Geosci. Model Dev. Discuss.,
https://doi.org/10.5194/gmd-2018-10-AC3, 2018


Geoscientific Model Development Discussions
Open Access
EGU



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

**Thomas Riddick et al.**

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Received and published: 16 June 2018

We thank Dai Yamazaki for his helpful comments.

**Comment 1**: Provide a literature review on the method for generating paleo river direction map. There is no citation to the previous method in the manuscript. If there is no previous study, please state so.

**Response:** We will add a literature review to the final text.

**Comment 2:** The method section is difficult to understand. The authors stated that the method is applied for every 10-100 years, but the method description suggested some



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manual processing is needed. It is not clear how the authors could update the river direction dynamically during the paleo climate simulation.

**Response:** No manual processing is required during a run; however, a certain amount of manual processing was required to setup the orography corrections for use with this method. We will clarify how dynamic river direction generation fits into the wider transient paleo-run ESM setup and that the orography corrections need to be generated only once prior to starting using this method in long transient paleo-runs in the text.

**Comment 3:** Related to above, only one river direction for the paleo climate was shown, though the method must have been applied multiple times during the simulation. As long as the authors stated that the method is for "dynamic river direction", the time series of gradual river direction change should be shown as a figure.

**Response:** We will add a short time series of plots showing the changing river routes in North America during deglaciation at around 12000 years BP. This should display a clear series of changes in the river routing.

**Comment 4:** P2. L26: Negative values of are set to a constant. Please clarify which value was used. I guess, zero slope is also problematic, this the authors actually used "minimum threshold". Please clarify.

**Response:** The constant value used to replace negative values is 0.00001315. This value is also used to replace zero slope. We will add this value and note it also applies to zero slope in the revised text. Very small positive slopes are also replaced by a constant below a certain height difference threshold but the threshold is so small (a change in height of less than 0.00000000488281m) that this only acts as a guard against floating point errors and is not intended to affect any plausibly measurable height difference.

**Comment 5:** P3. L4: The challenge for a paleoclimate simulation is to develop a method for periodically updating the river directions and flow parameters used with





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sufficient accuracy. Please provide reference to previous papers. How LGM river map was prepared in past studies. Is there any previous method which can treat “dynamic” river map generation?

**Response:** Most previous ESM based simulations of the last glacial cycle have used the technique of extending present day river directions to the sea (this was the suggestion for PMIP-3). Previous paleoclimate modelling in our own ESM model MPI-ESM has used this technique, see Ziemen et. al. (2014). A number of authors have tackled the problem of modelling river routing during the last glacial cycle. Wickert (2016) provides river maps for various time points during the deglaciation derived directly from a 30-second orography combined with various ice-sheet reconstructions. However, this technique would be too computationally expensive to run fully automatically every 10 years during a transient simulation. Tarasov and Peltier (2006) present a dynamic river routing and lake model for North America during the Younger Dryas that is in many ways similar to that presented here and from which the basic principle of upscaling of effective hydrological heights was taken. However, our new model uses a different combination of upscaling techniques and orography corrections from those of Tarasov and Peltier (2006) as well as a different grid.

Most previous simulations of the last glacial cycle that use coupled Global Circulation Models (GCMs) have only treated time-slices; transient simulations having usually been run only in models of intermediate complexity (EMICs). The first transient synchronously coupled GCM simulation of the deglaciation was Liu et. al. (2009). This used a time-varying prescribed forcing to simulate the release of glacial meltwater from rivers. However; the PalMod project, which the approach presented here is intended for, aims to run simulations that limit external forcings to solar and volcanic forcings, thus running transient models using a fully self-consistent earth system model and clearly precluding a proscribed forcing-based approach to meltwater runoff.

In Ziemen et al. (subm) a simplified method was used, following similar ideas as we used here. We will add this discussion to our new literature review in the text.

Liu, Z., Otto-Bliesner, B.L., He, F., Brady, E.C., Tomas, R., Clark, P.U., Carlson, A.E., Lynch-Stieglitz, J., Curry, W., Brook, E., Erickson, D., Jacob, R., Kutzbach, J., Cheng, J.: Transient simulation of last deglaciation with a new mechanism for bolling-allerod warming, Science, 325 (5938), pp. 310-314 , 2009.

Wickert, A. D.: Reconstruction of North American drainage basins and river discharge since the Last Glacial Maximum, Earth Surf. Dynam., 4, 831-869, https://doi.org/10.5194/esurf-4-831-2016, 2016.

Ziemen, F. A., Rodehacke, C. B., and Mikolajewicz, U.: Coupled ice sheet–climate modeling under glacial and pre-industrial boundary conditions, Clim. Past, 10, 1817-1836, https://doi.org/10.5194/cp-10-1817-2014, 2014.

Ziemen, F., Kapsch, M.-L., Klockmann, M. Mikolajewicz, U. (submitted). Heinrich events show two-stage climate response in transient glacial simulations, Climate of the Past, in open review, doi: 10.5194/cp-2018-16. doi:10.5194/cp-2018-16

The other reference (Tarasov and Peltier, 2006) is already in the bibliography of the paper.

**Comment 6:** P3. L20: False sinks also appear at higher resolutions due to various imperfections in the measurement of orography satellite: Recommended citation to the errors in DEM is: Yamazaki D., D. Ikeshima, R. Tawatari, T. Yamaguchi, F. O'Loughlin, J.C. Neal, C.C. Sampson, S. Kanae P.D. Bates A high accuracy map of global terrain elevations Geo- physical Research Letters, vol.44, pp.5844-5853, 2017 doi: 10.1002/2017GL072874

**Response:** Thanks for pointing this out to us. We will add it to the revised text.

**Comment 7:** P4:L8 A brief outline is given here From this section, it seems all steps are automated. While in Section 2.3 the authors mentioned the “by-hand” method which must be not automated. Please clarify this discrepancy. The “by-hand” correction was applied only once at the first step? Then, the description in Section 2.1 should be revised to avoid confusion.

**Response:** Yes, all the steps listed in Section 2.1 are automatic. The only manual work is the preparation of a set of orography corrections that is done offline beforehand and provided as an input file to the dynamic hydrology scripts at the start of a long transient run. We will clarify this in the text.

**Comment 8:** P4. L19: any intervening cells It is not clear that what “intervening cell” means.

**Response:** We mean a river passing through other cells on route to the cell in question. We will change ‘i.e. without passing through any intervening cells’ to ‘i.e. without passing through any other cells first’ and ‘passing through intervening cells’ to ‘i.e. passing through other cells first’ to make this clearer.

**Comment 9:** P4. L24: 2.2 Changing the present-day base orography This section is very difficult to understand. What is the difference between the present-day-base-orography and present-day-reference-orography? Do they have different characteristics? Which data is used as “present-day-base-orography”? Do the two DEMs have the spatial resolution? Please clarify.

**Response:** As we intend to use our dynamic hydrology model both DEM’s have the same spatial resolution (however, it would be theoretically possible to use a lower resolution present day base orography). The present-day base orography is the orography to which isostatic corrections (note these isostatic corrections are completely distinct and entirely independent of the other corrections, hydrological corrections, discussed here and throughout the paper) derived from a solid earth model (such as VILMA) will be applied during a transient paleoclimate simulation to generate the (general purpose ‘physical’) orography for a given past time. The present-day reference orography is the orography we used as a basis when developing the set of relative corrections used in our dynamic hydrology model; to be specific the present-day orography used by the ice sheet reconstruction ICE5G.

Our original plan was to apply the orography corrections (developed using the present-day reference orography) directly to the present-day base orography (which for the purposes of testing was ICE6G) and orographies derived from it; however, testing showed that this produced very poor results for the present-day: many previously corrected river directions were now wrong. Investigation showed that the ICE5G and ICE6G present-day orographies differed and that the poor results were due to these differences. Our solution is to essentially convert the orography used at a given time to be the changes due to isostatic corrections (generated by a solid earth model) applied to the present-day reference orography. This can't be done directly as solid earth model output is shared by several other components of the transient ESM setup so instead we convert the isostatic rebound corrections to relative isostatic corrections by subtracting the present-day base orography from the orography including the isostatic corrections. We then add these relative isostatic corrections to the present-day reference orography and then add the (hydrological) corrections to give the working orography for a given past time for determining river routing.

**Comment 10:** P5. L15: effective hydrological heights It is not clear what is the "effective hydrological height". Please write a brief explanation when it first appears.

**Response:** This is merely a list enumerating the names of the three techniques to be discussed below in detail. Effective hydrological height is defined on p6 L23. We feel that inserting the definition on P5 L15 would break the flow of the text and result in the definition being isolated from the main discussion of this topic. We suggest that we add to P5 L15 "Each of these techniques is described (including definitions of the terms 'intelligent river burning' and 'effective hydrological heights') individually below" to make it clear a definition and explanation is to come.

**Comment 11:** P6. L2: below a given threshold What threshold was used? Please clarify.

**Response:** A different threshold can be chosen for each region where intelligent burning is applied. The thresholds are chosen by hand in order to ensure that only the cells in the super fine orography through which the main river flows (in the region where the intelligent burning is being applied) are left unmasked. This is discussed on P6 L10; we will add this explanation of how the thresholds are chosen to the revised text.

**Comment 12:** P6. L23: as the height of the highest point in the most likely river pathway It is not clear why "highest point" was used. Please explain.

**Response:** The highest point is used as this represents either the height of the (potential) river's bed as it flows into the cell (if the highest point on the path is on an edge; which it often will be) or the height of a lake sill if the cell is the boundary between an enclosed lake basin and a river basin; i.e. the height of a barrier blocking this pathway. Either way this is the height that will control whether a river flows along this pathway or another pathway.

**Comment 13:** P6: L25: lowest highest point This expression is confusing. Please revise.

**Response:** We will revise the wording of this sentence to remove this.

**Comment 14:** P7. L1: "flooding each coarse cell" It is not clear what "flooding" means here. Please explain in detail.

**Response:** Flooding is a term taken from the terminology of priority flood algorithms (upon which the structure of this algorithm is based). It is a quasi-physical description of the way the algorithm proceeds to process the fine cells that fit into the area of a given coarse cell; the processing order of the fine cells is the order in which they would fill with water were the entire coarse cell to be gradually filled with water starting from the lowest point on the coarse cell's boundary (and assuming that the coarse cell was surrounded by a continuous body of water such that disconnected basins within the cell would start flooding from separate edges).

**Comment 15:** P7. L13: If the detailed description here is not needed to explain the





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main work (re- generating river maps during the climate simulation) proposed in the manuscript, I recommend to move this section to Appendix.

**Response:** Agreed, we will move the detailed description of the algorithm to the appendix.

**Comment 16:** P10. L8: For this paper we upscale the unconditioned 30-second orography SRTM30 PLUS (Becker et al., 2009) to a 10-minute grid Is this used as "present day base orography" in Eq(3)? It is not clear how this data is used.

**Response:** The orography upscaling algorithm was applied to this and then the section for North America was extracted. This was converted to a set of relative corrections by subtracting the original "present day reference orography" and then added to the other relative corrections as described in the paper to form an improved set of relative corrections. We will clarify the wording of this section.

**Comment 17:** P13. L19: as all true sinks will be removed for actual paleoclimate simulation Is this a reasonable assumption? Please discuss.

**Response:** Water conservation is important for ESM based climate simulations and in particular for long transient simulations. In the case of paleo-climate simulations full treatment of true sinks requires a dynamic lake model so a terminal lake can be formed and filled until it either overflows (and thus ceases to be a sink and becomes a lake with through flowing water) or achieves a balance between inflow and evaporation. We are now actively developing such a lake model but that is future work beyond the scope of this paper. In the absence of such a dynamic lake model it is necessary to ensure water flowing to true sink points still reaches the sea by other means.

The standard (non-dynamic) HD model in JSBACH which predates this work and which this work is based upon conserves water by adding any water reaching true sink points to the outflow from rivers into the sea, distributing that water in proportion to the size of those rivers.

Here we choose to use an alternative scheme and by removing all true sinks force the water flowing to true sinks into an adjacent river basin across the lowest point along the watershed of the true sinks basin. Changing to this alternative scheme increased the total water flux into the Indo-Pacific and reduced that into the Atlantic for the present day as noted in the paper; however, this had little effect on large-scale ocean circulation. Changing to this alternative scheme will facilitate future work on lakes and ensure the water that would fill any large lakes during deglaciation is routed via the correct spill pathway without actually modelling the lake itself. The removal of true sinks is a necessary assumption in the absence of dynamic lakes. We acknowledge the lack of dynamic lakes will be a significant error in this dynamic hydrology scheme; however, we should be able to generate useful scientific results without them (we will just lack the buffering effect of filling periglacial lakes and the periglacial lake outburst 'mega'-floods) and given the timeframe of PalMod we are likely to make significant use of the current scheme in scientific runs before it is possible to add in dynamic lakes.

**Comment 18:** P14. L14: in all cases they are either due to minor errors in the manually corrected JSBACH river directions The error could be "minor" for the purpose of climate simulation, but the same error could be critical for different purpose. The authors have to acknowledge the method is suitable for climate simulations, but the accuracy could be not adequate for different use (such as water resource assessment or flood risk modelling).

**Response:** The manually corrected JSBACH river directions predate this work on dynamic hydrology by many years and are an essential component of the Hydrological Discharge model either as part of JSBACH or run as a standalone model of present day global hydrology. They have thus been used for a variety of non-paleoclimate modelling purposes for which they have been deemed appropriate either as part of a standalone HD model, a standalone land-surface model, a standalone global hydrology model, or as part of a full Earth System Model (a coupled ocean, atmosphere and land model). Note that the HD model as part of the global hydrology model MPI-HM (Stacke

Hagemann 2012) was not performing noticeably different than other global hydrology models (Haddeland et al. 2012). In this paper our focus is exclusively on making this present -day HD model into a dynamic HD model for paleoclimate modelling and it is not our intention to comment on the suitability of the base HD model for other purposes; it is described and discussed in the references given in the paper (Hagemann and Dümenil,1998b; Hagemann and Dümenil Gates, 2001).

Haddeland, I., D.B. Clark, W. Franssen, F. Ludwig, F. Voß, N.W. Arnell, N. Bertrand, M. Best, S. Folwell, D. Gerten, S. Gomes, S.N. Gosling, S. Hagemann, N. Hanasaki, R. Harding, J. Heinke, P. Kabat, S. Koirala, T. Oki, J. Polcher, T. Stacke, P. Viterbo, G.P. Weedon and P. Yeh, 2011. Multi-Model Estimate of the Global Terrestrial Water Balance: Setup and First Results . J. Hydrometeor. 12, 10.1175/2011JHM1324.1, 869-884.

Stacke, T. and S. Hagemann, 2012 Development and validation of a global dynamical wetlands extent scheme. Hydrol. Earth Syst. Sci. 16, doi:10.5194/hess-16-2915-2012: 2915-2933

**Comment 19:** P14. L31: Application to a LGM simulation P14.L32: Figure 7 I guess, many readers want to check how the algorithm calculates gradual change in river directions following the change in orography. Given that the authors stated in Section 2.1 that “River directions are regenerated approximately every 10-100 years”, there must me multiple river maps for glacier period simulations. However, the authors showed only 1 river map for the paleo climate simulation. I think this is not adequate to proof the usefulness of the proposed method. I here suggest to show the time series of river map development, by focusing on some locations where the authors can observe the gradual change of river directions during the paleo simulation. Otherwise, it is difficult to state that the proposed method is “dynamics” river direction mapping.

**Response:** As discussed above, we will add a short time series of plots showing the changing river routes in North America during deglaciation at around 12000 years BP.





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This should display a clear series of changes in the river routing.

**Comment 20:** Figure 7: Please use different color for the “new land” or “new ocean” in Figure 7 to show the change in land sea mask.

**Response:** We will highlight new land with a distinct shade of brown and new ocean with a distinct shade of blue.

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