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Technical note: A hydrological routing scheme for the Ecosystem Demography model (ED2+R) tested in the Tapajós River basin in the Brazilian Amazon

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Abstract. Land surface models are excellent tools for studying how climate change and land use affect surface hydrology. However, in order to assess the impacts of Earth processes on river flows, simulated changes in runoff need to be routed through the landscape. In this technical note, we describe the integration of the Ecosystem Demography (ED2) model with a hydrological routing scheme. The purpose of the study was to create a tool capable of incorporating to hydrological predictions the terrestrial ecosystem responses to climate, carbon dioxide, and land-use change, as simulated with terrestrial biosphere models. The resulting ED2+R model calculates the lateral routing of surface and subsurface runoff resulting from the terrestrial biosphere models' vertical water balance in order to determine spatiotemporal patterns of river flows within the simulated region. We evaluated the ED2+R model in the Tapajós, a 476 674 km^2 river basin in the southeastern Amazon, Brazil. The results showed that the integration of ED2 with the lateral routing scheme results in an adequate representation (Nash–Sutcliffe efficiency up to 0.76, Kling–Gupta efficiency up to 0.86, Pearson's R up to 0.88, and volume ratio up to 1.06) of daily to decadal river flow dynamics in the Tapajós. These results are a consistent step forward with respect to the "no river representation" common among terrestrial biosphere models, such as the initial version of ED2.

1 Introduction

Understanding the impacts of deforestation (e.g., Lejeune et al., 2015; Medvigy et al., 2011; Andréassian, 2004) and climate change (e.g., Jiménez-Cisneros et al., 2014) on the Earth's water cycle has been a topic of substantial interest in recent years given its potential implications for ecosystems and society (e.g., Wohl et al., 2012; Brown et al., 2005). Analyses of climate change impacts on the Earth's water cycle increasingly use terrestrial biosphere models, which are capable of estimating changes in the vertical water balance as a function of climate forcing and/or land-use-induced changes in canopy structure and composition (Zulkafli et al., 2013). Terrestrial biosphere models actively used for hydrological and Earth system sciences include the Joint UK Land Environment Simulator (JULES) (Best et al., 2011; Clark et al., 2011), the Community Land Model (CLM) (Lawrence et al., 2011; Oleson et al., 2010), the Lund–Potsdam–Jena (LPJ) land model (Gerten et al., 2004; Sitch et al., 2003), the Max

Planck Institute MPI-JSBACH model (Vamborg et al., 2011; Raddatz et al., 2007), and the Integrated Biosphere Simulator (IBIS) (Kucharik et al., 2000).

Initial formulations of the hydrological processes within terrestrial biosphere models were based on simple "bucket" model formulations (Cox et al., 1999 after Carson, 1982). Moisture within each climatological grid cell of the domain was simulated in a single below-ground pool in which surface temperature and specific soil moisture factors determined evaporation, while runoff was equal to the bucket overflow (Cox et al., 1999; Carson, 1982). Recently, the hydrologic schemes within terrestrial biosphere models have become increasingly sophisticated. In the most recent generation of land surface models, water fluxes in and out of the soil column are vertically resolved and take into account feedback from the different components, for instance, through an explicit formulation of the soil–plant–atmosphere continuum. This enables the models to provide a detailed representation of the interactions between evapotranspiration, soil moisture, and runoff (Clark et al., 2015).

To couple the calculation of the one-dimensional water balance with the estimation of daily river flows, it is necessary to simulate multiple hydrological dynamics involved in the lateral flow propagation through the landscape, ideally including the most complex hydraulic features of floodplains, lakes, and wetlands (Yamazaki et al., 2011). The first step towards representing the finer-scale hydrodynamic processes responsible for patterns in river gauge observations is to consider the topographic and geomorphological features that control water flow (Arora et al., 1999). The coarse spatial resolution of regional land surface models, imposed by computational constraints, does not allow for proper simulation of the complex hydrological dynamics determined by fine-scale topography in river channels and floodplains (Yamazaki et al., 2011; Kauffeldt et al., 2016). However, the combination of the terrestrial models with routing schemes can be used to simulate the implications of global and regional environmental changes for flood/drought forecasting, water resources planning and management, and infrastructure development (Andersson et al., 2015). Consequently, several terrestrial biosphere models have been integrated with routing schemes. For example, JULES has been integrated with the Total Runoff Integrating Pathways (TRIP) to evaluate the accuracy of its estimates of annual streamflow (Oki et al., 1999). This integrated model was used to investigate the status of the global water budget (Oki et al., 2001). Rost et al. (2008) also used a modeling framework composed of the global dynamic vegetation model, LPJ, and a simple water balance model to quantify the global consumption of water for rain-fed and irrigated agriculture. An offline coupling of the dynamic vegetation model, ISIS, and HYDRA – which simulates the lateral transport of water through rivers, lakes, and wetlands – was proposed in Coe et al. (2008) with the purpose of reproducing linkages between land use, hydrology, and climate. Moreover, Liang et al. (1994) developed and tested the coupling of the well-known VIC model with a general circulation model (GCM) to improve the GCM's ability to capture the interactions between surface hydrology and atmosphere. For the same purpose, the MPI hydrological discharge model was validated with NCEP reanalysis and parameterized for simulating the river routing for climate analysis at global scale (Hagemann and Gates, 2001; Hagemann and Dumenil, 1997). Several routing schemes have been designed to date, including normal depth, modified pulse, simple Muskingum, and Muskingum–Cunge (USACE, 1991). Most notably, the semi-distributed kinematic wave-routing Muskingum–Cunge method has been recognized for its stability over different spatial and temporal modeling resolutions (USACE, 1991; Miller and Cunge, 1975; Cunge, 1969), and has been adopted by the most widely used regional-scale hydrological models, such as VIC, SWAT, and MGB-IPH.

Recent studies have investigated the influence of land use on regional patterns of rainfall and biosphere temperature (Ostberg et al., 2015; Bahn et al., 2014; Pearson et al., 2013). These studies tracked how the occurrence of conversion of land from its natural state over the same time frame as observed fluctuations of rainfall and air temperature occurred – aspects fully analyzed by terrestrial biosphere models (Hurtt et al., 2006; Goldewijk, 2001; Ramankutty and Foley, 1999). However, these models assumed that global and regional changes in the biosphere were a result of dynamics of vegetation in a collection of landscapes given by forests, deserts, and farmland only. Inland surface waters (e.g., rivers, lakes, and wetlands) were not considered as an interactive component of the biosphere and hence the climate system (Cole et al., 2007).

The Ecosystem Demography (ED2) is a terrestrial biosphere model that simulates the coupled water, carbon, and energy dynamics of terrestrial land surfaces (Longo, 2014; Medvigy et al., 2009; Moorcroft et al., 2001) to describe the coupled water, carbon, and energy dynamics of heterogeneous landscapes (Hurtt et al., 2013; Medvigy et al., 2009; Moorcroft et al., 2001). ED2's ability to incorporate sub-grid-scale ecosystem heterogeneity arising from land-use change makes the model suited for investigating how the combined impacts of changes in climate, atmospheric carbon dioxide concentrations, and land cover affect terrestrial ecosystems. For example, ED2 was successfully used to simulate the carbon flux dynamics in the North American continent (Hurtt et al., 2002; Albani et al., 2006) and to assess the impacts on Amazonian ecosystems of changes in climate, atmospheric carbon dioxide, and land use (Zhang et al., 2015). Moreover, ED2, coupled with a regional atmospheric circulation component, has also been successfully applied to assess the impacts of deforestation on the Amazonian climate (Knox et al., 2015; Swann et al., 2015). The aforementioned studies were not aimed at assessing hydrological implications of changes in land use and climate. These works demonstrated the validity of ED2 for assessing impacts of global and regional changes on ecosystem function and built

Figure 1. Schematic of the enthalpy fluxes (all arrows) and water fluxes (all but solid black arrows) that are solved in ED2. The schematic is based on Walko et al. (2000) and Medvigy et al. (2009). (Figure courtesy of Marcos Longo.)

the foundations for an integrated tool aimed at analyzing hydrological implications.

In this technical note, we describe the integration of ED2 with a hydrological routing scheme. The hydrological routing scheme chosen was adapted from the MGB-IPH (Collischonn et al., 2007). This exercise aims to calculate the lateral propagation and attenuation of the surface and subsurface runoff resulting from the vertical balance calculations in order to simulate daily river flows through a large river basin. The advantage of the proposed model is its ability to predict the sensitivity of river flows to global and regional environmental changes such as climate and land-use changes. The new product combines the advantages of biosphere and hydrological models, bringing together global-, regional-, and local-scale hydrological dynamics in a single modeling framework. The resulting model is intended to be used in future studies as a computational tool to explore a variety of research questions. In particular, it could be used to analyze how current and future climate and land cover affect water availability in river systems; how land-use-driven changes can influence the water availability for human activities (hydropower, food production, urban supply); and what the implications of those changes are for water and land resources management.

The identified research areas are in line with key problems raised in the literature, focusing on the importance of large-scale modeling and remote sensing to fill knowledge gaps in water resources and hydrological dynamics (Alsdorf et al., 2007; Prigent et al., 2007). The product obtained from this exercise was tested in the Tapajós Basin, a large river system in the southeastern Amazon, Brazil.

2 Ecosystem Demography (ED2) model

ED2 is a terrestrial biosphere simulation model capable of representing biological and physical processes driving the dynamics of ecosystems as a function of climate and soil properties. Rather than using a conventional "ecosystem as big-leaf" assumption, ED2 is formulated at the scale of functional and age groups of plants. Ecosystem-scale dynamics and fluxes are calculated through a scaling procedure which reproduces the macroscopic behavior of the ecosystem within each climatological grid cell. It simulates ecosystem structure and dynamics as well as the corresponding carbon, energy, and water fluxes (Fig. 1; Hurtt et al., 2013; Med-

Figure 4. (a) Organization of the Tapajós Basin into seven sub-basins: Upper Juruena (UJ); Lower Juruena (LJ); Upper Teles Pires (UTP); Lower Teles Pires (LTP); Jamanxim (JA); Upper Tapajós (UT); and Lower Tapajós (LT). (b) ED2CR represents the domain in grid cells with 0.5 resolution (55 km). The black segments indicate the flow accumulation network.

Soils vary from those typically seen in the Brazilian shield in the south of the basin to alluvial sediments in the north. Land use, almost completely represented by primary forest until the 1970s, was radically changed in recent decades. As estimated from the land-use/land-cover dataset used in this study (Hurtt et al., 2006), in the late 2000s only about 56 % of the basin (270 000 km^2) was covered by the original vegetation cover. Large parts of the basin lying in the territory of Mato Grosso were cleared to make room for agricultural and livestock production, while vast areas around the border between the state of Pará and Mato Grosso were cleared for cattle production. The northern portion of the basin is largely protected by natural parks or indigenous lands, but significant deforestation hotspots could be identified around the cities of Santarém and Itaituba and along the main transportation routes (Fig. 3c). For a more detailed description of the basin's physical characteristics and historical analysis of trends in deforestation, precipitation, and discharge, we refer the reader to Arias et al. (2017) and Farinosi et al. (2017).

For calibration purposes, the basin was divided into seven sub-basins, each of them with a corresponding gauge for which historical daily river flow observations were available (Fig. 4a). The domain was gridded with a spatial resolution of 0.5 by 0.5 , roughly corresponding to 55 km by 55 km. Simulations were carried out for the period 1970–2008. The ED2 model was forced using reconstructed climate (Sheffield et al., 2006) and land-use/land-cover data (Hurtt et al., 2006; Soares-Filho et al., 2006) at 1 spatial resolution. The original meteorological dataset has a 3 h temporal resolution, which was downscaled to an hourly resolution, as described in Zhang et al. (2015). In this technical note, we describe the calibration of the flow-routing component of ED2CR. The parameterization of the ED2 terrestrial biosphere model was developed and evaluated independently using eddy-flux tower observations of carbon, water, and energy fluxes and forest inventory observations of above-ground biomass dynamics. Further details are available in Zhang et al. (2015) and Longo (2014).

ED2CR model calibration

The ED2CR model was manually calibrated using gauge observations (ANA, 2016; Observation Service SO HYBAM, 2016) spanning a period of 17 years from 1976 to 1992 (the period 1970–1975 was not considered in order to avoid simulation initiation effects) through a two-step procedure, as highlighted in Fig. 2. The first step is partitioning the flows from the two reservoirs (surface and subsurface) of the ED2 biosphere model into the three reservoirs (surface, intermediate, base) of the ED2CR routed biosphere model (parameters

al., 2004). We believe that the error is arising from the complexities associated with deep soils present in the headwaters of the Tapajós Basin. In particular, in the model application developed, soil layers are represented to a depth of 6 m (Table 1), which might be too shallow to realistically represent the conditions in the headwaters of the basin. The importance of groundwater is also evident from the calibration of the residence time parameter of the subsurface water flow: as shown in Fig. 7, in fact, especially in the headwaters, even small variations in the CB parameter greatly affect the model performance (specifically quantified with NSE in Fig. 7). The combined effect of groundwater interactions and spatial resolution is more evident in the upstream sub-basins because of the greater marginal contribution of baseflow in these areas. Surface flow accumulation, in fact, is lower in the headwaters. Therefore, in relative terms, the role of baseflow is more relevant in this portion of any basin. Further downstream, the effect of groundwater interactions and spatial resolution is, at least in part, masked by the larger rainfall–runoff contribution and the overall flow accumulation from the upstream sub-basins. Other recent hydrological simulations of the Tapajós have obtained higher accuracy (e.g., Mohor et al., 2015; Collischonn et al., 2008; Coe et al., 2008); however, these simulations were set up discretizing the basin into a finer spatial resolution grid (9 to 20 km vs. ~ 55 km grid cells) and using hydrological tools able to reproduce highly detailed hydrodynamic characteristics of complex river systems (i.e., floodplain, lakes, wetlands, backwater effects) that are out of the scope of the tool presented in this study. The advantage of the ED2+R model is the ability to study the sensitivity of the river flows to global and regional changes as computed by traditional terrestrial biosphere models, but adding a more detailed hydrological feature with respect to a very simplistic- or no-river representation. The coarse spatial resolution of the global datasets used as input for ED2+R is, however, a limiting factor. Higher-resolution climatological data, vegetation, and land-use datasets, which would allow a finer resolution of the hydrological grid, are expected to improve the performance of the model by providing more detailed hydrological processes. On the other hand, a finer spatial resolution of the hydrological grid would also require a more detailed representation of the subsurface water in the model. In general, the tool can be used to study how different hydrological systems are being affected by changes in climate forcing and changes in ecosystem composition and structure arising from the combination of changing climate, rising atmospheric carbon dioxide, and land-use transformation. Additionally, ED2+R could potentially bridge one of the missing gaps for diagnosing and assessing feedback between atmosphere and biosphere with inland surface waters being represented as a dynamic system.

7 Conclusion

In this technical note, we present the integration of the terrestrial biosphere model Ecosystem Demography 2 (ED2) with the Muskingum–Cunge routing scheme. We tested the integrated model (ED2+R) in the Tapajós River basin, a large tributary of the Amazon in Brazil, for the period 1970–2008. The results showed that the integration of a biosphere model with a routing scheme improves the ability of the land surface simulation to reproduce the hydrological and river flow dynamics at the basin scale. The main limitations highlighted in this case study were linked to the relatively coarse spatial resolution of the model and the rough representation of subsurface water flow typical of these kinds of models. Moreover, the terrestrial biosphere model ED2 and the routing scheme are presented here in a one-way integration. The full coupling of the routing scheme and ED2 could further improve the tool's ability to reproduce the water balance considering flooded ecosystems, a relevant feature in the simulation of environments like the tropical forest, where local evapotranspiration plays a primary role in the specific ecosystem's dynamics. In this first integration, our goal was to give the terrestrial biosphere model the ability to reproduce river flows through a routing scheme. With a fully coupled (i.e., two-way) integration, the model would be able to determine the grid cells that are likely to be saturated and use this information for the modeling of the ecosystem's dynamics. For instance, this could determine the increase of the mortality rate of plants that are sensitive to inundation. An additional limitation of the model could be identified in its inability to reproduce highly detailed hydrological dynamics of complex river systems (as, for instance, floodplain hydraulic features or backwater effects). However, such a detailed hydrological complexity was out of the scope of this study. Future efforts will address the highlighted limitations, while upcoming studies will use ED2+R to understand historical changes and future projections of the impacts of climate change and deforestation on the Amazon's water resources.

Data availability. Meteorological forcing data are derived from Sheffield et al. (2006) – https://doi.org/10.1175/JCLI3790.1; land use data are derived from Hurtt et al. (2006) – https://doi.org/10.1111/j.1365-2486.2006.01150.x; topographic data are derived from the Shuttle Radar Topography Mission (SRTM) 90 m resolution (USGS, 2016); soil map is derived from Quesada et al. (2010) – https://doi.org/10.5194/bg-7-1515-2010 – and IGBP-DIS global soil data (Global Soil Data Task, 2014) – https://doi.org/10.3334/ORNLDAAC/565; geomorphological relations are obtained from Coe et al. (2008) – https://doi.org/10.1002/hyp.6850; streamflow observations are obtained from Observation Service SO HYBAM (2016) and ANA (2016).

Appendix A

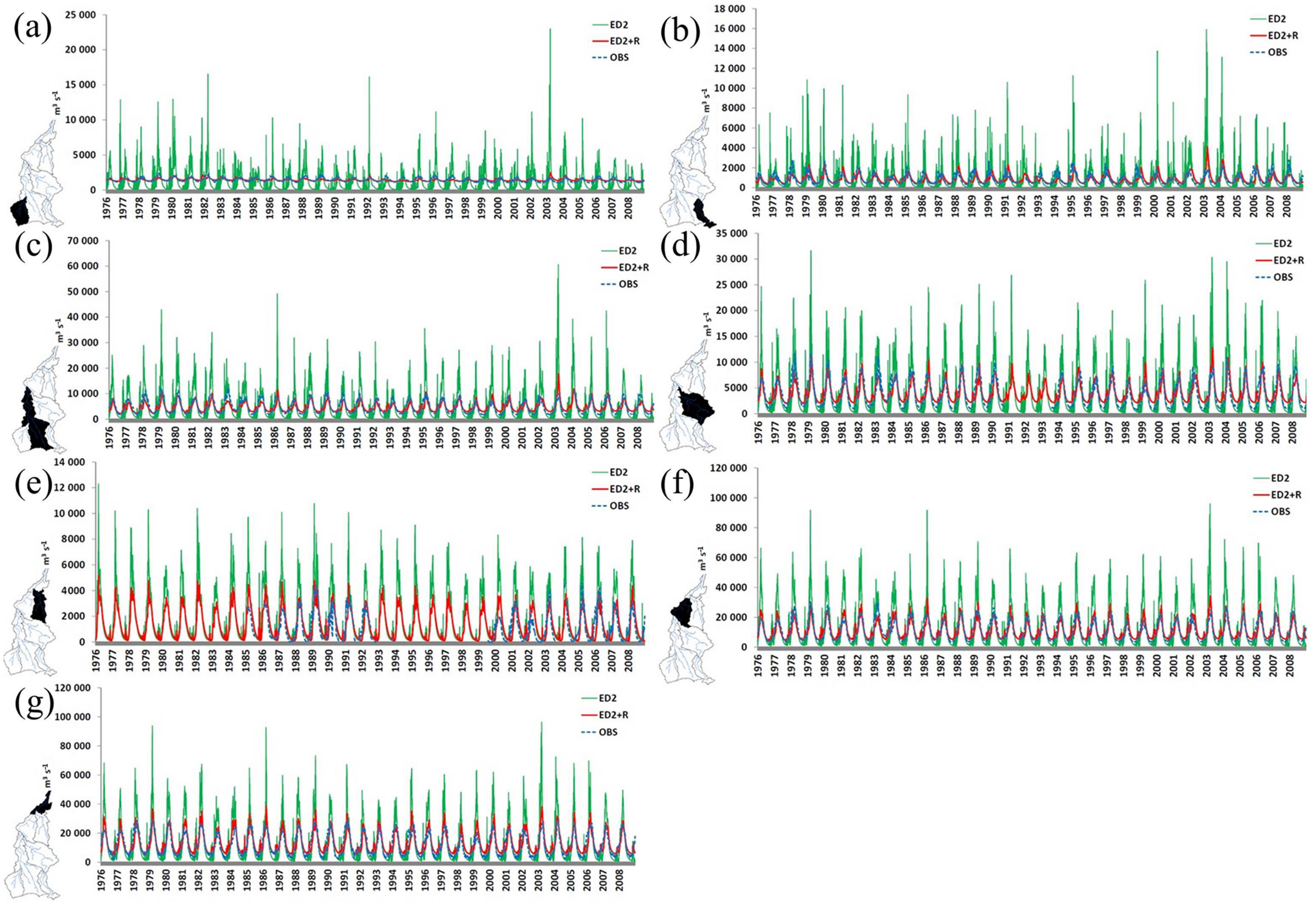

Figure A1. Time series of river flow ($m^3\,s^{-1}$) at the outlet of each sub-basins. ED2 output (green line), ED2+R (red line), and observations (blue dotted line). **(a)** Upper Juruena (UJ); **(b)** Upper Teles Pires (UTP); **(c)** Lower Juruena (LJ); **(d)** Lower Teles Pires (LTP); **(e)** Jamanxim (JA); **(f)** Upper Tapajós (UT); and **(g)** Lower Tapajós (LT).

Author contributions. FP, PM, and JB designed the study; FP developed the ED2+R model code; FF, MA, and EL calibrated the model and carried out the analysis; FF, MA, and PM wrote the paper.

Competing interests. The authors declare that they have no conflict of interest.

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References

Albani, M., Medvigy, D., Hurtt, G. C., and Moorcroft, P. R.: The contributions of land-use change, CO_2 fertilization, and climate variability to the Eastern US carbon sink, Glob. Change Biol., 12, 2370–2390, https://doi.org/10.1111/j.1365-2486.2006.01254.x, 2006.

Alsdorf, D. E., Rodríguez, E., and Lettenmaier, D. P.: Measuring surface water from space, Rev. Geophys., 45, RG2002, https://doi.org/10.1029/2006RG000197, 2007.

ANA: Plano Estratégico de Recursos Hídricos da Bacia Amazônica – Afluentes da Margem Direita, Brasilia, Brazil, Brazil, available at: http://margemdireita.ana.gov.br/ (last access: 7 September 2017), 2011 (in Portuguese).

ANA: Hidroweb –Sistema de informações hidrologicas, available from: http://www.snirh.gov.br/hidroweb/, (last access: 7 September 2017), 2016.

Anderson, E. A.: Calibration of Conceptual Models for Use in River Forecasting, available at: http://www.nws.noaa.gov/oh/hrl/calb/calibration1102/main.htm (last access: 7 September 2017), 2002.

Andersson, J. C. M., Pechlivanidis, I. G., Gustafsson, D., Donnelly, C., and Arheimer, B.: Key factors for improving large-scale hydrological model performance, Eur. Water, 49, 77–88, 2015.

Andréassian, V.: Waters and forests: from historical controversy to scientific debate, J. Hydrol., 291, 1–27, https://doi.org/10.1016/j.jhydrol.2003.12.015, 2004.

Arias, M. E., Lee, E., Farinosi, F., Pereira, F. F., Moorcroft, P. R., and Briscoe, J.: Decoupling the effects of deforestation and climate variability in large tropical river basins, J. Hydrol., in review, 2017.

Arora, V. K., Chiew, F. H. S., and Grayson, R. B.: A river flow routing scheme for general circulation models, J. Geophys. Res., 104, 14347, https://doi.org/10.1029/1999JD900200, 1999.

Bahn, M., Reichstein, M., Dukes, J. S., Smith, M. D., and McDowell, N. G.: Climate-biosphere interactions in a more extreme world, New Phytol., 202, 356–359, https://doi.org/10.1111/nph.12662, 2014.

Baker, T. R., Phillips, O. L., Malhi, Y., Almeida, S., Arroyo, L., Di Fiore, A., Erwin, T., Killeen, T. J., Laurance, S. G., Laurance, W. F., Lewis, S. L., Lloyd, J., Monteagudo, A., Neill, D. A., Patino, S., Pitman, N. C. A., Silva, J. N. M., and Vasquez Martinez, R.: Variation in wood density determines spatial patterns in Amazonian forest biomass, Glob. Change Biol., 10, 545–562, https://doi.org/10.1111/j.1365-2486.2004.00751.x, 2004.

Best, M. J., Pryor, M., Clark, D. B., Rooney, G. G., Essery, R. L. H., Ménard, C. B., Edwards, J. M., Hendry, M. A., Porson, A., Gedney, N., Mercado, L. M., Sitch, S., Blyth, E., Boucher, O., Cox, P. M., Grimmond, C. S. B., and Harding, R. J.: The Joint UK Land Environment Simulator (JULES), model description – Part 1: Energy and water fluxes, Geosci. Model Dev., 4, 677–699, https://doi.org/10.5194/gmd-4-677-2011, 2011.

Brown, A. E., Zhang, L., McMahon, T. A., Western, A. W., and Vertessy, R. A.: A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation, J. Hydrol., 310, 28–61, https://doi.org/10.1016/j.jhydrol.2004.12.010, 2005.

Calvo-Alvarado, J., McDowell, N., and Waring, R.: Allometric relationships predicting foliar biomass and leaf area: sapwood area ratio from tree height in five Costa Rican rain forest species, Tree Physiol., 11, 1601–1608, 2008.

Carson, D.: Current parametrisations of land-surface processes in atmospheric general circulation models, in: Land surface processes in atmospheric general circulation models, edited by: Eagleson, P., Cambridge University Press, Cambridge, UK, 1982.

Clark, D. B., Mercado, L. M., Sitch, S., Jones, C. D., Gedney, N., Best, M. J., Pryor, M., Rooney, G. G., Essery, R. L. H., Blyth, E., Boucher, O., Harding, R. J., Huntingford, C., and Cox, P. M.: The Joint UK Land Environment Simulator (JULES), model description – Part 2: Carbon fluxes and vegetation dynamics, Geosci. Model Dev., 4, 701–722, https://doi.org/10.5194/gmd-4-701-2011, 2011.

Clark, M. P., Fan, Y., Lawrence, D. M., Adam, J. C., Bolster, D., Gochis, D. J., Hooper, R. P., Kumar, M., Leung, L. R., Mackay, D. S., Maxwell, R. M., Shen, C., Swenson, S. C., and Zeng, X.: Improving the representation of hydrologic processes in Earth System Models, Water Resour. Res., 51, 5929–5956, https://doi.org/10.1002/2015WR017096, 2015.

Coe, M. T., Costa, M. H., and Howard, E. A.: Simulating the surface waters of the Amazon River basin: impacts of new river geomorphic and flow parameterizations, Hydrol. Process., 22, 2542–2553, https://doi.org/10.1002/hyp.6850, 2008.

Cole, J. J., Prairie, Y. T., Caraco, N. F., McDowell, W. H., Tranvik, L. J., Striegl, R. G., Duarte, C. M., Kortelainen, P., Downing, J. A., Middelburg, J. J., and Melack, J.: Plumbing the Global Carbon Cycle: Integrating Inland Waters into the Terrestrial Carbon Budget, Ecosystems, 10, 172–185, https://doi.org/10.1007/s10021-006-9013-8, 2007.

Cole, T. G. and Ewel, J. J.: Allometric equations for four valuable tropical tree species, For. Ecol. Manage., 229, 351–360, https://doi.org/10.1016/j.foreco.2006.04.017, 2006.

Collischonn, B., Collischonn, W., and Tucci, C. E. M.: Daily hydrological modeling in the Amazon basin using TRMM rainfall estimates, J. Hydrol., 360, 207–216, https://doi.org/10.1016/j.jhydrol.2008.07.032, 2008.

Collischonn, W., Allasia, D., Da Silva, B. C., and Tucci, C. E. M.: The MGB-IPH model for large-scale rainfall–runoff modelling, Hydrol. Sci. J., 52, 878–895, https://doi.org/10.1623/hysj.52.5.878, 2007.

Cox, P. M., Betts, R. A., Bunton, C. B., Essery, R. L. H., Rowntree, P. R., and Smith, J.: The impact of new land surface physics on the GCM simulation of climate and climate sensitivity, Clim. Dynam., 15, 183–203, https://doi.org/10.1007/s003820050276, 1999.

Cunge, J. A.: On The Subject Of A Flood Propagation Computation Method (Musklngum Method), J. Hydraul. Res., 7, 205–230, https://doi.org/10.1080/00221686909500264, 1969.

Farinosi, F., Arias, M. E., Lee, E., Longo, M., Pereira, F. F., Livino, A., Moorcroft, P. R., and Briscoe, J.: Future climate and land use change impacts on river flows in the Tapajós Basin in the Brazilian Amazon, Earth's Future, in review, 2017.

Gerten, D., Schaphoff, S., Haberlandt, U., Lucht, W., and Sitch, S.: Terrestrial vegetation and water balance – hydrological evaluation of a dynamic global vegetation model, J. Hydrol., 286, 249–270, https://doi.org/10.1016/j.jhydrol.2003.09.029, 2004.

Global Soil Data Task: Global Soil Data Products CD-ROM Contents (IGBP-DIS), Data Set, Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA, https://doi.org/10.3334/ORNLDAAC/565, 2014.

Goldewijk, K. K.: Estimating global land use change over the past 300 years: The HYDE Database, Global Biogeochem. Cy., 15, 417–433, https://doi.org/10.1029/1999GB001232, 2001.

Gupta, H. V., Kling, H., Yilmaz, K. K., and Martinez, G. F.: Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling, J. Hydrol., 377, 80–91, https://doi.org/10.1016/j.jhydrol.2009.08.003, 2009.

Hagemann, S. and Dumenil, L.: A parametrization of the lateral waterflow for the global scale, Clim. Dynam., 14, 17–31, https://doi.org/10.1007/s003820050205, 1997.

Hagemann, S. and Gates, L. D.: Validation of the hydrological cycle of ECMWF and NCEP reanalyses using the MPI hydrological discharge model, J. Geophys. Res., 106, 1503, https://doi.org/10.1029/2000JD900568, 2001.

Hurtt, G. C., Pacala, S. W., Moorcroft, P. R., Caspersen, J., Shevliakova, E., Houghton, R. A., and Moore, B.: Projecting the future of the U.S. carbon sink, P. Natl. Acad. Sci. USA, 99, 1389–1394, https://doi.org/10.1073/pnas.012249999, 2002.

Hurtt, G. C., Frolking, S., Fearon, M. G., Moore, B., Shevliakova, E., Malyshev, S., Pacala, S. W., and Houghton, R. A.: The underpinnings of land-use history: three centuries of global gridded land-use transitions, wood-harvest activity, and resulting secondary lands, Glob. Chang. Biol., 12, 1208–1229, https://doi.org/10.1111/j.1365-2486.2006.01150.x, 2006.

Hurtt, G. C., Moorcroft, P. R., and Pacala, S. W.: Ecosystem Demography Model: Scaling Vegetation Dynamics Across South America, Ecosyst. Demogr. Model Scaling Veg. Dyn. Across South Am. Model Prod., available at: http://daac.ornl.gov/MODELS/guides/EDM_SA_Vegetation.html (last access: 7 September 2017), 2013.

Jiménez-Cisneros, B. E., Oki, T., Arnell, N. W., Benito, G., Cogley, J. G., Döll, P., Jiang, T., and Mwakalila, S. S.: Freshwater resources, in: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Field, C. B., Barros, V. R., Dokken, D. J., Mach, K. J., Mastrandrea, M. D., Bilir, T. E., Chatterjee, M., Ebi, K. L., Estrada, Y. O., Genova, R. C., Girma, B., Kissel, E. S., Levy, A. N., MacCracken, S., Mastrandrea, P. R., and White, L. L., 229–269, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, available at: https://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-Chap3_FINAL.pdf (last access: 7 September 2017), 2014.

Kauffeldt, A., Wetterhall, F., Pappenberger, F., Salamon, P., and Thielen, J.: Technical review of large-scale hydrological models for implementation in operational flood forecasting schemes on continental level, Environ. Model. Softw., 75, 68–76, https://doi.org/10.1016/j.envsoft.2015.09.009, 2016.

Kim, Y., Knox, R. G., Longo, M., Medvigy, D., Hutyra, L. R., Pyle, E. H., Wofsy, S. C., Bras, R. L., and Moorcroft, P. R.: Seasonal carbon dynamics and water fluxes in an Amazon rainforest, Glob. Change Biol., 18, 1322–1334, https://doi.org/10.1111/j.1365-2486.2011.02629.x, 2012.

Kling, H., Fuchs, M., and Paulin, M.: Runoff conditions in the upper Danube basin under an ensemble of climate change scenarios, J. Hydrol., 424–425, 264–277, https://doi.org/10.1016/j.jhydrol.2012.01.011, 2012.

Knox, R. G.: Land Conversion in Amazonia and Northern South America: Influences on Regional Hydrology and Ecosystem Response, PhD Thesis, Massachusetts Institute of Technology, available at: https://dspace.mit.edu/handle/1721.1/79489 (last access: 7 September 2017), 2012.

Knox, R. G., Longo, M., Swann, A. L. S., Zhang, K., Levine, N. M., Moorcroft, P. R., and Bras, R. L.: Hydrometeorological effects of historical land-conversion in an ecosystem-atmosphere model of Northern South America, Hydrol. Earth Syst. Sci., 19, 241–273, https://doi.org/10.5194/hess-19-241-2015, 2015.

Kucharik, C. J., Foley, J. A., Delire, C., Fisher, V. A., Coe, M. T., Lenters, J. D., Young-Molling, C., Ramankutty, N., Norman, J. M., and Gower, S. T.: Testing the performance of a dynamic global ecosystem model: Water balance, carbon balance, and vegetation structure, Global Biogeochem. Cy., 14, 795–825, https://doi.org/10.1029/1999GB001138, 2000.

Lawrence, D. M., Oleson, K. W., Flanner, M. G., Thornton, P. E., Swenson, S. C., Lawrence, P. J., Zeng, X., Yang, Z.-L., Levis, S., Sakaguchi, K., Bonan, G. B., and Slater, A. G.: Parameterization improvements and functional and structural advances in Version 4 of the Community Land Model, J. Adv. Model. Earth Syst., 3, M03001, https://doi.org/10.1029/2011MS000045, 2011.

Lejeune, Q., Davin, E. L., Guillod, B. P., and Seneviratne, S. I.: Influence of Amazonian deforestation on the future evolution of regional surface fluxes, circulation, surface temperature and precipitation, Clim. Dynam., 44, 2769–2786, https://doi.org/10.1007/s00382-014-2203-8, 2015.

Li, R., Chen, Q., and Ye, F.: Modelling the impacts of reservoir operations on the downstream riparian vegetation and fish habitats in the Lijiang River, J. Hydroinformatics, 13, 229, https://doi.org/10.2166/hydro.2010.008, 2011.

Liang, X., Lettenmaier, D. P., Wood, E. F., and Burges, S. J.: A simple hydrologically based model of land surface water and energy fluxes for general circulation model, J. Geophys. Res., 99, 14415–14428, 1994.

Lobligeois, F., Andréassian, V., Perrin, C., Tabary, P., and Loumagne, C.: When does higher spatial resolution rainfall information improve streamflow simulation? An evaluation using 3620 flood events, Hydrol. Earth Syst. Sci., 18, 575–594, https://doi.org/10.5194/hess-18-575-2014, 2014.

Longo, M.: Amazon Forest Response to Changes in Rainfall Regime: Results from an Individual-Based Dynamic Vegetation Model, Harvard University, available at: http://dash.harvard.edu/handle/1/11744438 (last access: 7 September 2017), 2014.

Medvigy, D., Wofsy, S. C., Munger, J. W., Hollinger, D. Y., and Moorcroft, P. R.: Mechanistic scaling of ecosystem function and dynamics in space and time: Ecosystem Demography model version 2, J. Geophys. Res.-Biogeo., 114, G01002, https://doi.org/10.1029/2008JG000812, 2009.

Medvigy, D., Walko, R. L., and Avissar, R.: Effects of Deforestation on Spatiotemporal Distributions of Precipitation in South America, J. Climate, 24, 2147–2163, https://doi.org/10.1175/2010JCLI3882.1, 2011.

Miller, W. A. and Cunge, J. A.: Simplified equations of unsteady flow, in: Unsteady Flow in Open Channels, edited by: Mahmood, K. and Yevjevich, V., Colorado State University, Water Resources Publication, Fort Collins, CO, USA, 1975.

Mohor, G. S., Rodriguez, D. A., Tomasella, J., and Siqueira Júnior, J. L.: Exploratory analyses for the assessment of climate change impacts on the energy production in an Amazon run-of-river hydropower plant, J. Hydrol. Reg. Stud., 4, 41–59, https://doi.org/10.1016/j.ejrh.2015.04.003, 2015.

Moorcroft, P. R., Hurtt, G. C., and Pacala, S. W.: A method for scaling vegetation dynamics: The ecosystem demography model (ED), Ecol. Monogr., 71, 557–586, https://doi.org/10.1890/0012-9615(2001)071[0557:AMFSVD]2.0.CO;2, 2001.

Nash, E. and Sutcliffe, V.: River flow forecasting Through conceptual models PART I- A Discussion of principles, J. Hydrol., 10, 282–290, 1970.

Observation Service SO HYBAM: SO HYBAM – Geodynamical, hydrological and biogeochemical control of erosion/alteration and material transport in the Amazon, Orinoco and Congo basins, available from: http://www.ore-hybam.org/index.php/eng, (last access: 7 September 2017), 2016.

Oki, T., Nishimura, T., and Dirmeyer, P.: Assessment of Annual Runoff from Land Surface Models Using Total Runoff Integrating Pathways (TRIP), J. Meteorol. Soc. Japan, 77, 235–255, 1999.

Oki, T., Agata, Y., Kanae, S., Saruhashi, T., Yang, D., and Musiake, K.: Global assessment of current water resources using total runoff integrating pathways, Hydrol. Sci. J., 46, 983–995, https://doi.org/10.1080/02626660109492890, 2001.

Oleson, K. W., Lawrence, D. M., Bonan, G. B., Flanner, M. G., Kluzek, E., Lawrence, P. J., Levis, S., Swenson, S. C., and Thornton, P. E.: Technical Description of version 4.0 of the Community Land Model (CLM), Boulder, CO, USA, available at: http://www.cesm.ucar.edu/models/cesm1.0/clm/CLM4_Tech_Note.pdf (last access: 7 September 2017), 2010.

Ostberg, S., Schaphoff, S., Lucht, W., and Gerten, D.: Three centuries of dual pressure from land use and climate change on the biosphere, Environ. Res. Lett., 10, 044011, https://doi.org/10.1088/1748-9326/10/4/044011, 2015.

Paiva, R. C. D., Collischonn, W., and Tucci, C. E. M.: Large scale hydrologic and hydrodynamic modeling using limited data and a GIS based approach, J. Hydrol., 406, 170–181, https://doi.org/10.1016/j.jhydrol.2011.06.007, 2011.

Paiva, R. C. D., Buarque, D. C., Collischonn, W., Bonnet, M. P., Frappart, F., Calmant, S., and Bulhões Mendes, C. A.: Large-scale hydrologic and hydrodynamic modeling of the Amazon River basin, Water Resour. Res., 49, 1226–1243, https://doi.org/10.1002/wrcr.20067, 2013a.

Paiva, R. C. D., Collischonn, W., and Buarque, D. C.: Validation of a full hydrodynamic model for large-scale hydrologic modelling in the Amazon, Hydrol. Process., 27, 333–346, https://doi.org/10.1002/hyp.8425, 2013b.

Paz, A. R., Collischonn, W., and Lopes da Silveira, A. L.: Improvements in large-scale drainage networks derived from digital elevation models, Water Resour. Res., 42, W08502, https://doi.org/10.1029/2005WR004544, 2006.

Pearson, K.: Note on regression and inheritance in the case of two parents, Proc. R. Soc. London, 58, 240–242, https://doi.org/10.1098/rspl.1895.0041, 1895.

Pearson, R. G., Phillips, S. J., Loranty, M. M., Beck, P. S. A., Damoulas, T., Knight, S. J., and Goetz, S. J.: Shifts in Arctic vegetation and associated feedbacks under climate change, Nat. Clim. Chang., 3, 673–677, https://doi.org/10.1038/nclimate1858, 2013.

Pontes, P. R. M., Collischonn, W., Fan, F. M., Paiva, R. C. D., and Buarque, D. C.: Modelagem hidrológica e hidráulica de grande escala com propagação inercial de vazões, Rev. Bras. Recur. Hídricos, 20, 888–904, 2015.

Poorter, L., Bongers, L., and Bongers, F.: Architecture of 54 moist-forest tree species: traits, trade-offs, and functional groups, Ecology, 87, 1289–1301, https://doi.org/10.1890/0012-9658(2006)87[1289:AOMTST]2.0.CO;2, 2006.

Prigent, C., Papa, F., Aires, F., Rossow, W. B., and Matthews, E.: Global inundation dynamics inferred from multiple satellite observations, 1993–2000, J. Geophys. Res., 112, D12107, https://doi.org/10.1029/2006JD007847, 2007.

Quesada, C. A., Lloyd, J., Schwarz, M., Patiño, S., Baker, T. R., Czimczik, C., Fyllas, N. M., Martinelli, L., Nardoto, G. B., Schmerler, J., Santos, A. J. B., Hodnett, M. G., Herrera, R., Luizão, F. J., Arneth, A., Lloyd, G., Dezzeo, N., Hilke, I., Kuhlmann, I., Raessler, M., Brand, W. A., Geilmann, H., Moraes Filho, J. O., Carvalho, F. P., Araujo Filho, R. N., Chaves, J. E., Cruz Junior, O. F., Pimentel, T. P., and Paiva, R.: Variations in chemical and physical properties of Amazon forest soils in relation to their genesis, Biogeosciences, 7, 1515–1541, https://doi.org/10.5194/bg-7-1515-2010, 2010.

Raddatz, T. J., Reick, C. H., Knorr, W., Kattge, J., Roeckner, E., Schnur, R., Schnitzler, K.-G., Wetzel, P., and Jungclaus, J.: Will the tropical land biosphere dominate the climate–carbon cycle feedback during the twenty-first century?, Clim. Dynam., 29, 565–574, https://doi.org/10.1007/s00382-007-0247-8, 2007.

Ramankutty, N. and Foley, J. A.: Estimating historical changes in global land cover: Croplands from

1700 to 1992, Global Biogeochem. Cy., 13, 997–1027, https://doi.org/10.1029/1999GB900046, 1999.

Reed, S. M.: Deriving flow directions for coarse-resolution (1–4 km) gridded hydrologic modeling, Water Resour. Res., 39, SWC 4, https://doi.org/10.1029/2003WR001989, 2003.

Rost, S., Gerten, D., Bondeau, A., Lucht, W., Rohwer, J., and Schaphoff, S.: Agricultural green and blue water consumption and its influence on the global water system, Water Resour. Res., 44, W09405, https://doi.org/10.1029/2007WR006331, 2008.

Sheffield, J., Goteti, G., and Wood, E. F.: Development of a 50-Year High-Resolution Global Dataset of Meteorological Forcings for Land Surface Modeling, J. Climate, 19, 3088–3111, https://doi.org/10.1175/JCLI3790.1, 2006.

Sitch, S., Smith, B., Prentice, I. C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J. O., Levis, S., Lucht, W., Sykes, M. T., Thonicke, K., and Venevsky, S.: Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model, Glob. Change Biol., 9, 161–185, https://doi.org/10.1046/j.1365-2486.2003.00569.x, 2003.

Smith, M. B., Koren, V. I., Zhang, Z., Reed, S. M., Pan, J.-J., and Moreda, F.: Runoff response to spatial variability in precipitation: an analysis of observed data, J. Hydrol., 298, 267–286, https://doi.org/10.1016/j.jhydrol.2004.03.039, 2004.

Soares-Filho, B. S., Nepstad, D. C., Curran, L. M., Cerqueira, G. C., Garcia, R. A., Ramos, C. A., Voll, E., McDonald, A., Lefebvre, P., and Schlesinger, P.: Modelling conservation in the Amazon basin, Nature, 440, 520–523, https://doi.org/10.1038/nature04389, 2006.

Swann, A. L. S., Longo, M., Knox, R. G., Lee, E., and Moorcroft, P. R.: Future deforestation in the Amazon and consequences for South American climate, Agric. For. Meteorol., 214–215, 12–24, https://doi.org/10.1016/j.agrformet.2015.07.006, 2015.

USACE: A Muskingum-Cunge Channel Flow Routing Method for Drainage Networks, available at: http://www.hec.usace.army.mil/publications/TechnicalPapers/TP-135.pdf (last access: 7 September 2017), 1991.

USGS: Shuttle Radar Topography Mission (SRTM), available from: https://lta.cr.usgs.gov/SRTM1Arc, (last access: 7 September 2017), 2016.

Vamborg, F. S. E., Brovkin, V., and Claussen, M.: The effect of a dynamic background albedo scheme on Sahel/Sahara precipitation during the mid-Holocene, Clim. Past, 7, 117–131, https://doi.org/10.5194/cp-7-117-2011, 2011.

Walko, R. L., Band, L. E., Baron, J., Kittel, T. G. F., Lammers, R., Lee, T. J., Ojima, D., Pielke, R. A., Taylor, C., Tague, C., Tremback, C. J., and Vidale, P. L.: Coupled Atmosphere–Biophysics–Hydrology Models for Environmental Modeling, J. Appl. Meteorol., 39, 931–944, https://doi.org/10.1175/1520-0450(2000)039<0931:CABHMF>2.0.CO;2, 2000.

Wohl, E., Barros, A., Brunsell, N., Chappell, N. A., Coe, M., Giambelluca, T., Goldsmith, S., Harmon, R., Hendrickx, J. M. H., Juvik, J., McDonnell, J., and Ogden, F.: The hydrology of the humid tropics, Nat. Clim. Chang., 2, 655–662, https://doi.org/10.1038/nclimate1556, 2012.

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

Zambrano-Bigiarini, M.: hydroGOF: Goodness-of-fit functions for comparison of simulated and observed hydrological time series. R package version 0.3–8, available at: http://cran.r-project.org/package=hydroGOF (last access: 7 September 2017), 2014.

Zhang, K., de Almeida Castanho, A. D., Galbraith, D. R., Moghim, S., Levine, N. M., Bras, R. L., Coe, M. T., Costa, M. H., Malhi, Y., Longo, M., Knox, R. G., McKnight, S., Wang, J., and Moorcroft, P. R.: The fate of Amazonian ecosystems over the coming century arising from changes in climate, atmospheric CO_2, and land use, Glob. Change Biol., 21, 2569–2587, https://doi.org/10.1111/gcb.12903, 2015.

Zulkafli, Z., Buytaert, W., Onof, C., Lavado, W., and Guyot, J. L.: A critical assessment of the JULES land surface model hydrology for humid tropical environments, Hydrol. Earth Syst. Sci., 17, 1113–1132, https://doi.org/10.5194/hess-17-1113-2013, 2013.