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Towards a More Flexible Representation of Hydrological Discharge Transport in (Paleo-)Climate Modelling

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Abstract: In this extended abstract we motivate the development of the Flexible Hydrological Discharge Model (FHD-Model). We give a general overview on the FHD-Model's function and – based on a selection of case studies – we illustrate its application in the framework of climate modelling studies at a global scale. Furthermore, we offer an outlook to upcoming applications and a following publication. The new FHD-Model is required, both, in the field of future climate projections and paleoclimatology. In these research areas, it satisfies the emerging need for flexible discharge transport schemes that react to sea level variations, which are related to variability and evolution of ice sheets. Furthermore, the FHD-Model easily adapts to variations in topography. Therefore, this discharge model is suitable for climate modelling studies on time scales that involve the evolution of land surface, ice sheets, discharge basins, and river systems.

Zusammenfassung: In diesem Beitrag legen wir unsere Motivation zur Entwicklung des Flexiblen Hydrologischen-Abfluss-Modells (FHD-Modell) dar. Wir geben einen Überblick über die Funktion des FHD-Modells und illustrieren – auf der Grundlage von ausgewählten Fallstudien – die Anwendung im Rahmen von globalen Klima-Modell-Studien. Weiterhin weisen wir auf zukünftige Anwendungen des Modells und eine anstehende Publikation hin. Das neue FHD-Modell wird im Zusammenhang mit Projektionen des zukünftigen Klimas und der Paläoklimatologie benötigt. In diesen Forschungsgebieten bedient es den sich abzeichnenden Bedarf an flexiblen kontinentalen Abfluss-Schemata, die auf die Änderung des Meeresspiegels reagieren können, der mit der Variabilität und Entwicklung von kontinentalen Eisschilden verknüpft ist. Darüber hinaus ist das FHD-Modell leicht für geographische Änderungen adaptierbar, die folgende Charakteristika umfassen: Landoberfläche, Eisschilde, Einzugsgebiete der Abflusssysteme, Flussläufe. Das FHD-Modell ist daher anwendbar für Zeitskalen, auf denen sich solche Eigenschaften der Erdoberfläche verändern.

INTRODUCTION

In the hydrological cycle, vast amounts of water are moved between different parts of the climate system. Water that evaporates at the ocean surface may be transported over land masses, form clouds, and precipitate over continents. Excess water that cannot be stored in the soil by vegetation or in Polar Regions as land ice, forms runoff that is subsequently transported along the topographic gradient back to the ocean. Although the amount of water volume transported by rivers is small if compared to other pathways in the hydrological cycle (CHAHINE 1992, TRENBERTH et al. 2007), rivers need to be correctly represented in climate models. It has been stated that the lack of land-bound lateral water transfer in climate simulations leads to a misrepresentation of the hydrological cycle (KITE 1998). Furthermore, changes in coastal discharge volume have a profound influence on the ocean's regional salinity budget, and may subsequently impact on the buoyancy-driven part of ocean circulation at high latitudes (MANABE & STOUFFER 1993, 1999). The exact region of high-latitude river discharge may potentially impact on the Atlantic Ocean meridional overturning circulation (RENNERMALM et al. 2007) and may influence sea-ice formation (DÜMENIL & TODINI 1992, p. 130) in Polar Regions.

Until recently, the focus of (paleo-)climatological modelling on a global scale has been on applications where land surface conditions, and particularly polar ice sheets, sea level, and river routes, do not dramatically change during the course of a simulation. Consequently, hydrological discharge routing in climate models has so far focused on high resolution discharge transport schemes, which are precise but often static, with prescribed and fixed river routes, while flexibility in discharge routing has so far not been of profound importance. Yet, the advent of fully coupled atmosphere – ocean – ice-sheet Earth System Models (e.g., BARBI et al. 2014), together with the emergence of scientific questions that focus on the state of the Arctic and the Antarctic, require dynamic consideration of variations in ice-sheets and sea-level height in the hydrological cycle, and represent a paradigm shift in (paleo)climatological modelling. This poses new challenges for hydrological discharge transport schemes. While there are already various discharge transport models in use in combination with general circulation models (for example DECHARME et al. 2008, ALKAMA et al. 2010, DECHARME et al. 2010, YAMAZAKI et al. 2011, MIGUEZ-MACHO & FAN 2012), these generally depend on high-resolution information of present-day river direction or elevation. Such information characteristic for present day is rarely a suitable choice for paleoclimatological applications at tectonic time scales, as assumptions on past or future land surface conditions that influence the discharge transport over land are uncertain and sparse. Consequently, for paleoclimatic applications of discharge transport schemes in climate models the importance is not so much on high resolution, while resolution is on the other hand of profound interest for the correct representation of watershed characteristics in present-day applications. In contrast, it is necessary for a discharge transport scheme in paleoclimatology to flexibly react to changes in boundary conditions, for example land-surface elevation of ice sheets as well as sea-level height. These considerations are the foundation for the development of the Flexible Hydrological Discharge Model (FHD-Model).

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In the following, we give a short first overview on design, validity, and performance of the FHD-Model as an optional part of the Community Earth System Models (COSMOS). The FHD-Model is designed to integrate into the main components of this climate model toolbox – the fifth generation of the European Centre Hamburg Model (ECHAM5, Roeckner et al. 2003) and the Max Planck Institute Ocean Model (MPIOM, Marsland et al. 2003). The new discharge scheme shall overcome some of the practical disadvantages of common hydrological discharge schemes with fixed river routes in (palaeo-) climatological applications of climate models.

The performance of the COSMOS in combination with the standard hydrological discharge scheme of ECHAM5 (HD-Model, Hagemann & Dümenil 1998), which is based on fixed river paths derived from high resolution orographic data, was evaluated for preindustrial conditions (Wei et al. 2012), the Holocene (Wei & Lohmann 2012, Lohmann et al. 2013), the last millenium (Jungclaus et al. 2010), glacial millenial-scale variability (Gong et al. 2013, Kageyama et al. 2013, Stärz et al. 2013, Zhang et al. 2013, Weber et al. 2014, Zhang et al. 2014, Gong et al. 2015), the Last Interglacial (Lunt et al. 2013, Felis et al. 2015, Pfeiffer & Lohmann 2016), and warm climates in the Miocene (Knorr et al. 2011, Knorr & Lohmann 2014) and Pliocene (Stepanek & Lohmann 2012, Haywood et al. 2013). In most of these publications, in particular those that investigate the climate of time slices earlier than the Preindustrial and the Holocene, various assumptions were necessary in adjusting the high resolution present-day topography setup of the HD-Model for the respective past land surface conditions. The availability of the FHD-Model as a flexible discharge transport scheme, which is able to accept reconstructed topography data of arbitrary resolution, would have been of help in such studies. This topic is of relevance particularly for paleoclimate modelling at tectonic time scales and with a focus on the evolution of ice sheets: At tectonic time scales there is no sufficient information on past global river networks that could be used as a constraint for the river routing in climate simulations, necessitating a more flexible approach as in the FHD-Model. For the evolution of ice sheets, the FHD-Model is able to automatically reroute river flow in response to changes in ice sheets and the related impact on the land surface. Furthermore, the FHD-Model is able to resolve the response of flow direction to any sea level variation that results from volume change of land ice.

METHODOLOGY

The FHD-Model's physical core is based on the Gauckler-Manning-Strickler formula (GMS), which describes the velocity of gravity-driven sheet-flow (e.g., Chow 1959, p. 99, Eq. 5–6). The GMS may be used to describe the flow rate Q in dependence of the water surface slope s (defined in Fig. 1a), the water height f in the flow bed, and a scalar real-valued flow capacity parameter c, which has the physical unit of $m^{4/3} \cdot s^{-1}$. This parameter is a system characteristic of the rectangular channel in which the computed discharge is assumed to occur – c is directly proportional to the width w of the flow bed, indirectly proportional to the roughness of the channel bed material (commonly referred to as Manning's roughness coefficient n), and describes how much volume may be transported by the channel in the four considered directions (Fig. 1b) for a given gravitational forcing that acts on the water volume along the topographic slope.

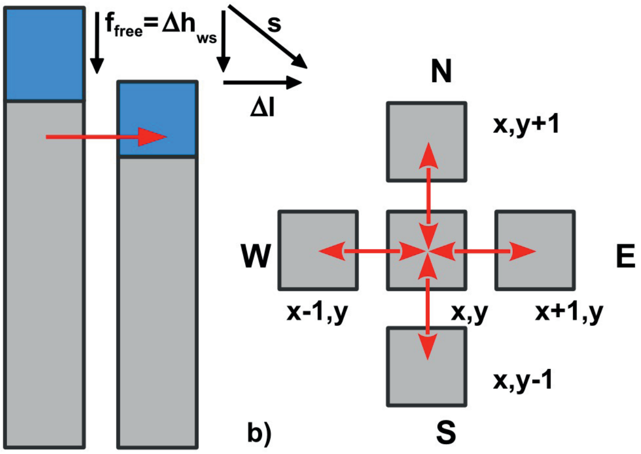

Fig. 1: Flow scheme of the FHD-Model. a): regulators of direction and strength of the flow include the slope of the water surface in the flow direction (red arrow), that is determined by time-depending height differences of water surfaces of neighbouring grid cells Δh_{ws} (in this case identical to the free flow height f_{free}) and the horizontal grid cell dimension Δl. b): currently, volume flow in the FHD-Model may occur between neighbouring grid cells along the four cardinal directions (N, E, S, W).

Abb. 1: Fluss-Schema des FHD-Modells. a): Regulatoren von Richtung und Stärke des Flusses enthalten das Gefälle der Wasseroberfläche in Flussrichtung (roter Pfeil), das durch die zeitabhängige Höhendifferenz der Wasseroberfläche benachbarter Gitterzellen Δh_{ws} (welche in diesem Fall identisch ist mit der freien Flusshöhe f_{free}) und die horizontale Ausdehnung einer Gitterzelle Δl bestimmt wird. b): in der aktuellen Version des FHD-Modells kann der Fluss zwischen benachbarten Gitterzellen entlang der vier Himmelsrichtungen (N, E, S, W) erfolgen.

Equation 1 is an adapted version of the GMS and suited for application on a discrete model grid: f is replaced by the free flow height f_{free}, which is defined by the difference between the flow heights of neighbouring grid cells (Fig. 1a).

$$Q = c \cdot f_{free}^{5/3} \cdot s^{1/2} \qquad (1)$$

The simulation of hydrological discharge transport in the FHD-Model is performed by adding runoff and discharge at grid cell scale, which is computed in ECHAM5 by means of a bucket model, to the local value of f_{free}. Via an explicit time stepping method, this volume is subsequently transported between neighbouring grid cells as overland flow, as described by Equation 1, until it reaches either the coast or an unfilled endorheic basin. Choosing Equation 1 as the foundation of the discharge transport scheme has several advantages:

i) It enables flexibility of the flow simulation with respect to both, flow rate and flow direction of the hydrological discharge, which is a major difference to other common discharge schemes in climate models, that rather rely on prescribed and fixed flow paths – the highly accurate HD-Model, for example, which is the standard hydrological discharge scheme of ECHAM5, is strongly optimised for present-day topography as discussed in the literature (Hagemann & Dümenil 1998).

ii) The presence of directly observable physical quantities on the right hand side of Equation 1, namely f_{free} and s, enables easy application of the equation in climate models. The information necessary to derive a complete set of boundary conditions for the flow simulation (Fig. 2) is

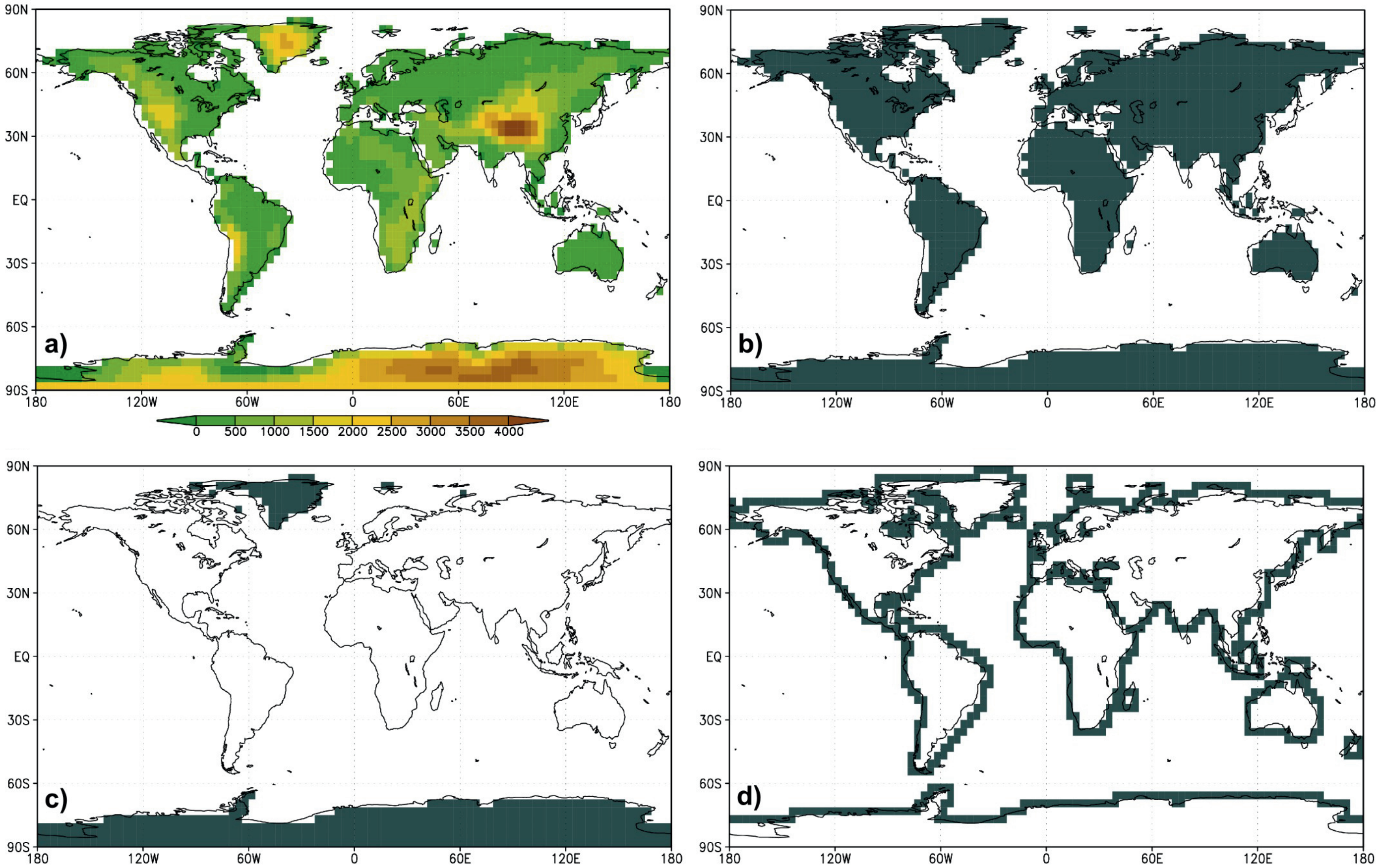

Fig. 2: A complete set of boundary conditions of the FHD-Model, here for present day at T31-resolution (3.75° × 3.75°). a): land topography (m); b): land-sea-mask; c): ice-sheet-mask (for coupling of the FHD-Model to an ice-sheet model); d): coastal discharge collection mask (for coupling the FHD-Model to an ocean model). a), b), and c) stem directly from the boundary conditions of the Atmosphere General Circulation Model ECHAM5, d) may be easily derived from b) based on a dedicated algorithm.

Abb. 2: Ein vollständiger Satz von Randbedingungen für das FHD-Modell, hier für heutige Bedingungen in T31-Auflösung (3.75° × 3.75°). a): Topographie über Land (m); b): Land–Ozean-Maske; c): Eisschild-Maske (zur Kopplung des FHD-Modells an ein Eisschild-Modell); d): Maske für die Sammlung des kontinentalen Abflusses an der Küste (zur Kopplung des FHD-Modells an ein Zirkulationsmodell des Ozeans). a), b) und c) entspringen direkt den Randbedingungen des Atmosphärenmodells ECHAM5; d) ist auf einfache Weise von b) mit Hilfe eines entsprechenden Algorithmus abgeleitet.

already present in common model setups of general circulation models, and the formulation of Equation 1 does not depend on a preferred resolution of the considered physical quantities. Therefore, the derivation of these quantities does not impose a significant amount of additional workload during the generation of a model setup, as it is often the case for common discharge transport schemes in climate models.

RESULTS AND DISCUSSION

Calibration of the model parameter c

The model parameter *c* in Equation 1 is an integrated quantity at grid-cell scale. There is no evident analytical method to find a value that is suitable for a global hydrological discharge simulation, where many different environmental conditions – for example sand, soil, vegetation, snow, and ice – pose various different background characteristics for the flow. Therefore, a parameter calibration against a benchmark is performed for spatially integrated coastal discharge at the spatial scale of interest for global climate simulations – that is catchments of major ocean basins. A simulation of hydrological discharge transport of the model ECHAM5 with the HD-Model is chosen as a benchmark. The calibration is shown here for present-day conditions, and it is principally necessary to repeat the calibration for any set of land surface conditions that shall be used as a boundary condition for the discharge transport simulation. Later, we will shortly discuss why we assume the derived value of *c* to be a good first-order guess also for other time slices than present day.

Results shown here refer to a present-day topography and ice sheet distribution at T31-resolution (3.75° × 3.75°) – a resolution that is still common for paleoclimatological application of global climate models. Ocean-basin-integrated coastal discharge, derived from a comparable discharge transport simulation with the HD-Model, serves as benchmark and reference dataset for the calibration. The model configuration, from which we derive, both, the benchmark and the hydrological forcing for the discharge simulation with the FHD-Model, is based on the ECHAM5 model with a horizontal resolution of 3.75° × 3.75° and 19 vertical layers, complemented by a land-surface scheme, including dynamic vegetation (Brovkin et al. 2009). The ocean component MPIOM, including the dynamics of sea ice formulated using viscous-plastic rheology, has an average horizontal resolution of 3.0° × 1.8° with 40 vertical layers of differing thickness.

Details of the calibration must be omitted here due to space limitations and will be presented in detail in a later publication that focuses on the model description. However, the three main results of the calibration are summarized in the following:

i) For every considered catchment (Arctic Ocean, Atlantic Ocean, Indian Ocean, and Pacific Ocean), a distinct optimum value of the model parameter c exists, for which the root mean square deviation (FHD-Model *versus* benchmark) of the catchment-integrated coastal discharge takes a minimum;

ii) The best fit of simulations with the FHD-Model to the benchmark occurs for Indian Ocean and Pacific Ocean – for Atlantic Ocean and Arctic Ocean the agreement is slightly worse;

iii) The best fit is generated by assuming high flow-resistance (small c, approximately 10 $m^{4/3} \cdot s^{-1}$) in the catchments of Pacific Ocean and Indian Ocean; this pays regard to the relatively short distance between grid cells in the continental interior and the coast in these regions, creating relatively short river systems.

iv) In contrast, best agreement with the benchmark is found if assuming low flow resistance in the discharge simulation with the FHD-Model (large c, approximately 40 $m^{4/3}\ s^{-1}$) for the catchments of Arctic Ocean and Atlantic Ocean, where longer flow systems (the polar rivers Ob, Yenisey, and Lena, for example) are predominant.

Annual discharge climatology in the FHD-Model

One key parameter of a discharge simulation in a coupled atmosphere – ocean climate simulation, that necessitates verification during the development of a discharge transport scheme, is the annual cycle of the integrated discharge to a specific ocean basin. Here, the annual discharge climatology for present-day land surface conditions is shown at the example of the Indian Ocean catchment. Generally, timing of peaks and troughs in the discharge climatology is governed by the climatology of net-precipitation, which depends on physical conditions as computed by the atmosphere model and by the bucket model, the latter defining amplitude and timing of runoff-formation at grid cell scale. Yet, it must be verified that the time delay of the discharge volume along its path within a catchment is comparable to conditions in the respective natural flow system. Furthermore, the annually integrated amount of coastal discharge per catchment should be reasonable; that means it should agree with the benchmark. A respective discordance is likely caused by the misrepresentation of drainage divides in the discretized – and rather coarse-resolution – topography dataset utilised in the FHD-Model; differences in the water balance of the atmosphere model cannot explain such a deviation as the discharge curves derived from FHD-Model and benchmark are based on the same hydrological forcing from the atmosphere general circulation model.

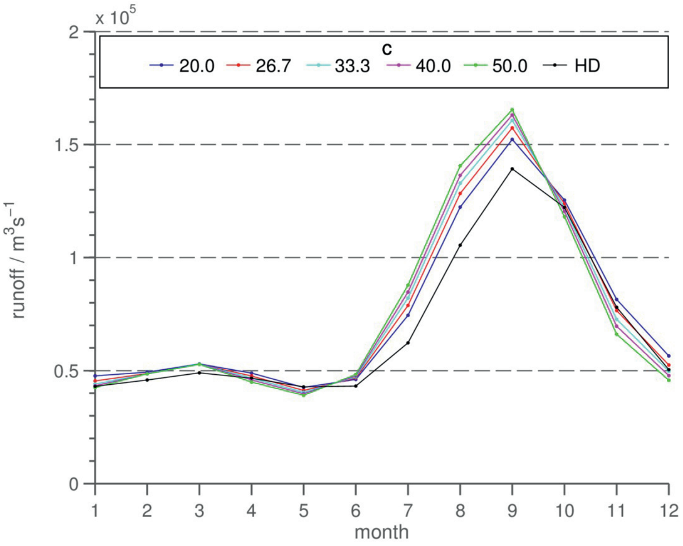

Fig. 3: Annual cycle of discharge to the Indian Ocean as simulated with the FHD-Model. Shown are results derived with various settings of the model parameter c ($m^{4/3}s^{-1}$). For reference, also the respective discharge climatology of the benchmark (a simulation based on the HD-Model, indicated by "HD" in the legend) is shown. The annually integrated discharge to the Indian Ocean in the given model setup with the FHD-Model is $2.37 \cdot 10^{12} m^3 yr^{-1}$, independently of the value of c. In the benchmark, the respective volume is slightly lower ($2.18 \cdot 10^{12} m^3 yr^{-1}$).

Abb. 3: Jahresgang des vom FHD-Modell simulierten kontinentalen Abfluss in den Indischen Ozean. Dargestellt sind Ergebnisse, die auf verschiedenen Werten des Modell-Parameters c beruhen. Zum Vergleich ist auch die entsprechende Datenreihe der Referenz (eine Simulation basierend auf dem HD-Modell, gekennzeichnet durch "HD" in der Legende) gezeigt. Der jährlich integrierte kontinentale Abfluss in den Indischen Ozean zu den vorgegebenen Randbedingungen ist im FHD-Modell $2.37 \cdot 10^{12} m^3 yr^{-1}$, unabhängig vom Wert des Parameters c. In der Referenzdatenreihe ist der Wert geringfügig kleiner ($2.18 \cdot 10^{12} m^3 yr^{-1}$).

Results of discharge simulations with various settings of the model parameter c show that the FHD-Model is able to reproduce the main characteristics of catchment-integrated discharge in the benchmark (i.e., the reference data set obtained from a comparable discharge simulation with the HD-Model, Fig. 3). In the FHD-Model, the annually integrated discharge to the Indian Ocean slightly overestimates the respective quantity of the benchmark. This indicates that the catchment area of the Indian Ocean inherent to the global coarse-resolution topography data set in the FHD-Model, which is taken over from ECHAM5, has a different size than and/or is shifted with respect to the catchment area in the higher resolution topography data set on which the benchmark is based. Indeed, area and location of the catchment of the Indian Ocean differ between the setups of FHD-Model and HD-Model (not shown here).

Application of the FHD-Model in a scenario of global sea level rise

In order to demonstrate the ability of the FHD-Model to flexibly adjust the flow direction of discharge transport in the climatologically interesting case of global sea-level rise, the FHD-Model is applied in a case study of continental flooding due to postglacial ice-sheet melt. In this case study, the FHD-Model is run offline (i.e., not coupled to an atmosphere – ocean model) and forced with a periodic time series of runoff and drainage at grid cell scale that has been derived from a climate simulation. The sea level time series, prescribed in this case study as a forcing, is based on a reconstruction of freshwater discharge (FAIRBANKS et al. 1992, Fig. 30.1B), and covers the time period from the Last Glacial Maximum (LGM) to about 7,000 years before present.

Figure 4 shows that the FHD-Model is able to correctly simulate the flooding of the initially exposed continental shelf of the LGM topography boundary condition (that is courtesy of ZHANG et al. 2013). The results imply that in coastal regions, and also in those regions of the low-lying continental interior where no topographic obstacles shield inflow from the ocean, the flow direction is indeed subject to change as indicated by the establishment of land-based volume reservoirs. Low-lying continental interior regions that are shielded by topographic obstacles from coastal inflow – for example the Amazon Basin and the Caspian Sea – on the other hand do not experience any change in regional water level.

CONCLUSIONS AND OUTLOOK

We have shown that the FHD-Model has characteristics that make it suitable for the computation of hydrological discharge transport at catchment scale of ocean basins in (palaeo)climatological applications of climate models. Due to the presence of only one model parameter, the FHD-Model is easily calibrated to a given discharge benchmark, which is currently done only for present-day conditions. Although this parameter calibration is not necessarily also valid for the application of the model for other land surface and climatic conditions, we believe that the derived value of *c* is generally a suitable first-order assumption in the framework of paleoclimatology, where the necessary auxiliary information for a model calibration is sparse or absent. Our rationale is based on the inference that for present-day land surface conditions, which are very different across the various continents, one globally uniform value can be found for which the FHD-Model provides a reasonable performance in the simulation of discharge to all the major ocean basins. Depending on the application, the value of *c* may be adjusted in the future, provided that the necessary benchmark data or sufficient information on land surface conditions are available.

The ability of the FHD-Model to automatically reroute the discharge and its ability to resolve the evolution of land-based water distribution in the presence of a changing sea level, enables sea-level height and ice-sheet variability to impact on

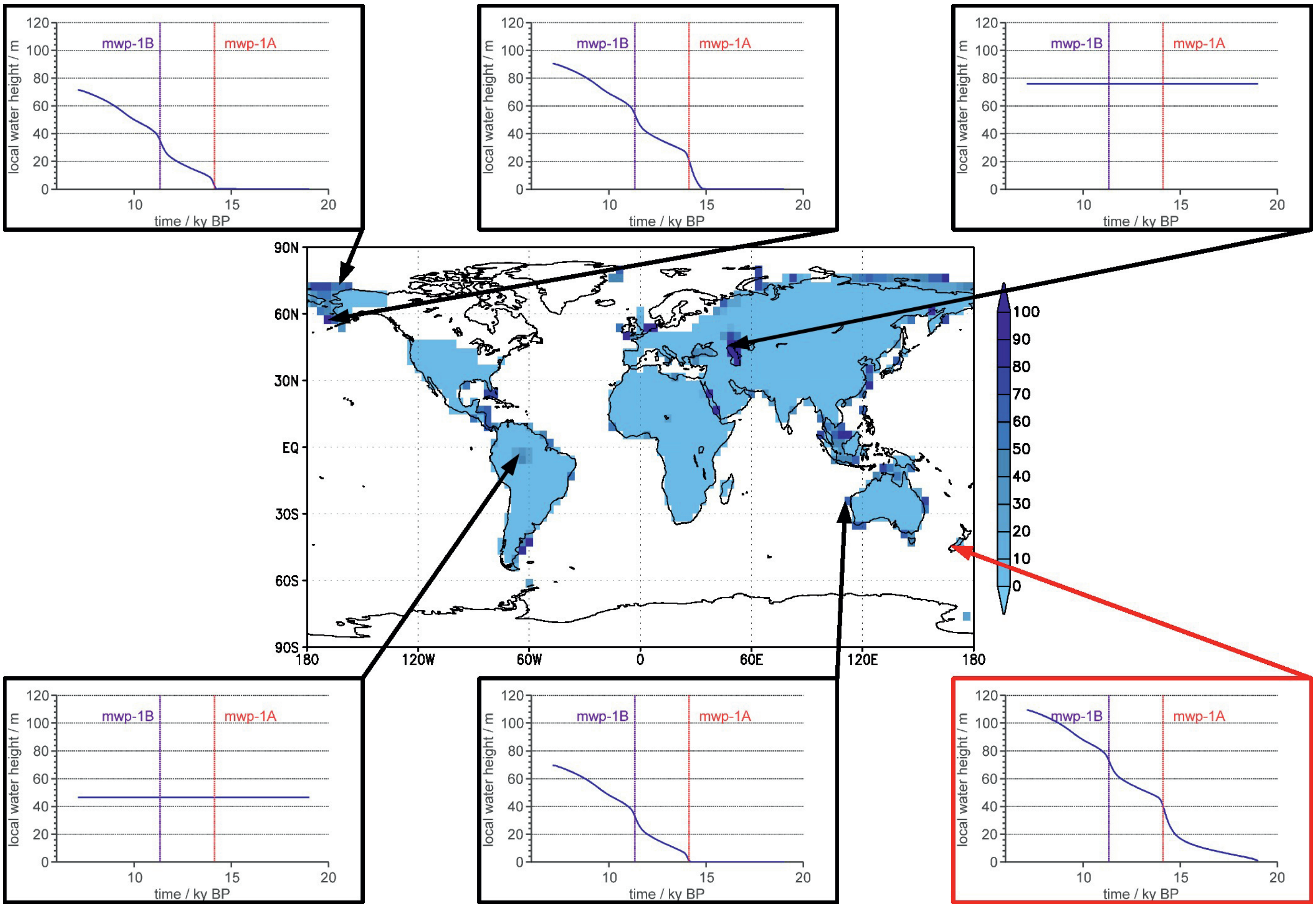

Fig. 4: Simulation of continental water surface height in the FHD-Model under the influence of postglacial sea-level rise, based on a topography boundary condition of the Last Glacial Maximum (courtesy of ZHANG et al. 2013). Shown is the height of the water column (m) at the end of the simulation (centre). Furthermore, the temporal evolution of regional water-surface height is illustrated for five locations of the continental interior (black) and one coastal location (red); the latter time series is identical to the applied sea-level forcing that considers major melt-water pulses (mwp).

Abb. 4: Simulation der Höhe des Wasserspiegels über den Kontinenten im FHD-Modell unter dem Einfluss von postglazialem Anstieg des globalen Meeresspiegels basierend auf einer topographischen Randbedingung für das letzte Hochglazial (bereitgestellt durch ZHANG et al. 2013). Gezeigt ist die Höhe der Wassersäule (m) am Ende der Simulation (Mitte). Daneben wird die zeitliche Entwicklung der regionalen Höhe der Wasseroberfläche an fünf verschiedenen Orten im Innern der kontinentalen Landmasse (schwarz), sowie an der Küste (rot) illustriert. Die letztgenannte Zeitserie ist identisch mit dem vorgeschriebenen Meeresspiegel, welcher ausgeprägte Schmelzwasser-Abflüsse (mwp) berücksichtigt.

the continental part of the hydrological cycle. These characteristics allow a more realistic simulation of the climate system with COSMOS, as routing of hydrological discharge is by design at all times consistent with topography, ice-sheet distribution, and sea level.

The FHD-Model improves the practical application of ECHAM5/MPIOM for use in combination with ice-sheet models. It is therefore of particular interest in applications that focus on the state of the Earth's Polar Regions. This also recommends the use of the FHD-Model for the application in future climate scenarios that include fully coupled ice-sheet models and consider the resultant variability in sea level. The FHD-Model improves the integration of the discharge scheme into climate models in that it accepts land surface conditions of arbitrary resolution. While the focus in the FHD-Model clearly is on global-scale climate modelling, the underlying physical formalism is also in use at smaller spatial scale, for example for the simulation of floods in river catchments (Dag Lohmann pers. com. 2013). Therefore, the FHD-Model may in principle be used also for climate modelling at spatial scales as small as river catchments. The necessity of only a small number of boundary conditions that may be easily derived from any common climate model setup, further simplifies the use of the FHD-Model in practical applications of climate modelling.

Currently, the FHD-Model only serves as a means of transporting land-bound water volume in a meaningful way back to the coast. Yet, it is intended to extend its capability in that the flow volume may be redistributed to the soil along the discharge route, wherever local climatic conditions suggest such a process. This additional mechanism will further enhance the completeness of climate simulations with COSMOS and its model components.

This publication is not intended to give a conclusive overview on all the properties, capabilities and the performance of the FHD-Model, which have been outlined only roughly here. Currently, a more detailed manuscript is in preparation that will present more results and a more detailed description and discussion of the FHD-Model.

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References

Alkama, R., Decharme, B.R., Douville, H., Becker, M., Cazenave, A., Sheffield, J., Voldoire, A., Tyteca, S. & Le Moigne, P. (2010): Global evaluation of the ISBA-TRIP continental hydrological system. Part I: Comparison with GRACE terrestrial water storage estimates and in situ river discharges.- J. Hydrometeorol. 11: 583-600, doi: 10.1175/2010JHM1211.1.

Barbi, D., Lohmann, G., Grosfeld, K. & Thoma, M. (2014): Ice sheet dynamics within an Earth System Model: downscaling, coupling and first results.- Geosci. Model Dev. 7: 2003-2013, doi: 10.5194/gmd-7-2003-2014.

Brovkin, V., Raddatz, T., Reick, C.H., Claussen, M. & Gayler, V. (2009): Global biogeophysical interactions between forest and climate.- Geophys. Res. Lett. 36: L07405, doi: 10.1029/2009GL037543.

Chahine, M.T. (1992): The hydrological cycle and its influence on climate.- Nature 359: 373-380.

Chow, V.T. (1959): Open-Channel Hydraulics.- McGraw-Hill, New York, NY, 1-680.

Decharme, B., Douville, H., Prigent, C., Papa, F. & Aires, F. (2008): A new river flooding scheme for global climate applications: Off-line evaluation over South America.- J. Geophys. Res. 113: D11110, doi: 10.1029/2007JD009376.

Decharme, B., Alkama, R., Douville, H., Becker, M. & Cazenave, A. (2010): Global evaluation of the ISBA-TRIP continental hydrological system. Part II: Uncertainties in river routing simulation related to flow velocity and groundwater storage.- J. Hydrometeorol. 11: 601-617, doi: 10.1175/2010JHM1212.1

Dümenil, L. & Todini, E. (1992): A rainfall-runoff scheme for use in the Hamburg climate model.- In: J.P.O'KANE (ed): Advances in theoretical hydrology: a tribute to Jim Dooge, Elsevier, Amsterdam, European Geophysical Society Series on Hydrological Sciences (1): 129-157.

Fairbanks, R.G., Charles, C.D. & Wright, J.D. (1992): Origin of global meltwater pulses.- In: R.E. TAYLOR, A. LONG & R.S. KRA (eds): Radiocarbon after four decades, Springer, New York: 473-500.

Felis, T., Giry, C., Scholz, D., Lohmann, G., Pfeiffer, M., Pätzold, J., Kölling, M. & Scheffers, S.R. (2015): Tropical Atlantic temperature seasonality at the end of the last interglacial.- Nat. Commun. 6: 1-8, doi: 10.1038/ncomms7159.

Gong, X., Knorr, G., Lohmann, G. & Zhang, X. (2013): Dependence of abrupt Atlantic meridional ocean circulation changes on climate background states.- Geophys. Res. Lett. 40: 3698-3704, doi: 10.1002/grl.50701.

Gong, X., Zhang, X., Lohmann, G., Wei, W., Zhang, X. & Pfeiffer, M. (2015): Higher Laurentide and Greenland ice sheets strengthen the North Atlantic ocean circulation.- Clim. Dyn. 45: 139-150, doi: 10.1007/s00382-015-2502-8.

Hagemann, S. & Dümenil, L. (1998): A parametrization of the lateral waterflow for the global scale.- Clim. Dynam. 14: 17-31.

Haywood, A.M., Hill, D.J., Dolan, A.M., Otto-Bliesner, B., Bragg, F., Chan, W.-L., Chandler, M.A., Contoux, C., Jost, A., Kamae, Y., Lohmann, G., Lunt, D.J., Abe-Ouchi, A., Pickering, S.J., Ramstein, G., Rosenbloom, N.A., Sohl, L., Stepanek, C., Yan, Q., Ueda, H. & Zhang, Z. (2013): Large-scale features of Pliocene climate: Results from the Pliocene Model Intercomparison Project.- Clim. Past 9: 191-209, doi: 10.5194/cp-9-191-2013.

Jungclaus, J.H., Lorenz, S.J., Timmreck, C., Reick, C.H., Brovkin, V., Six, K., Segschneider, J., Giorgetta, M.A., Crowley, T.J., Pongratz, J., Krivova, N.A., Vieira, L.E., Solanki, S.K., Klocke, D., Botzet, M., Esch, M., Gayler, V., Haak, H., Raddatz, T.J., Roeckner, E., Schnur, R., Widmann, H., Claussen, M., Stevens, B. & Marotzke, J. (2010): Climate and carbon-cycle variability over the last millennium.- Clim. Past 6: 723-737, doi: 10.5194/cp-6-723-2010.

Kageyama, M., Merkel, U., Otto-Bliesner, B., Prange, M., Abe-Ouchi, A., Lohmann, G., Ohgaito, R., Roche, D.M., Singarayer, J., Swingedouw, D. & Zhang, X. (2013): Climatic impacts of fresh water hosing under Last Glacial Maximum conditions: a multi-model study.- Clim. Past 9: 935-953, doi: 10.5194/cp-9-935-2013.

Kite, G. (1998): Land surface parameterizations of GCMs and macroscale models.- J. Amer. Water Resour. Assoc. 34: 1247-1254.

Knorr, G., Butzin, M., Micheels, A. & Lohmann, G. (2011): A warm Miocene climate at low atmospheric CO2 levels.- Geophys. Res. Lett. 38: L20701, doi: 10.1029/2011GL048873.

Knorr, G. & Lohmann, G. (2014): Climate warming during Antarctic ice sheet expansion at the Middle Miocene transition.- Nat. Geosci. 7: 376-381, doi: 10.1038/NGEO2119.

Lohmann, G., Pfeiffer, M., Laepple, T., Leduc, G. & Kim, J.-H. (2013): A model-data comparison of the Holocene global sea surface temperature evolution.- Clim. Past 9: 1807-1839, doi: 10.5194/cp-9-1807-2013.

Lunt, D.J., Abe-Ouchi, A., Bakker, P., Berger, A., Braconnot, P., Charbit, S., Fischer, N., Herold, N., Jungclaus, J.H., Khon, V.C., Krebs-Kanzow, U., Langebroek, P.M., Lohmann, G., Nisancioglu, K.H., Otto-Bliesner, B.L., Park, W., Pfeiffer, M., Phipps, S.J., Prange, M., Rachmayani, R., Renssen, H., Rosenbloom, N., Schneider, B., Stone, E.J., Takahashi, K., Wei, W., Yin, Q. & Zhang, Z.S. (2013): A multi-model assessment of last interglacial temperatures.- Clim. Past 9: 699-717, doi: 10.5194/cp-9-699-2013.

Manabe, S. & Stouffer, R.J. (1993): Century-scale effects of increased atmospheric CO_2 on the ocean-atmosphere system.- Nature 364: 215-218.

Manabe, S. & Stouffer, R.J. (1999): The role of thermohaline circulation in climate.- Tellus B 51: 91-109.

Marsland, S.J., Haak, H., Jungclaus, J.H., Latif, M. & Roeske, F. (2003): The Max-Planck-Institute global ocean/sea ice model with orthogonal curvilinear coordinates.- Ocean Model. 5: 91-127.

Miguez-Macho, G. & Fan, Y. (2012): The role of groundwater in the Amazon water cycle: 1. Influence on seasonal streamflow, flooding and wetlands.- J. Geophys. Res. 117: D15113, doi: 10.1029/2012JD017539.

Pfeiffer, M. & Lohmann, G. (2016): Greenland Ice Sheet influence on Last Interglacial climate: global sensitivity studies performed with an atmosphere–ocean general circulation model.- Clim. Past 12: 1313-1338, doi:10.5194/cp-12-1313-2016.

Rennermalm, A.K., Wood, E.F., Weaver, A.J., Eby, M. & Déry, S.J. (2007): Relative sensitivity of the Atlantic meridional overturning circulation to river discharge into Hudson Bay and the Arctic Ocean.- J. Geophys. Res. 112: G04S48, doi: 10.1029/2006JG000330.

Roeckner, E., Brokopf, R., Esch, M., Giorgetta, M., Hagemann, S., Kirchner, I., Kornblueh, L., Manzini, E., Rhodin, A., Schlese, U., Schulzweida, U. & Tompkins, A. (2003): The atmospheric general circulation model ECHAM 5. PART I: Model description.- Max Planck Institute for Meteorology, MPI-Report 349: 1-127.

Stärz, M., Lohmann, G. & Knorr, G. (2013): Dynamic soil feedbacks on the climate of the mid-Holocene and the Last Glacial Maximum.- Clim. Past Discuss. 9: 2717-2770, doi: 10.5194/cpd-9-2717-2013.

Stepanek, C. & Lohmann, G. (2012): Modelling mid-Pliocene climate with COSMOS.- Geosci. Model Dev. 5: 1221-1243, doi: 10.5194/gmd-5-1221-2012.

Trenberth, K.E., Smith, L., Qian, T., Dai, A. & Fasullo, J. (2007): Estimates of the global water budget and its annual cycle using observational and model data.- J. Hydrometeorol. 8: 758-769, doi: 10.1175/JHM600.1.

Weber, M.E., Clark, P.U., Kuhn, G., Timmermann, A., Sprenk, D., Gladstone, R., Zhang, X., Lohmann, G., Menviel, L., Chikamoto, M.O., Friedrich, T. & Ohlwein, C. (2014): Millennial-scale variability in Antarctic ice-sheet discharge during the last deglaciation.- Nature 510: 134-138, doi: 10.1038/nature13397.

Wei, W. & Lohmann, G. (2012): Simulated Atlantic Multidecadal Oscillation during the Holocene.- J. Climate 25: 6989-7002, doi: 10.1175/JCLI-D-11-00667.1.

Wei, W., Lohmann, G. & Dima, M. (2012): Distinct modes of internal variability in the Global Meridional Overturning Circulation associated to the Southern Hemisphere westerly winds.- J. Phys. Oceanography 42: 785-801, doi: 10.1175/JPO-D-11-038.1.

Yamazaki, D., Kanae, S., Kim, H. & Oki, T. (2011): A physically based description of floodplain inundation dynamics in a global river routing model.- Water Resour. Res. 47: W04501, doi: 10.1029/2010WR009726.

Zhang, X., Lohmann, G., Knorr, G. & Xu, X. (2013): Different ocean states and transient characteristics in Last Glacial Maximum simulations and implications for deglaciation.- Clim. Past 9: 2319-2333, doi:10.5194/cp-9-2319-2013.

Zhang, X., Lohmann, G., Knorr, G. & Purcell, C. (2014): Abrupt glacial climate shifts controlled by ice sheet changes.- Nature 512: 290-294, doi: 10.1038/nature13592.