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Geoscientific Model Development Discussions

Interactive comment on "Dynamic hydrological discharge modelling for coupled climate model simulations of the last glacial cycle" *by* Thomas Riddick et al.

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We thank Lev Tarasov for his useful comments. We give our initial responses below; we will give further responses and add corrections to the manuscript shortly.

1. Comment: The only two significant but easy to address deficiencies I found were the lack of lakes and no specific mention of other dynamic sources of uncertainty that need to be considered for accurate paleo-drainage modelling, specifically glacial isostatic adjustment (GIA) and the need to consider erosional changes in controlling outlet sills.

I don't understand why the algorithm can't handle lakes. Large pro-glacial lakes were

significant deglacial feature for Europe and especially North America, of relevance to both the climate (eg evaporative surface) and to the adjacent ice sheet (lacustrine calving margin). There is significant evidence in the glacial geological literature (eg, Fisher, 2005), that at least the southern outlet for Glacial Lake Agassiz experienced significant erosion and therefore lowering of the controlling sill depth over the lifetime of that lake. Higher older sills can force routing into other ocean basins with potentially significant climatic consequences. The paper should at least provide a brief explanation of why lakes aren't computed and the impacts thereof.

Response: We acknowledge the importance of lakes in palaeohydrology in both North America and Europe. A dynamic lake model is planned and a prototype of it is under active development. However, this work is likely to be ongoing for some time and given the schedule of the PalMod project (for which this tool is primarily intended) and also the time required to integrate changes to components successfully into a wider paleoclimate Earth System Model the present hydrological discharge model without dynamic lakes will receive a significant amount of usage in scientifically important runs. We will alter the manuscript to include a consideration of the impact of the omission of lakes and an explanation of the reasoning for this omission. We further clarify the reasoning for omitting them below.

There are two barriers to the inclusion of periglacial lakes in our model.

a) Apparent basins in the orography can be due to either false sinks (narrow river valleys), lakes or unfilled/partially unfilled endorheic basins (perhaps best thought of as 'potential lakes'). Neither a pit filling nor a river carving algorithm can distinguish between these. Our method of applying height corrections to the orography to give the correct present-day river directions will considerably reduce the number of blocked narrow river valleys but not eliminate all of them as in some cases the present-day river finds the correct route despite a narrow valley not resolved in the orography and thus no error occurs for the present day and no corrections are applied – however what was not an error for the present day may be an error for a past time slice if the tilt of the landscape has been changed by isostatic rebound. The technique of upscaling effective hydrological heights is likely even more effective at eliminating such blocked narrow valleys but will still not work in 100% of cases as errors can still occur and if in this case the present-day river finds the correct path regardless the need for corrections is again not apparent. Subsequent to the submission of this paper we have developed a new tool which will ensure that for the present day all false sinks have a 1 cell wide downslope path to the sea while respecting the basins of actual lakes and endorheic catchments and ensuring they have the correct sill height; from this a further set of relative corrections will be made and added to those that already exists for use in the generation of paleohydrologies. However as for the technical reasons to be discuss next we aren't able to include lakes in the present setup this tool is beyond the scope of this paper.

b) The hydrological discharge model or method presented in this paper doesn't require any modifications to the actual code of JSBACH itself but works by generating new input files for JSBACH every time the model is stopped and restarted (every 10 model years). As mentioned with the existing HD model of JSBACH there is already a lake model but this is unsuitable for modelling lakes whose size and depth changes or which cover multiple grid boxes; a lake cell in this existing model is in effect a single reservoir with an infinite holding capacity and a set average residency time for water – this is effective for modelling the buffering effect of modern day lakes on hydrological discharge but not for modelling lakes with dynamically changing sizes. To introduce a new lake model will require the HD model within JSBACH to be modified; like many GCM components JSBACH was not design to cope with changing input data and thus this modification is likely to require a significant technical development within the model. We agree that erosion of lake sills has a potentially important impact on paleo-hydrology and hope to address this in the lake model we are now developing. We will add a comment noting this lack of sill erosion as a source of error in the text and discuss the effects of this.

2. Comment: Fisher, T.G., 2005. Strandline analysis in the southern basin of glacial Lake Agassiz Minnesota and North and South Dakota, USA. Geological Society of America Bulletin 117 (11/12), 1481–1496.) GIA and determines geographic and geoidal deflections and therefore errors from common simplified GIA schemes can also potentially significantly affect drainage routing. Again, all that is needed is a short statement to this effect. I note the authors do mentions "inaccuracies in the underlying topography" as an issue, but I think it would be useful to readers to spell out the key dynamical sources of this.

Response: Hypothetically our method can be used with any GIA scheme. Within PalMod it will be used with the VILMA model. We will add a short statement noting the GIA scheme used is a potentially important source of error and discuss the sources of this; both those in the original topography as a representation of the present day and those due to the imperfect transformation of that topography to represent a past time including accounting for erosion.

3. Comment: My only other comment (which may be due to my ignorance of conda) relates to all the listed version specific required libraries in the code archive dynamic_hd_env.txt. I suspect this was auto generated and I would strongly urge the authors to reduce this to the bare bones required. Ideally, code should port without special language features, and the only versions issues should be to avoid known bugs in specific versions.

Response: Although this list was indeed automatically generated all of these libraries are required directly or indirectly by some element of the either the dynamic hydrological discharge code or the plotting code that goes with it. Extensive use of external libraries is typical for scientific python code. Many are included in the very extensive python standard library but some are part of a number of third party libraries. Python itself has a number of dependencies on other packages: openssl, readline, sqlite, tk, zlib, pip, setuptools and wheel. Scipy (which Numpy is part of; see http://www.numpy.org) is de facto the standard toolkit for scientific computing with Python. netcdf4-python is a package that allows netCDF4 files to be loaded and written in python. It has a lot of dependencies on other packages; namely: hdf5, libnetcdf, numpy, gfortran, zlib, curl, mkl, krb5, openBLAS. Matplotlib is a very popular plotting package for Python (designed to emulate MATLAB's functionality) and also has a number of dependencies, namely: cycler, freetype, libpng, numpy, pyparsing, pyqt, python-dateutil, pytz, six, qt, sip and openssl. Also used for plotting is the backend cairo, on which depends fontconfig, libxml2, pixman and pycairo. We could create separate environments for the plotting code and reduce this list of packages somewhat however it would still be long enough with the netCDF4 module and its dependencies to require the use of a package manager and with the Conda package manager using the Anaconda repository the setup of these libraries should be done automatically. The Conda package manager and the associated Anaconda repository is used as it is a recommended method of installing Matplotlib according to Matplotlib's own install instructions and the top listed method of installing Scipy on the Scipy website. Its use allows close control over the python environment setup to ensure the correct version of each package is installed.

4. Comment: # I'm confused here. You describe this as "present-day", so presumably just a routing matrix for present-day topography, but then below you indicate this does down-slope routing, in which case this does not need the "present-day" qualifier.

Response: Prior to this work on dynamic hydrology we had a fully static hydrology in the HD model in JSBACH with a set of prescribed river directions for the present day – this is still the HD model used for non-paleo work with JSBACH. The river directions for this were derived manually in several steps. First the orography was pit-filled; then a downslope routing was generated. The river directions thus generated were then themselves corrected by hand to ensure the correct paths for the world's main rivers and further corrections to the river directions were made based on a careful comparison of the catchment of each major river to reference catchments to ensure that each catchment was as far as possible correct.

5. Comment: # shouldn't this be run continuously in async mode? Ice sheet margins

can significantly change drainage routes within a century.

Response: We will most likely run with a 10-year interval. True continuous running would be technically very difficult to implement within the MPI-ESM structure and this method is not fast enough to be run in such a way. It would be possible to run this method in parallel to provide a half yearly update to the river routing with a half year delay/offset however this would also be technically problematic as we would either have to stop and start the main ESM model every half year or allow it to let the river directions change during the course of a run. The former would likely be computationally inefficient and the latter very complicated to implement. Also, even if we implemented it would only be possible to update the ice margins every half year unless we also ran the GIA model VILMA as well which would be a further computational expense. We note the other referee has said our explanation of how the method is applied is unclear; thus, we will include a short explanation of how a paleoclimate ESM models will be/are run in transient mode – i.e. a series of 10-year model runs each using the starting conditions of the previous run and calculating river routing, GIA adjustments and the changing land-sea mask between runs.

6. Comment: "During the last glacial cycle, the courses of rivers in North America, .." # should provide appropriate references

Response: Agreed; we will add one to the final text

7. Comment: "however such lakes are switched off entirely in the version of the HD model used for dynamic hydrological discharge modelling by this paper" # why? Can the not be run with the dynamic upscaled topography?

Response: The lakes provided in the existing HD model of JSBACH are not suitable for a changing topography; they can only be single grid cell in size (multiple lake grid cells can be placed together but they are independent of one another) and their effect is to buffer throughflow. This gives a good representation of non-endorheic lakes for the present day but basin-filling lakes covering multiple grid cells will need a completely new model. As noted above this is future work and lies beyond the scope of this paper. The current lake models buffering effect was not seen as useful for paleolakes as we would have had to use present day parameters which would not be accurate for paleohydrologies. Given that the exact timing of discharge is not of great importance for the kind of coupled climate model paleo simulations this model is intended for it was thus preferred to drop the existing lake model entirely.

8. Comment: # For ice sheet modelling, the meridional grid convergence towards the poles means that it makes much more sense to use eg 0.5 longitude by 0.25 latitude degree resolution.

Response: We need to use 0.5-degree grid to match that of the existing Hydrological Discharge model code in JSBACH3. On the one hand, implementing a 0.5 by 0.25-degree resolution would require significant technical changes to the JSBACH3 code itself; something this method has so far avoided as experience shows that changes to the land surface model itself are often time consuming to implement even when apparently simple in theory. On the other hand, the generation of a the present-day model orography and river direction on the HD 0.5 degree grid has required a significant amount of time, as many corrections are necessary to derived a realistic and consistent orography from an existing orography dataset (see our response to comment 4 and Hagemann and Dümenil 1998).

9. Comment: "We define the effective hydrological height of a cell within a DEM as the height of the highest point in the 'most likely' river" # more succinct description would be "elevation of river sill within the cell" C3

Response: Agreed, we will change to this wording.

10. Comment: "Upscaling effective hydrological heights could also potentially be applied beneficially to Eurasia however we decided against doing so because of the significant additional effort required." # I'm confused here as I understood from the reading that the core upscaling process is automated, in which case the effort is negligible.

Farther down I note

Response: Yes, it is automated. . . but see our next comment below

11. Comment: "The orography upscaling process (which need only be run once) takes approximately 25 minutes to run for the entire globe" # so why not use the generated global field?

Response: Despite notably improving the accuracy of the river directions produced the orography upscaling method doesn't remove all errors in present day river directions and some manual corrections are still required and it wasn't possible to make these for the entire globe due to time pressures. It is highly likely we will revisit this topic in future work on lakes and expand the use of this technique to the entire globe; possibly starting from an even higher resolution orography to reduce the number of manual corrections required.

12. Comment: "When these corrections are applied to an orography for a time other than the present day any relative corrections that are beneath ice sheets are temporarily suppressed until the region becomes ice free once more; thus the original unmodified height is always used for ice sheets" # How do you handle the transition? Eg, say 200 m thick ice in the Rocky Mountains will not over-ride the existing topography?

Response: We don't apply any special handling of the transition; we simply add the height of the ice-sheet to the unmodified 10-minute orography when deriving the orography of ice covered regions. We acknowledge this could be a source of error (and will add it to our limitations section in the text) but it is not clear to the authors how to realistically model the growth of ice over the kind of narrow valley not resolved in the unmodified 10-minute orography and at what point an ice sheet growing over it would essentially smooth out this feature. This could potentially be future work although the first step would be to investigate how likely this is to occur and if so what effect it might have. It would likely be only a small impact unless such a thin ice sheet occurred for an extended period at a point critical for the determination of drainage directions.

13. Comment: Another important limitation is the lack of verification for time-slices other than the present day (due to the lack of easily comparable data); # This is an arguable statement. One could take the LGM topographic deflection from GIA, apply it to the hydro-1k DEM, overwrite ice topography, and then use eg the R hydrological flow solver (or equivalent in other GIS apps) to extract drainage maps and compare to your results.

Response: This could be interesting; we will try making this comparison. However, this process is also really a model rather than data; thus, this is a model to model comparison. We hope to make more extensive comparisons to data during future work on lakes; this will obviously be directed mostly at the lakes but necessarily validate also river directions. We will remove "(due to the lack of easily comparable data);" in the final text.

14. Comment: algorithmic pseudocode # I found this hard to follow. eg it's not clear what all the variables such as p, d, h, i represent. As long as all the code is provided, I would suggest simplifying the pseudo code somewhat and use more descriptive names than single letter indices. Try running the pseudo code by some colleagues and see what doesn't make sense to them.

Response: As suggested we will change the single letter indices for more descriptive names and provide comments to better clarify the pseudo-code. The pseudo-code is certainly difficult to understand however we are very hesitant to simplify the pseudo-code as it would no longer provide an essentially complete description of the algorithm and this would then make it very similar to the description provided in the main text. We have actually provided 4 different descriptions of the same algorithm (if we count the code) and it is our intention that each one describes it to a different level of detail and thus with a different level of readability. We would not expect a reader to be able to understand the pseudo-code from a single reading; this is the purpose of the written description of the algorithm in the main text (which is admittedly also complicated but is simplified as far as is possible); instead it functions as a template for anyone trying to

rewrite the code in another language and as a reference to check details against while reading the description in the main text. The code itself (mostly found in fill_sinks.cpp and sink_filling_algorithm.cpp) is very considerably less readable still (despite being documented with comments in the proscribed C++ style), particularly as it shares a code base with two variants of the sink filling/river carving algorithm, has additional options for dealing with true sinks not described in the paper (and not presently used), is designed to be sufficiently abstract to be applicable to any arbitrary grid and as a consequence of these requirements uses the C++ features multiple-inheritance and generic programming (i.e. templates). We hope in the pseudo-code to present a description of the complete algorithm in a 'clean' code-like form without all of this additional technical infrastructure and without any account for issues such as memory management.

15. Comment: # I tried to set up the code set, but the required conda environment manager is not an available (apt-get accessible) package for Linux and installing this along with what I take are a lot of specific versions of python libraries.. was more than I was willing to go.

Response: For reasons unknown to the authors the Anaconda python distribution (of which the open source Conda is the package manager) can't be installed via apt-get. Linux installation instructions are given here: https://conda.io/docs/user-guide/install/linux.html

We will produce another release of the code for the final version of the paper including more extensive instructions on setting up the code and suggestions of how you might install scipy, matplotlib and netCDF4 without using Conda/Anaconda if preferred.

16. Comment: Figure 1, # what does upscale by "meaning" mean?

Response: We mean upscaling by taking the mean value of the height of all the fine DEM cells that are contained within the area covered by a given coarse DEM cell as the average height of that coarse DEM cell. We will clarify this in the caption or on the figure itself if there is room.

17. Comment: Figure 8, # would be much more informative to show change in volume flux eg in deci Sverdrups than change in water velocities.

Response: We will try plotting this and see how it looks. We originally preferred to use a quantity that was per unit area because of the uneven grid cell size (this figure uses the ocean models grid) but there could be an argument for replacing this with deci Sverdrups.

18. Comment: # small typos: ### Artic Coast -> Arctic coast Coast -> coast northern Pacific -> Northern Pacific

Response: Thanks, we will correct these in the final text.

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