an error as you pointed out). We would like to express our gratitude for pointing out these two errors, and feel these comments and correcting these errors made our paper much stronger.

Major Comments:

l. 51: "In another study, Ullman et al. (2015) found that the SMB of the LIS for key time slices, when forced by an AOGCM (Schmidt et al., 2014), was positive throughout much of the deglaciation, therefore suggesting that ice flow and dynamic discharge was mostly the cause of mass loss until about 9 ka." This is inaccurate. When solid ice discharge is nonzero, SMB must be positive for an ice sheet in balance. When SMB decreases, but still remains positive, the ice sheet will lose mass. This is for instance the case for the contemporary Greenland ice sheet. Exactly as you state one sentence later "Moreover, this study implied that the sign of SMB is not a good predictor of glacial growth or decay."

We agree and revise the text to clarify, as follows:

> In another study, Ullman et al. (2015) found that the SMB of the LIS for key time slices (24, 21, 19, 16.5, 15.5, 14, 13, 11.5, and 9 ka), when forced by a GCM (Schmidt et al., 2014), was positive (that is, contributing the ice sheet growth rather than withdrawal) throughout much of the deglaciation. Ice flow could lead to a reducing ice mass even in the presence of a positive SMB, and Ullman et al. (2015) concluded that ice flow and dynamic discharge was indeed the main cause of mass loss until about 9 ka. This study therefore implied that the sign of the SMB is not a good predictor of ice sheet growth or decay.

l. 68: "...independent geophysical constraints as represented by ICE-6G". It is great that these constraints are independent, but how accurate and suitable for this goal are they? One weakness is that GIA depends on the ice volume history used, and represents mass changes from both surface and ice dynamical processes.

Thank you for mentioning this. While ICE-6G may not be the best reconstruction and geophysical constraints may not be perfect, but AOGCMs have their own issues, and confronting the two should add value. In addition, ICE-6G is used by iTraCE and therefore, to be self-consistent, we chose to use it for this analysis. We have added the additional sentence to make this more clear:

> We acknowledge that geophysical ice reconstructions have their issues, including that they depend on ice volume history used and on uncertain assumptions regarding the isostatic processes involved. Yet, simulations of the SMB by climate models are, of course, far from perfect as well, and the comparison of the two therefore represents an interesting test of both approaches.

and

> Therefore, and for consistency with the iTraCE boundary conditions, we use ICE-6G (rather than other ice reconstructions, e.g., Tarasov et al., 2012) as an upper bound on the magnitude and a point of comparison for the SMB mass loss rate.

l. 120, Equation (1): (a) The equation contains the geothermal heat flux, but this flux is usually neglected in the surface energy balance as it is so small. Moreover, at the surface of a thick ice sheet the bedrock is even further away, further reducing this flux. You mention this later, but the text and even figure devoted to GF in l. 126-130 is too elaborate, given its insignificance (and uncertainty).

Thank you for this comment. We removed the geothermal flux, included instead the ground flux from iTrace. We now use the geothermal flux as a bottom boundary condition in our diffusion equation, which examines the sensitivity of the ground flux to refreezing latent heat release (Sections 2.4, 3.4).

l. 120, Equation (1): (b) What is however missing from the equation is the subsurface (or ground) heat flux, usually denoted by G. It is the conductive heat flux along temperature gradients just below the surface. This flux cannot be neglected and plays an important role in the modulation of surface melt, see e.g. a recent paper by Van den Broeke on the various energy contributions to melt in Greenland and Antarctica (doi: 10.1371/journal.pclm.0000203). As the only non-latent heat transport process, the subsurface heat flux also is important in the subsurface refreezing process. Why was this flux not included?

Thank you for mentioning this. We have now included the ground heat flux in our surface energy balance calculation, as well as provided a comparison of the CESM-computed to a diffusion equation model of the ground heat flux. We find that the ground heat flux is indeed a critical part of the analysis, and including it led to significant changes to our results. We are grateful for this comment.

l.121-125: Radiative fluxes are the most important drivers of surface melt. By using the net surface radiative fluxes from CLM, you commit to CAM's radiation schemes and CLM's (snow/ice) albedo scheme. Please describe these schemes here. What albedo values are used for ice and snow, are impurities considered, impact of clouds and snow wetness/grain size etc.? The modern CLM has an elaborate snow albedo scheme.

We have added a discussion of the radiation scheme as follows,

> The atmospheric model used in iTraCE, the Community Atmospheric Model (CAM5, Neale et al., 2012) uses the Rapid Radiative Transfer Method parameterization (RRTMG, Iacono et al., 2008; Mlawer et al., 1997), which uses a correlated k distribution method for calculating radiative fluxes and heating rates. RRTMG is a widely used radiative transfer code, and shows improvements in its agreement with line-by-line radiative calculations compared to the older CAM radiation package (CAMRT, Neale et al., 2012).

And the snow albedo values:

> The Snow, Ice, and Aerosol Radiative Model (SNICAR) is used to simulate snow albedo and the absorption of solar energy within individual snow layers. The snow albedo is influenced by the solar zenith angle, IR band, the albedo of the surface beneath the snow, concentrations of aerosols deposited from the atmosphere (e.g., black carbon, mineral dust, and organic carbon), and the effective grain size of ice (r_e), which is modeled through a snow aging process (Oleson et al., 2013; Flanner and Zender, 2005; Flanner et al., 2007). Glacier albedos are set to 0.80 and 0.55 in the visible and near-infrared, respectively (Lipscomb and Sacks, 2012).

Section 2.3: Other important information is missing in this section. What was the time step used for the melt calculation? Many processes associated with melt over polar ice caps are highly nonlinear, so using e.g. daily averages of energy fluxes to calculate melt will lead to large uncertainties, especially in regions where melt is non-continuous.

The iTraCE dataset has monthly outputs, and following both reviewer's suggestions, we now calculate melt on a monthly basis. We then take annual averages of snow accumulation and melt to be used for the refreeze parameterization. when presenting the surface energy budget and surface mass budget (SEB,SMB) analysis, we average over months in which melting occurs only to show the resulting annual averaged fluxes. Please see our revised Eqs. (1), (5).

l. 145, Equation 2: Upon refreezing, large amounts of latent heat are released in the snow/firn. This will reduce the subsequent refreezing capacity. Is this accounted for?

Thank you for this important comment. To our knowledge, refreezing is not included in iTraCE and the refreezing latent heat release is therefore not accounted for in the CESM computed ground heat flux. However, following this comment, we added a diffusion equation analysis and perform a sensitivity test by including a parameterized latent heat of refreezing term into our diffusion model of the ground heat flux in our results section. We find that the latent heat release due to refreeze does not substantially affect the results of the diffusion model. Please see Sections 2.4, 3.4 and Figure 5.

l. 150, Equation 3: this way of defining SMB includes refreezing or 'internal accumulation' and is formally referred to as 'climatic mass balance' (see glossary of mass balance here: `https://wgms.ch/downloads/Cogley_etal_2011.pdf`). Fine to define SMB this way (many do it) but for clarity it's good to show that you're deviating from the formal SMB definition.

Thank you for mentioning this potential point of confusion. We have added the following:

> Note that by including refreezing or "internal accumulation", we are formally modeling the "climatic mass balance" (Cogley et al., 2011) and are therefore choosing to deviate from the formal definition of SMB. Although, as shown later, the inclusion of this specific refreeze parameterization has a very small effect on overall ice sheet mass balance.

Same line: I find the notation of the mass fluxes confusing. If 'P' stands for precipitation, I interpret P_s as solid precipitation (snowfall) and P_l as liquid precipitation (rainfall). The SMB equation then becomes, with $P_s - SU$ being snow accumulation: $SMB = P_s + P_l - SU - RU$ where SU is sublimation and RU is runoff, which can be written as $RU = (ME + P_l)(1 - f)$ where f is the refrozen fraction. Substitution gives $SMB = P_s - SU + fP_l - (1 - f)ME$. Cautionary note: you use 'SMB' both for ice sheet integrated mass change (kg/yr, Fig. 1) as for specific mass loss (m/yr, Fig. 2). Avoid the term 'net melt', instead use runoff or the likes.

Thanks for pointing this out. We changed the presentation to first show the surface energy budget and then use that for the surface mass balance. We hope the revised presentation is clearer. whenever using "net melt" we add (runoff) to clarify, following this suggestion.

Figure 2: Are these fluxes averaged during melt?

Yes, the fluxes contributing to melt are now averaged during melt months only.

Figure 3: Not sure if I understand the signs of all these fluxes. Should netLW not be negative and SHF predominantly positive? In meteorology, SHF is defined positive

when warming the surface.

We revise all fluxes to be positive toward the surface. That is, atmospheric fluxes are positive downward, and the ground flux is positive upwards, again toward the surface.

> All fluxes are defined as positive downwards toward the ice surface, except the ground heat flux GHF which is defined as positive upwards (that is, again positive towards the ice surface).

Minor and textual comments:

l. 3: "...the isotope-enabled transient climate model experiment (iTraCE)." Is the fact that the model is isotope enabled relevant for this work? If so, please state that here and explain why. Also applies to l. 66.

The isotope part is not relevant for this work, and we now mention this explicitly.

> While this version of the model also simulates water isotopes, this study uses only the physical climate variables from the simulation.

Figure A1: Please include ice thickness over Greenland also.

We now show the ice thickness over Greenland in Figure fig:ice-6g, as suggested.

l. 115: "Snow accumulation is denoted by PS". Do you mean snowfall? Snow accumulation is usually defined as snowfall minus sublimation.

Thank you, we made sure to use accumulation rate or snowfall in the appropriate contexts.

l. 116: "liquid rain accumulation". This is unclear, rain is always liquid and rain does not tend to accumulate. Did you perhaps mean rainfall?

Yes, thank you for mentioning the lack of clarity with this. We changed to be "rainfall".

Figure 1: In y-axis labels adding "w.e." is not relevant, because you provide integrated mass fluxes in kg/yr. On the other hand, in Fig. 2 (units m/yr) adding 'w.e.' is relevant, but not done...

Thank you for pointing this out. Corrected.

Figure 1: How deep does the ICE-6G curve dip below the x-axis in the BA? Ah, I see this is presented in Fig. A2.

Yes, it drops to approximately -12×10^{15} kg/yr and this value is now noted in the caption.

Reference list: the reference list was messy and hard to read, as it contained a mix of names with/without first names and did not start with last names.

Thank you for pointing this out. We have now fixed it.

l. 192: "Given the abrupt warming during the BA period, it is possible that ice flow and calving account for the difference between SMB and the estimated trajectory of the ice mass rate of change based on ICE-6G." Would be good to mention some processes that explain why strong warming could lead to enhanced ice flow and calving.

Thank you for mentioning this. We have added the following after the text that was at Ln. 192 in the previous version:

> It is possible that this abrupt warming during the BA period triggered enhanced ice flow and calving and a regime change from mass loss due to SMB to ice flow-dominant mass loss. Overall, the negative sign of the SMB is consistent with the decay of the LIS (note that this is not the case for the present-day Greenland Ice Sheet). Enhanced surface melting can lead to stronger injection of water into the base of the ice sheet via moulins (Colgan and Steffen, 2009; Banwell et al., 2016). This can accelerate the ice flow and calving, consistent with the fact that our calculation indicates stronger effect of ice flow and calving later in the deglaciation, where the SMB indicates more melting. While increased surface melting associated with negative SMB during a deglaciation can accelerate ice flow and enhance calving, the ice dynamics are also influenced by internal properties and subglacial interactions (Golledge et al., 2009; Williams et al., 2020; Schoof, 2010), limiting the ability of SMB to project overall mass loss.

Figure 2 caption: centured → centered

Corrected, thank you.

l. 310: "which would be out of the scope of this present study". Still it would be interesting to provide a first order-of-magnitude comparison with RCM produced LIUS SMB.

We removed this section of the manuscript.

l. 332: " XX references"

Thank you for catching that. Fixed!

l.385: "by an error in one of these two estimates". Or in both.

Added, thank you!