Geosci. Model Dev. Discuss., 6, C1045–C1062, 2013
www.geosci-model-dev-discuss.net/6/C1045/2013/

Geoscientific Model Development Discussions
Open Access

Interactive comment on "A technique for generating consistent ice sheet initial conditions for coupled ice-sheet/climate models" *by* J. G. Fyke et al.

J. G. Fyke et al.

fyke@lanl.gov

Received and published: 19 July 2013

Reply to reviewer 3 comments:

General comments and responses:

The reviewers have several general concerns which we believe can be summarized as follows:

1. The models used in the experiment were not adequately described 2. The resulting preindustrial state was not extensively validated against observations 3. No test was made of whether transiently spun-up initial conditions significantly impact future

Full Screen / Esc
Printer-friendly Version
Interactive Discussion
Discussion Paper

ice sheet evolution, relative to an equivalent equilibrium-based spin up set of initial conditions 4. The paper text is generally not clear

We briefly and generally address these three concerns before reviewing the 'Specific Comments'.

1. We understand the reviewer's concern about a lack of model description: this was also mentioned by another reviewer. To this end, we have included a new figure which is a schematic describing the model 'work-flow'. We have also greatly expanded, reworded, and clarified the model description and methodology sections.

2. We certainly appreciate the reviewer's concern that not enough observations were used to validate the model. However, we suggest that a comprehensive validation procedure as described by the reviewer is outside the scope of this manuscript, which was explicitly submitted as a GMD 'techniques and methods' paper. As a 'techniques and methods' submission, we intended the manuscript to focus primarily on describing the new technique for generating general initial ice sheet conditions in coupled models. A focus on a comprehensive observation-based validation of the initial CESM-generated ice sheet state, as the reviewer suggests, would necessarily expand to include a detailed analysis of the performance of the entire climate model (at least as it pertains to surface mass balance, surface temperature, and coupled ice-sheet/climate behavior, for both preindustrial and past climates). This is a very large task (which is currently underway, see, for example, Vizcaino et al. 2013 and Lipscomb et al. 2013) that is outside the scope of the present manuscript. Furthermore, any model-observation validation would change significantly as climate model development proceeds (such as an ongoing transition from version 4 to version 5 of the Community Atmosphere Model, which we are currently seeing results in quite large changes to SMB and temperature). To limit this 'techniques and methods' manuscript to description of one aspect of ongoing work in generating a robust coupled ice-sheet/climate model, and also to keep the manuscript pertinent to future CESM model versions (and other models, if they choose to use this technique) we specifically avoided a rigorous model-observation validation.

GMDD

6, C1045–C1062, 2013

Having said that, we did recognize the need to evaluate the performance of the technique in some way and felt that demonstration of the basic feasibility of the approach was best provided with a simple model-model comparison approach. This is because the 'delta' between equilibrium and transient spin-ups clearly highlights the impact of inclusion of a climate history on the preindustrial model state, without confounding information introduced by comparing model output (with intrinsic climate-model-based biases) to observations. Furthermore, we suggest this 'delta' will remain relatively constant despite evolution of the climate model architecture, making this diagnostic a a better independent evaluator of the spin-up technique. By focussing on a model-model comparison we simply intended to demonstrate that inclusion of transient climate history alters the preindustrial GIS state in a manner that is significant, and qualitatively an improvement, relative to the equilibrium spin-up approach. The primary conclusion is simply that the technique 'works', despite it's validity for use in a general coupled-model setting, which was a main goal of the manuscript.

3. We believe that the importance of including the impact of past climate history on the state of the preindustrial ice sheet, for future simulations, has been previously demonstrated by many authors.ÂăÂăIn fact, the main motivation for this study was that other studies have indicated that a proper preindustrial initial condition is an important aspect of modeling future trends to ice sheets.ÂăÂăThus primary purpose of this paper is to provide a model description of such a technique for generating ice sheet initial conditions, as opposed to assessing the performance of modeled predictions (this is the main reason we submitted to GMD). Thus, we feel that re-justifying the necessity of a transient spin-up is not necessary, within this paper.ÂăÂăFurthermore, at the present moment, due to a present lack of deep-future climate simulations, CESM is limited to simulations ending at the year 2100.ÂăÂăThe spin-up technique developed here is intended not so much to significantly impact these 'short-term' (from an ice-sheet perspective) simulations, but rather to be 'in-place' when longer simulations are carried out in the coming year(s).ÂăÂăWhen we have carried out (very expensive) fully coupled simulations we will certainly test the role of the initial spin-up in determining

GMDD
6, C1045–C1062, 2013

long-term future deglacial GIS evolution: in fact, this is likely to be the subject of a separate study.

4. We have significantly clarified the text to respond to the reviewer's specific comments, and more generally to make the manuscript clearer and more accessible.

Specific comments and responses:

REVIEWER: Page 2493: Is there a reference to the statement: "The internal temperature plays an important role in long-term ice dynamics. . ."

We suggest the fundamental role of internal temperature on ice rheology and basal sliding (and thus, long-term ice dynamics) is most succinctly described by Cuffey and Paterson.

REVIEWER: Page 2494: What is meant by the term 'reasonable'?

We agree, in retrospect this term is very misleading. We have removed it entirely from the Introduction.

REVIEWER: Page 2494: What is meant by 'instill ice sheet components'?

We meant 'install', this has been changed.

REVIEWER: Pages 2494-2495: The list does not contain shortcomings of the approaches

We did include shortcomings, for all bullet points after the text "However,". To be clearer, we have replaced this text with the text "Shortcoming: " to be more consistent with the preamble to the list.

REVIEWER: Page 2495: what is meant by consistent?

In the real world, the Antarctic and Greenland states are consistent (but not in equilibrium) with both the present climate, and past climate states. For example, the near surface characteristics of the ice sheet are consistent with present climate, while the

GMDD

6, C1045–C1062, 2013

state of the deep interior state, and the overall geometry, is consistent with the signal of past glacial climate conditions. This is the state that one hopes to replicate using a transient spin-up condition, and is what we mean by consistent. We have altered the wording of this sentence to more clearly reflect this goal.

REVIEWER: Page 2495: suggest to rewrite these lines to reflect content of Section 4.

These lines have been completely re-written.

REVIEWER: Section 2 would benefit from thorough editing.

This request was also echoed by other reviewers. We have thus spent some time re-writing this section significantly, to clarify the model description. As part of this revision, we included a diagram of the model work-flow, to graphically describe how the models are utilized. Yes, we forced the model with temperature fields in addition to SMB fields, this was neglected in much of the manuscript (our mistake) and is now included.

REVIEWER: What is 'equilibrium 30-year SMB climatology matrices'? Why 30 years?

This wording was removed and replaced with a clearer summary of the method. 'Equilibrium 30-year climatology matrices' was a poor way of describing the generation of SMB/T over 30 year time periods, at every (X,Y,Z) point in the Greenland model domain. We used 30 years, as this captures the range of interannual variability (so there is reduced risk that we are aliasing the SMB signal for any period due to a short sampling period).

REVIEWER: What does 'end-members' refer to?

This terminology has been much clarified. We still use 'end-member' to refer to the LGM, HMO, and preindustrial climate states that provide us with SMB/T fields, which we then interpolate between to generate a continous SMB/T record. But we ensure that this terminology is better introduced, prior to using it extensively.

REVIEWER: What does IG mean?

GMDD

6, C1045–C1062, 2013

This is just CESM terminology for standalone land-model simulations - we have removed this 'IG' reference, since as the reviewer indicates it is confusing and doesn't add useful information.

REVIEWER: Move Oleson 2010 reference

We have moved this reference up even farther than the reviewer suggested, to the very first mention of CLM (this reference is to the technical description of CLM).

REVIEWER: Clarify description of elevation classes

We have standardized our terminology for calculating elevation at multiple levels at a particular X,Y location. Now, we use the phrase "multiple elevation levels" uniformly.

REVIEWER: What is the difference between '30-year SMB climatologies' and 'simple SMB climatology'?

We have rephrased this to improve clarity. For reference, '30-year SMB climatologies' refers to a full 30 years of SMB data, whereas a 'simple mean SMB climatology' refers to one average annual SMB value that is the mean of 30 years of annual SMB fields.

REVIEWER: What is 'non-zero effects on SMB'?

We have rephrased this to mean 'non-zero residual impact on ice sheet evolution' due to interannual variability in SMB evolution. This was motivated by Pritchard et al, 2008, who found that interannual atmospheric variability had a non-negligible role to play in long-term ice sheet evolution.

REVIEWER: What does 'physically realistic SMB' mean? Sentence is awkward.

We have removed this phrase and rewritten the associated paragraph to better describe how SMB/T at any point on the GIS surface, at any time, can be determined through basic interpolation of SMB/T values.

REVIEWER: Page 2497: what does 'proper imprint' mean?

GMDD

6, C1045–C1062, 2013

We have removed this confusing phrase: it meant, that transient climate history was properly integrated into the ice sheet state

REVIEWER: What does 'basic lack' mean?

A CESM LIG simulation (using the same model version as was used to generate the LGM, MHO and preindustrial climates used here) has not been carried out. Running a fully coupled CESM LIG simulation is beyond the scope of this manuscript (though it is in the plans!).

REVIEWER: What do you mean by 'largely swept from the system?'

By this we mean that the initial state of the model resulting from MHO forcing during the LIG is largely forgotten during the course of the long simulation. In other words, the initial LIG state in the model does not appear to largely affect the final preindustrial state.

REVIEWER: Description of NGRIP averaging and thresholding is unclear

We have rewritten this paragraph, in response to requests from multiple reviewers. As we state in this paragraph, we used 600 years to avoid setting end-member climate weighting to periods that were not representative of the 'average' NGRIP value for these periods. NGRIP record fluctuates on centennial/millennial timescales. If we picked a single NGRIP value (representing a 20-year period), this could very easily fall on a peak or valley in the NGRIP record, that was not representative of the average NGRIP value for this time period. This is what we mean by 'aliasing'. After some experimenting, a 600 year averaging window was chosen as a time-frame that best sampled with average NGRIP values at end-member climate states, while not over-sampling the NGRIP record on the shoulders of these time-periods. Thus, this period was not chosen randomly.

REVIEWER: What impact does the length of the constant climate period have on the results?

GMDD

6, C1045–C1062, 2013

We did not run multiple simulations testing the impact of this length on the final results. This is primarily because we are confident that reasonable changes to this period (say, +/-100 years) would not affect the final preindustrial state in any fundamental way. As described above, we feel using this period is necessary to avoid aliasing of the NGRIP record, but beyond that it is not a critical 'model parameter' that deserves explicit attention for it's impact on final results.

REVIEWER: What is meant by looped climatology?

By looped 30-year climatology, we mean 30 years of SMB forcing are looped for 600 years (i.e. the loop is transited 20 times). This provides 600 years of continuous climate forcing.

REVIEWER: The symbology in equations 1-3 is confusing

We have now simplified the symbols used in these equations.

REVIEWER: Can you show that the consistent ice sheet model state is realistic as well?

As we state in the general response to the reviewer's comments, the primary purpose of this manuscript is not to perform a model-observation validation of the preindustrial ice sheet state (which would necessarily expand to a full analysis of the entire CESM climate model). Rather, we aim here to highlight the ability of the approach to generate an ice sheet that is consistent with the SIMULATED past and present climate states (whatever these states may be, though of course hopefully something looking reasonable). However, now we do include more discussion and plots of the raw SMB and temperature fields, and resulting time series of ice sheet changes, even though these are not meant to be evaluated directly, in this manuscript.

REVIEWER: What does 'physically reasonable' mean?

We have removed this phrase.

GMDD

6, C1045–C1062, 2013

REVIEWER: It would be useful to mark the locations on figures 5 or 6.

We have marked these locations on new Figure 1.

REVIEWER: The thresholding appears to affect the results, but it is not discussed how the results can be validated.

It is not entirely clear what the reviewer is discussing here. We do note that the thresholding does set potentially colds pre-LGM interstadials to LGM values. We now note that this could make the preindustrial interior temperatures from the transient spin-up slightly warmer.

The threshold values were set to the average NGRIP values at the absolute years that were used for the CO2 and orbital forcing for the CCSM paleoclimate simulations. This was done because, for example, the CCSM LGM simulation represented a time slice that was NOT the minimum in the NGRIP oxygen isotope time series. Thus in order to avoid 'extrapolation' of colder-than-simulated-LGM climate states, the thresholding was introduced. The realistic assumption here is that the LGM and MHO climates as simulated by CCSM represented the true end-member states, and that, for example, the minimum in d180 during the glacial period was not actually the coldest period, but simply rather the period with the greatest accumulation of ice on land. Our other option was to time-shift the end-member climatologies to the minima/maxima in the d18O record. However, this would then become inconsistent with the CO2/orbital forcings used to generate the climate simulations, and so we chose thresholding as the 'lesser of two evils'. In either case, we are quite confident final result (of thresholding, or time-shifting) on preindustrial GIS state is likely quite small.

REVIEWER: LWE is not explained

We now use "m w.e./yr".

REVIEWER: Only two points are shown and discussed, in terms of SMB evolution.

We have included an additional figure (Figure 1), which shows the average SMB field as

GMDD

6, C1045–C1062, 2013

generated by the model workflow, for the LGM, MHO and preindustrial climate states. These figures provide much more context for the text discussion.

REVIEWER: Can you show time series of total SMB

We now have an additional figure that shows these time series.

REVIEWER: How is the geometry modified?

Geometry is modified via the CISM dynamic ice sheet model.

REVIEWER: Here, for the first time, is temperature forcing mentioned. Include this information earlier in the manuscript.

We have now done so.

REVIEWER: Edit "Climate begins to drop into the glacial".

We have clarified this phase as follows: "The first $\sim$20 kyr of simulation are dominated by the slow spin-up of the ice temperature, mainly a cooling at mid-depths, a process that is accelerated by strong surface cooling corresponding to early glacial conditions."

REVIEWER: Periodic pulses are not clearly visible

Here we refer to the short pulses of surface cooling that generate cooler interior ice masses, prior to the onset of more permanent cold LGM-like conditions. However, this is not a very necessary observation, and we have thus simply removed it.

REVIEWER: "Significantly warmer deglacial and Holocene ice" doesn't make sense

We have replaced this phrase with: "warmer Holocene interglacial ice"

REVIEWER: Refer to figure 3b

We have now referred to this figure in the text.

REVIEWER: Alter "the increase in marginal thickening" to "the increase in marginal thickness"

GMDD

6, C1045–C1062, 2013

Altered.

REVIEWER: You have just discussed decrease in the glacial period, so the start of this sentence is strange

We have altered this statement to improve the flow of the text.

REVIEWER: . . .do you mean "spin up ice sheet model state"?

We have altered this text to: "A comparison of the final preindustrial states of the transient spin-up to the equilibrium spin-up simulations"

REVIEWER: Do you mean "transient spin-up procedure"; what is meant by "despite being driven solely by climate model forcing"?

We have reworded this section as follows:

"This marked improvement between the equilibrium and transient spin-up simulation temperature profiles relative to the observed temperature profile confirms the ability of the spin-up procedure to reflect past ice history in the ice sheet state accurately despite being driven by unadjusted climate model output."

With this statement we wished to convey the fact that the spin-up procedure can reproduce first-order features of the ice sheet state that are absent in the equilibrium spin-up (for example the internal temperature profile), by using pure climate model forcing, and not resorting to observation-based parameterizations or arbitrary tuning of the climatic input fields. We feel this is a valuable result of our study.

REVIEWER: "too-high geothermal heat flux"? What is the geothermal flux used?

The simulations here use a spatially uniform geothermal heat flux of 0.06 W/mˆ2. We did not intend to specifically compare against the real geothermal flux value at the base of the GRIP core location. We simply suggested possible reasons why the simulated temperature at the base of the GRIP core location is too warm in the simulations, one of which is that the real geothermal flux at this location is lower than 0.06 W/mˆ2.

GMDD
6, C1045–C1062, 2013

REVIEWER: What is meant by "slight spatial biases within the ice sheet model"?

We have reworded this comment as follows: ". . .and/or spatial biases in the simulated temperature distribution"

We compared a single temperature column to the GRIP temperature profile, at the location of the GRIP core. If we had carried out the comparison a few grid cells over, the basal temperature comparison would have been much improved. This suggests that the too-warm temperature at the GRIP location could quite easily be explained by small-scale spatial biases in the basal temperature distribution.

REVIEWER: What is equilibrium spin-up case?

This refers to the simulation in which SMB/T forcing was held constant at preindustrial levels. We have reworded this to make this clearer, and introduced this simulation earlier.

What do you mean by "recent mass gain"? Observations show largest mass loss around the margins.

REVIEWER: We have reworded this to "late Holocene mass gain". We are certainly not referring to the very recent trends, as described in Sorenson, 2011. We were rather to referring to 'relatively' recent Holocene trends.

REVIEWER: What about comparing to observations?

See our detailed response to this request in the 'General Comments and Responses' section, above.

REVIEWER: What is meant by "more recent"?

We meant "more recent" to refer to climate trends that are after the LGM. However, as this is not a necessary phrase, we have simply removed it.

REVIEWER: Here some validation of the method would be appropriate, not only that it

GMDD
6, C1045–C1062, 2013

is consistent

As we describe in the 'General Comments and Responses' section, the primary purpose here is to demonstrate an ice sheet model spin-up technique results in a preindustrial ice sheet state that is consistent with the SIMULATED preindustrial climate forcing yet retains a reasonable internal memory of past climate. We do note biases in the ice sheet state, and link these primarily to climate model biases which are beyond the scope of this manuscript to tackle. However, the purpose of this paper is not to reduce these biases in order to generate a perfect preindustrial ice sheet state. Rather, the goal is to introduce a general spin-up method. A full validation of the resulting preindustrial ice sheet against observations would necessarily entail evaluation of the entire climate model performance, which is beyond the scope of this manuscript.

REVIEWER: A statement on using a temperature matrix to force the model is introduced here, it should be done earlier.

We have now done so.

REVIEWER: What is meant by "accurate spin-up of an ice sheet model"?

We have replaced this confusing phrase with a more general one: "A requirement for transient spin-up of an ice sheet model is the presence of mutually consistent SMB and temperature forcing fields."

REVIEWER: "Energy-balanced SMB is not a clear term"

We have replaced the sentence that included this term with

"The significant novelty of the present procedure is that it extends these techniques by utilizing SMB and temperature values generated by an energy balance model embedded within a climate model, in order to generate an ice sheet state that is amenable for use in fully coupled ice-sheet/climate simulations. "

REVIEWER: "controlled is" -> "controlled in"

GMDD

6, C1045–C1062, 2013

This text has been altered in response to another reviewer's request: this phrase no longer exists.

REVIEWER: do you mean "(i.e. SMB)"

This text has been altered in response to another reviewer's request: this phrase no longer exists.

REVIEWER: missing references here, what do you mean by this procedure

This procedure has been discussed, but not published (to our knowledge) as a means for installing ice sheets with internal temperature history. For example, one could rescale an observationally-derived temperature field into a model-derived ice sheet geometry. Here we simply wished to note that this method results in a temperature field that is inconsistent with the geometry of the model.

REVIEWER: Pertinent references (e.g. Price et al, 2011 and Gillet-Chaulet, 2012) are missing.

These have now been added

REVIEWER: What do you mean by 'coupled models are in now way constrained by observations'?

We have slightly altered this phrase: "Since coupled models are in no way constrained by observations during run-time..."

By this we mean that during the course of a true coupled climate model simulation, there are no bias-minimizing procedures that drive the prognostic variables within the system towards any observed state: the model is internally completely freely evolving, and boundary conditions are limited to basic planetary boundary conditions. Of course, the output from these models (such as ice sheet volume, sea surface temperature, etc. etc.) are often evaluated against observations, but observations do not actually constrain the evolution of coupled climate model simulations during run-time (opposite

GMDD

6, C1045–C1062, 2013

to data assimilation approaches).

REVIEWER: What do you mean by "trade-off for full system consistency"?

We have altered this phrase to "trade-off for full coupled system consistency".

By this we mean that no fully coupled climate model perfectly replicates replicates the entire coupled climate system (including ice sheets). We are not sure what the reviewer quantitatively means by 'validated'? For example, all freely-evolving climate models exhibit persistent component biases that would probably be unacceptable to forecast models that use inverse procedures to obtain almost-perfect initial conditions. Thus it is almost certain that no initial condition of a freely evolving global coupled model could be successfully 'validated' using the same stringent criteria used to validate inversely-initialized model initial states.

REVIEWER: What do you mean by "very small biases" and, "inconsistent" with respect to what?

We have slightly altered this sentence to:

"Conversely, an ice sheet state that is in force balance and reproduces observed velocities will display negligible biases compared to observations but will very likely be inconsistent with any model-derived climate."

By inconsistent, we mean that an ice sheet initial state obtained through minimization of errors compared to observations, will mostly likely be inconsistent with the state of the simulated climate within a fully coupled climate model simulation, because the simulated climate will never perfectly mirror the observed climate. As a basic practical example, due to climate biases the CESM currently produces in-situ ice growth around some of the GIS margin (where it shouldn't). An inversely-initialized GIS model will obviously not have ice where it shouldn't. So if such a model is simply 'dropped' into the coupled model framework, it will spend the first $\sim$centuries growing excess ice around the margins, to regain geometric 'consistency' with the MODELLED climate

GMDD

6, C1045–C1062, 2013

state.

REVIEWER: What do you mean by 'surface conditions'?

We have added 'SMB and temperature' to clarify what we mean by surface conditions.

REVIEWER: What do you mean by "accurate migration of the summit elevation through time" - this has not been shown.

We refer here to the basic increase in elevation between the LGM and preindustrial that has been suggested by previous studies (now cited) in response to changing accumulation rates is also captured by the spin-up approached described here. By reasonable, we mean that the approach used here performs similarly to other, established spin-up techniques.

REVIEWER: "Energy-balanced-derived SMB fields" needs explanation, and discussion of forcing temperature field is missing

We have reworded this paragraph as follows:

"The technique was developed within the Community Earth System Model framework. It uses ice core data to guide interpolation of surface mass balance and temperature fields generated from CLM simulations (driven by forcing from previous fully-coupled Community Earth System Model simulations) in order to generate the time-continuous forcing required for long ice sheet spin-up simulations. Unique to this approach is the use of matrices of surface mass balance and temperature fields generated using an energy balance model instead of a simpler positive-degree-day approach. Importantly, the procedure results in an ice sheet geometry and temperature distribution that fully reflects both simulated preindustrial and earlier paleoclimate climate states yet avoids artificial climate forcing discontinuities, which we suggest is a necessary precondition for consistent fully-coupled simulations of future ice sheet changes."

REVIEWER: "summit migration" has not been shown in the paper

GMDD

6, C1045–C1062, 2013

We now included a time series of summit migration

REVIEWER: "improved in places by up to 500 m": compared to what?

We have clarified that this is compared to observed ice sheet thicknesses, and also improved this finding in the relevant Figure.

REVIEWER: Figure one is missing minus on vertical axes, and figure caption is not clear.

We have reworded the Figure caption to describe the thresholding process better. We now show the location corresponding to these time series in (new) Figures 1 and 2.

REVIEWER: Figure 2 minus sign in vertical axis is not visible, rewrite the figure caption. Why is SMB cutoff at 0 at the margin, during glacial times

We have re-written the figure caption. As for the marginal SMB during glacial times, it is actually slightly positive at this location, not zero (you can see this if you look closely at the plot). So there is not artificial pinning at 0.

REVIEWER: Figure 3: color scale could be improved

We have improved this color scale to make surface variability more visible. This comes at some expense to the resolution of the near-bed temperature gradients. On our version of the GMDD manuscript, we can see all minus sign(s).

REVIEWER: FIgure 4: the minus sign is not visible, no reference to the GRIP temperature profile is made in the caption.

We do see the minus sign(s) in our plot. We have now included a reference to the GRIP temperature profile in the caption.

REVIEWER: Figure 5: general comments..

We have now replaced figure 5 (now figure 7) with plots that show the absolute basal temperature for the transient and spin-up cases (this was suggested by another re-

GMDD

6, C1045–C1062, 2013

viewer). This now more clearly highlights the spatial pattern of temperature differences between the end states of the two simulations.

REVIEWER: Figure 6: The color scale should be changed to clearly identify zero and regions of positive/negative change (for example red/white/blue)

We have now changed the color scale of this figure (now Figure 10).

Interactive comment on Geosci. Model Dev. Discuss., 6, 2491, 2013.