Response to Anonymous Referee #3: "Interactive comment on *An ice sheet model validation framework for the Greenland ice sheet*"

We thank the reviewer for the detailed comments and thoughtful discussion. In general, it appears that the reviewer may have misunderstood the wider point of our paper, which is not focused on officially validating a particular numerical ice sheet model but rather on presenting and demonstrating a framework and metrics for use in the validation of *any* ice sheet model. Here, a particular numerical ice sheet model is used for that demonstration, but we are in no way claiming to have "validated" that ice sheet model in this paper. Since there is clearly a misunderstanding on this point, we have worked to revise the relevant sections of the paper so that our intent is clear. Additional point-by-point discussion along these same lines is given below.

Response to General Comments

My main concern is that the "most sophisticated" dynamic model reproduces the trends in altimetry and gravity for the wrong reasons. Correctly initializing ice flow models remains a challenge today and an active area of research (Seroussi et al., 2011; Aschwanden et al., 2013; 2016) due to the lack of reliable observations and the long response time of ice sheets. In order to bypass this problem, the authors impose an additional steady-state surface mass balance (SMB) on top of the climate derived SMB, therefore forcing the model to remain close to its initial conditions. Without this unphysical forcing, the model would likely diverge quickly from this initial state.

We appreciate and agree with these criticisms and acknowledge them in our paper. In our final few concluding sentences, we note that an important and necessary improvement is model initialization techniques that would allow for the use of non-anomaly-based forcing and / or that would allow for initialization with realistic transients (note that some of this work has been (and continues to be) done by authors on this paper, e.g., Perego et al. (2014)). In our revisions, we have expanded on this discussion to further emphasize its importance.

We also note that the application of flux corrections and anomaly forcing is not unique to this study and, at the beginning of section 3, we've noted several other recent publications that use these same techniques in studies of Greenland ice sheet dynamics. Most importantly, we emphasize that the main point of this paper is not to present and validate a perfect ice sheet model simulation (or to claim that we are validating a particular ice sheet model), but rather to demonstrate that the validation tool and metrics proposed here are useful for discerning between simulations. We have added a final paragraph to the introduction to explain this and make sure our intent is clear up front.

Furthermore, the physical model has to be not only forced with an unphysical SMB, but also constrained with imposed velocities over the most dynamic areas, in order to get close enough to the observed changes in gravity. At this point, there is not much physics left in this model.

We acknowledge these same shortcomings in 3rd paragraph of the Conclusions. At the same time, we disagree with the suggestion that "there is not much physics [=dynamics?] left in this model." The response of an ice sheet model to an applied forcing will vary immensely depending on the physical fidelity of that model. For example, we certainly do not expect that a model based on the shallow-ice approximation would be able to simulate the inland propagation of acceleration and thinning from perturbations at its margin as accurately as a model based on a first-order approximation to the Stokes equations (due to the lack of horizontal stress gradients). This expectation applies regardless of if those perturbations are applied in the somewhat artificial way used in this paper, or if those perturbations are applied through much more realistic model physics (e.g., a physically-based calving law and an evolving ice front) that serve as an intermediary between the model and external climate forcing (e.g., ocean warming and ice tongue melting). In this sense, we agree that the model is lacking "physics" (i.e., important physical processes and parameterizations) that one might like to test (as are most models), but the dynamic response of the model to an applied forcing is still worth testing. Here, it is that realistic dynamic response (first to only SMB forcing and then to SMB and outlet glacier dynamics forcing) that leads to (1) differences between our ideal vs. numerical model simulations, and (2) differences between numerical model simulations using different forcing (and as we show, these differences can be detected and quantified using the CmCt and our proposed metrics).

So if I don't question the development of this framework or the benefits to have a tool that can easily compare observations and model results, I am wondering if any validation of numerical models can be done today given the many improvements still needed by these models to become more accurate. I would therefore recommend to reduce the emphasis of this framework as a validation tool and rewrite the manuscript accordingly.

As noted above (and pointed to in the paper), there are currently significant advances being made in initialization methods, which result in realistic model steady states that are in agreement with observations AND that are in approximate equilibrium with specified climate forcing fields. And while we agree that many other improvements are still needed before models are accurate enough to make full use of such a validation tool, we would argue that those model developments and the development of tools, methods, and metrics for validation should happen in parallel. Indeed one can imagine model deficiencies that are presently unknown and that cannot be identified or remedied without the tools to aid in model validation.

Because many of the same concerns noted above are also repeated below, we address them further on a point-by-point basis there.

Response to Specific Comments

In the abstract (l.6) as well as several other places in the manuscript, the author qualify the static representation and the SMB only applied to this static representation as "non-dynamic models", which is misleading, as these representations do not include any physical model. The text should better distinguish between physical models and other *representations.*

The use of the word “model” refers, in this case, to a conceptual model, and we think that the qualifier “non-dynamic” is clear. Nevertheless, we have edited the section of the abstract the reviewer notes. The relevant sentence has been changed to:

“Based on basin- and whole-ice-sheet scale metrics, we find that simulations using both idealized conceptual models and dynamic, numerical models provide an equally reasonable representation of the ice sheet surface (mean elevation differences of <1 m).”

We also note that in two sections of the text, we do already go into detail about what these idealized models are based on (the 2nd paragraph of the section 3 introduction (lines 165-170 of original submission) and the last paragraph of section 3.2 (lines 258-265 of original submission)).

p.1 l.17: “simulations of varying complexity”: there is no varying complexity found in the models presented here (same stress balance approximation, ...). What varies between these simulations is the degree of “forcing” of the models, the velocity being applied as a Dirichlet forcing for one of the simulations.

We specify “**simulations** of varying complexity” as opposed to “**models** of varying complexity” for the exact reason the reviewer points out. Further, some of our simulations are based on idealized or conceptual models (arguably a simulation conducted using a dynamic, numerical model is more complex than a simulation based on an idealized conceptual model). We believe that the current descriptions for how the simulations differ from one another (section 3.2) is adequate to guide the reader in understanding what we mean by “varying complexity”.

p.2 l.20-21: The “most sophisticated” models are actually forced by imposing the velocity to be equal to observations at the border of the domain. Showing that such a simulation exhibits mass trends similar to gravity observations does not prove any predictive capability of the model. First, the velocity is not produced by the model but forced in all the dynamic areas. Furthermore, the flux correction applied to the physical models introduces a large mass change that prevents to compare simulations to observations. What this result mainly shows is that observations are rather consistent and that a large part of the mass change signal can be explained by changes in SMB and acceleration.

Again, proving predictive capability of the model is not the goal of this effort, as we clearly state at multiple points of the paper. The goal, as stated, is to demonstrate that the framework can distinguish between simulations of differing realism with respect to observations. That a simulation forced by the most complete set of forcing data exhibits similar mass trends to the observations is precisely the point; we expect that such a simulation will “score” much better than (i) a simulation forced by an less complete set of data (e.g., our “SMB-only” simulation) and / or (ii) simulations that do not allow for any dynamic response of the ice sheet (our “persistence” and “RACMO2-SMB-only” simultions). Recall that our stated goal is to demonstrate that our validation tool and metrics can distinguish between simulations with different levels or realism with respect to the observations. In order to demonstrate that, we first need to create simulation output that we expect will have those characteristics.

p.2 l.23: What about velocity changes? I would imagine that comparing the dynamic signal would be an important part of such a tool, as the main objective of an ice sheet model is to reproduce the dynamic signal, not the SMB.

Here, we examine the dynamic signal through thickness and mass changes. In our opinion, there are not yet enough velocity data with wide enough coverage to make those data useful for large-scale model validation. Also, at present, many models (including the one discussed here) use the available velocity data in their initialization procedure. As more velocity data become available in the future, they could certainly be included. For now, we've chosen to focus on data that is a proxy for dynamic evolution via changes in ice sheet thickness (or mass).

p.2 l.33-37: I don't agree with this statement. The main problem is that ice flow models are still unable to reproduce the observed changes, and that improving their initial conditions is a very active area of research. Models therefore have to either run spin- up or apply flux correction (similar to what is done in this manuscript), to get closer to observations. Accurately comparing model results and observations is therefore beyond the scope of most studies since lots of models cannot even capture the correct trend (Bindschadler et al., 2012).

As we've noted above, we do discuss and acknowledge problems, and future improvements, related to model initialization. And we would argue that validation tools should be developed in parallel to models, so that both can be improved simultaneously (rather than sequentially).

p.7 l.208: The authors explain how they apply an SMB correction to get closer to a steady-state equilibrium of the ice sheet. It is not clear what this correction represents, how large it is, and how it evolves with time as the model evolves from its steady-state.

It is clear from Equation 1 (and the related discussion) that the flux correction is a correction to the RACMO2 SMB forcing. We have added the word "static" to its initial description to clarify that it is unchanging in time (this should also be clear from Equation 1). We have also added references to several other recent papers where similar methods have been applied to SMB forcing in studies of Greenland ice sheet dynamics (Price et al., 2011; Shannon et al., 2013; Nowiki et al., 2013; Edwards et al., 2014). Also, we have added discussion to this same section noting that this process assumes that in 1990 Greenland was in equilibrium with its mean SMB over the previous three decades. Thus, perturbations, and volume trends following from them, are relative to this assumption of steady-state in 1990.

Also, how can the dynamics of the model be compared to observations that show clear evolution trends, if the model is artificially forced to be close to a steady-state?

The model is forced to be in steady-state in 1990 based on the longer-term mean SMB. Thus, modeled volume evolution trends will be a result of forcing applied after 1990.

Anticipating that this will result in a reasonable comparison between model and observations follows from the assumption that the bulk of Greenland's volume / mass change over the past few decades is a result of forcing applied over that time period (as opposed to resulting from some longer term transient). In turn, this assumption follows from satellite-based reconstructions of Greenland's net mass balance, which suggest that it was in quasi-equilibrium during the 1980's and 1990's (van den Broeke et al., 2009; Fig. 2), at least relative to *after* the mid-1990's and through to the present day.

We appreciate that the reviewer does not favor the use of anomaly SMB forcing, and we do acknowledge this as a shortcoming in our paper. Nevertheless, Figures 4 and 11 do show that modeled mass trends following from our applied SMB forcing provide a reasonable approximation of the observations in the sense expected they would (volume changes resulting from SMB-only forcing underestimate the overall mass loss to a greater degree than simulations that also account for mass loss via outlet glacier flux changes).

p.7 l.220-225: This part is not very clear. Also it does not seem very natural to force the velocity. If the velocity at the flux gates is prescribed there is not much freedom anymore in the model. It would make more sense in my opinion to force the ice front position for example.

We agree it would be more desirable to force the ice front position. But doing so in a manner that was able to match the actual flux observations is something that is beyond possible right now for any model (as far as we know). As noted above (and as discussed in the paper), the goal here is not to do a perfect job on the model simulations, but to show that simulations that we expect to do relatively better or worse with respect to matching the observations can be shown to do so using our tool and the validation metrics we propose (we also note that this section has been edited as per comments from other reviewers).

p.8 l.249: What is the treatment of the calving front? What is the calving law used and how does the ice front evolve in the code? Why is the ice front allowed to retreat but not advance?

There is no calving law applied. The ice front position is assumed to stay fixed in time and space and any ice that reaches it is removed from the domain. Reasons for why the ice front is allowed to retreat but not advance (and arguments for why this is a reasonable simplification) are discussed on lines 246-256 (original version). Again, we note that (1) these same simplifying approximations have been made in numerous other modeling-based studies of Greenland ice sheet dynamics (see references listed above and below) and (2) the purpose of this study is not to provide a perfect model simulation or argue that we have validated a particular model. The purpose is to provide model outputs that are quasi-realistic with respect to observations to demonstrate the use of the validation tool and metrics. We have added some text to this section of the paper to make it clear that no explicit calving model is used.

p.13 l.431-433: This sentence is not clear as it seems that all models start from the same thickness and same datasets in general. As the flux correction is applied to ensure that *the model remains close to a steady-state, it is not surprising that the dynamic model and persistent representation remain close to each other.*

The point of these lines (and which we think is clear as written) is that the model initial condition is based on a DEM that was constructed using some of the same ICESat observations that we are comparing our model output against. In this sense, the model initial condition is already somewhat biased to "look" like the ICESat observations.

p.14 l.465: The physical ice sheet models have not yet reach a state where they can be reliable and compare with observations and capture the dynamic processes at play. Some important physical processes could even be missing. So it might be unfortunately a little premature to pretend to compare observations with models, even if this remains a long-term objective. For these reasons, the distinction of more accurate models with this tool seems difficult to achieve, and results presented here are largely influenced by the flux correction applied in the physical models.

This sounds like a value judgment and one that we disagree with. In the paper, we acknowledge shortcomings in model initialization methods, model physics, and simplifications made in the modeling conducted here. But we would argue that there is no reason to wait for a perfect model before assembling the tools to be used for validation models and making those tools as widely available and useful as possible. In our opinion, model development and the development and testing of validation tools, should be conducted in parallel.

p.14 l.466: "dynamic models that account for known changes in ice dynamics": this statement is a little biased in my opinion, as the model is forced with observed velocities to reproduce the dynamic signal, while the physics alone should be able to reproduce this effect.

Our statement says nothing about whether or not we include appropriate model physics (and nowhere do we claim to have accounted for all necessary model physics). Our claim here is that model dynamics, when forced appropriately, are capable of mimicking observed dynamic changes, and that when ignoring some forcings or using a model that does not respond dynamically, the ability of a model to reproduce observed dynamic changes is measurably degraded.

We further note that a model could have a perfect and complete representation of dynamics and physics (e.g., calving, subglacial hydrology), and without applying the correct forcing (e.g., SMB or submarine melt rates), that model would still fail to match observations. Here, we are showing that IF models could translate the appropriate climate forcing to the correct boundary perturbations (e.g., IF the correct SMB and submarine melt rates were applied by a climate model, and IF the coupling and model physics then translated those correctly to land ice model perturbations), then models can be expected to provide a realistic response, relative to observations.

p.14 l.501: As mentioned above, it would be more natural to constrain the evolution of ice front position with observations instead of constraining the velocity. Ice front retreat *triggers acceleration and would have a similar effect but would include the physical processes involved in this process.*

While ice velocity / flux time series with relatively complete spatial and temporal coverage do exist, we are not aware of any similarly detailed and complete datasets for ice front position. Further, if such a dataset did exist, it is not clear how it would / could be used to force a large-scale model. Would a time series of calving rates need to be specified for each outlet glacier, in order to force the appropriate ice front motion? Again, such an effort, if feasible, would be well beyond the stated goals of the modeling in this paper, which is to produce realistic outputs that we can use to demonstrate the use of our validation tools and metrics. As noted above, we have now made this goal very explicit at the beginning of the paper.

p.15 l.518: It seems difficult to asses if sophisticated physical models perform better as their evolution is largely influenced by the flux correction. When such a correction is not applied, many models are not even capable of reproducing a mass loss for the Greenland ice sheet (Bindschadler et al., 2013).

Our numerical ice sheet model maintains a steady-state when forced by the mean, 1960-1990 SMB with a flux correction applied. When this same flux correction is applied to the time series of RACMO2 surface mass balance and that anomaly time series is used to force our ice sheet model, the result is a change in ice sheet mass over the 2002-2012 time period that is ~60% of the observed change (red line in Figure 11 – recall that we don't expect the SMB forcing alone to be capable of recreating the full fraction of the observed change). This speaks to the effectiveness of forcing a dynamic ice sheet model with anomaly SMB forcing. Further, if we compare the *difference* between our model simulation forced only by SMB anomalies and the observations, we find that both the sign and the magnitude of the mass difference (+700 Gt in 2012) are very similar to the *difference* found for similarly targeted simulations in other studies that do *not* use anomaly SMB forcing methods (In Alexander et al. (2016), the difference between the simulated and observed cumulative mass anomaly in 2012 relative to 2003 – the same observational time period considered here – is also approximately +700 Gt). We have added a sentence pointing out this level of similarity in the second to last paragraph of section 6.

Technical Comments

Model names "SMB-only" and "RACMO-SMB-only" are rather confusing, this should be clarified.

In 3.2 of the paper, we clearly state what these two simulations consist of and how they differ from one another.

p.5 l.138: What is C_20?

C_20 is a harmonic term. We've updated the text so this is now clear.

p.7 l.213: How large is FC?

For 2003 to 2009, the time-averaged, spatially integrated SMB for Greenland, based on our RACMO2 forcing dataset, is approximately 330 Gt/yr (in agreement with values reported by van Angelen et al. (2013), Table 2). The spatially integrated value of our flux correction (FC), is 297 Gt/yr (~10% smaller).

p.8 l.249: How is the ice margin retreating in CISM? This is not something commonly used and should be detailed. What is the criterion for calving? for moving the ice front?

See response to related discussion above.

p.9 l.281: Remove one "thickness"

Corrected.

p.10 l.298: How are the values averaged? What happens when cells are split between several GRACE-like grids?

Ice thickness values on the 1 km ice sheet grid are treated as point masses. As such, they are assumed to "belong" to whichever 0.5 deg. grid cell they fall into. Given the disparity in size between a 1x1 km ice model grid cell and a 0.5x0.5 deg. GRACE grid cell, this is a reasonable simplification.

p.11 l.355: add parenthesis after Figure 11 p.13 l.403-404: Rephrase

Corrected.

p.14 l.440-441: No clear: why do they only partly account for surface elevation changes? The RACMO data should include that. What is missing?

The RACMO forcing data are in ice equivalent units. For a given mass change, the relative thickness change for solid ice will be approximately half that for the same mass of firn (because near-surface firn has a density approximately half that of solid ice). Thus, seasonal elevation changes in the model due to the application of (ice equivalent) SMB forcing will be a muted expression of the seasonal elevation changes seen by ICESat. We have added some clarifying text to this paragraph of the manuscript.

p.15 l.495: Missing parenthesis after (Joughin et al., 2004)

Corrected.

p.16 l.334: "in prep." → the paper appeared in GMDD

Corrected.

p.16 l.541: What about velocity observations? That would be a very valuable metric for dynamic changes.

Please see related discussion above.

p.18: It would be easier to have references listed alphabetically.

Corrected (an incorrect style file was used in the submitted version of the manuscript).

p.26 Fig.7: Rescale the yaxis

This was also suggested by another reviewer and has been corrected.

p.29 Fig.12: It might be easier to add letters on the subplots (instead of e.g. lower-right)

Corrected for Figures 9, 10, and 12.

p.14 l.455: that they see HALF of the GRACE signal

Corrected.

References

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