Empirical Glacier Mass-Balance Models for South America - Supplementary Material

Sebastian G. MUTZ,[1] Johannes ASCHAUER[1*]

[1] *Department of Geosciences, University of Tübingen, Germany*

Correspondence: Sebastian Mutz <sebastian.mutz@uni-tuebingen.de>

EMPIRICAL GLACIER MASS-BALANCE MODEL APPLICATION EXAMPLE

Forcing with CMIP5 - MPI-ESM-MR Simulations

The fifth phase of the Coupled Model Intercomparison Project (CMIP5) provides a framework for a series of climate change experiments (Taylor and others, 2011) based on different atmospheric forcing scenarios or representative concentration pathways (RCPs) (van Vuuren and others, 2011). Experiments conducted with the mixed resolution version of the Max-Planck-Institute's Earth System Model (MPI-ESM-MR) model (Giorgetta and others, 2013) provide the basis for an application example for the constructed empirical glacier mass-balance models (EGMs). More specifically, the EGMs of this study are applied to predictors that are reconstructed from MPI-ESM-MR simulations forced with three RCPs (RCP2.6, RCP4.5 and RCP8.5). Monthly averaged data is bilinerarly interpolated onto the same 0.75° x 0.75° grid as the ERA-Interrim dataset and used for the reconstructions of predictors. The EGM predictions are calibrated for the temporal overlap between simulation and ERA-Interim data, thus correcting for the bias between them.

Predictions of Mass-Balance Changes

EGM-based estimates forced with ERA-Interim data mostly follow the trend of measured cumulative annual mass-balance (B_a) changes in the observed time period (Fig. 1a in supplemental material). The predictions forced with ERA-Interim follow the trend of the observed mass-balance time series well for most glaciers. The calibrated EGM-based estimates forced with the RCPs (Fig. 1b-d, supplemental material) show significant variation, but the predominantly negative observed trend is predicted to continue into the 21st century for most glaciers. While this is the case for all RCPs, the most severe mass losses are

*now at the WSL Institute for Snow and Avalanche Research SLF , Switzerland

predicted for the RCP8.5 forcing. In the period from 2006 to 2100, the average cumulative mass-balance decrease is ∼65 m w.e. for RCP2.6, ∼75 m w.e. for RCP4.5 and ∼90 m w.e. for RCP8.5. Glaciers Los Amarillos (LAM), Amarillo (AMA) and Martial Este (MAR) generally show little change in mass over this time period. The cumulative mass-balance changes of glaciers MAR, Guanaco (GUA), Piloto Este (PIL) and Brown Superior (BRO) are similar for the different emission scenarios. The glaciers Zongo (ZON), Charquini Sur (CHS), Echaurren Norte (ECH) show increasing mass-balance loss with higher greenhouse gas concentrations (RCP4.5 and RCP8.5). Glacier AMA has a less negative or even positive mass-balance trend for higher greenhouse gas concentrations.

Discussion of the Application Example

The estimates for future mass-balance changes are based on our EGMs and predictors reconstructed from CMIP5 MPI-ESM-MR simulations forced with different RCPs. By the end of the century, all three senarios considered in this application example (RCP2.6, RCP4.5 and RCP8.5) result in the severe diminishment or disappearance of several glaciers, such as ECH. Since the predicted mass loss exceeds the current dimensions for several glaciers, they would disappear before the end of the century. The slightly positive trend of AMA for RCP8.5 may be attributed to an intensification of the Antarctic Oscillation (AAO), which has previously been noted for RCP8.5 simulations (Zheng and others, 2013), since zonal wind at 850 hPa (u) and Antarctic Oscillation Index (aaoi) are chosen as the primary predictors for mass-balance changes of AMA and both are a measure of AAO activity in the region. While the predominantly negative mass-balance trend in the 21st century is in agreement with the results of previous modelling efforts for glaciers in South America (Réveillet and others, 2015; Buttstädt and others, 2009; Schaefer and others, 2013; Marzeion and others, 2012), these predictions should merely be regarded as an application demonstration. Since our EGMs are unable to produce a dynamic response to climate change (see *Limitations and Suggestions* in the main manuscript), they are still unsuitable for such long-term predictions.

Caveats

In addition to the general limitations of the EGMs highlighted in the main manuscript, a source of uncertainty for the 21st century predictions is the general accuracy of general circulation model (GCM) simulations and the representation of chosen predictors in the GCMs. The representation of El Niño-Southern Oscillation (ENSO) in GCMs remains partially poor (e.g. Bellenger and others, 2014) and therefore com-

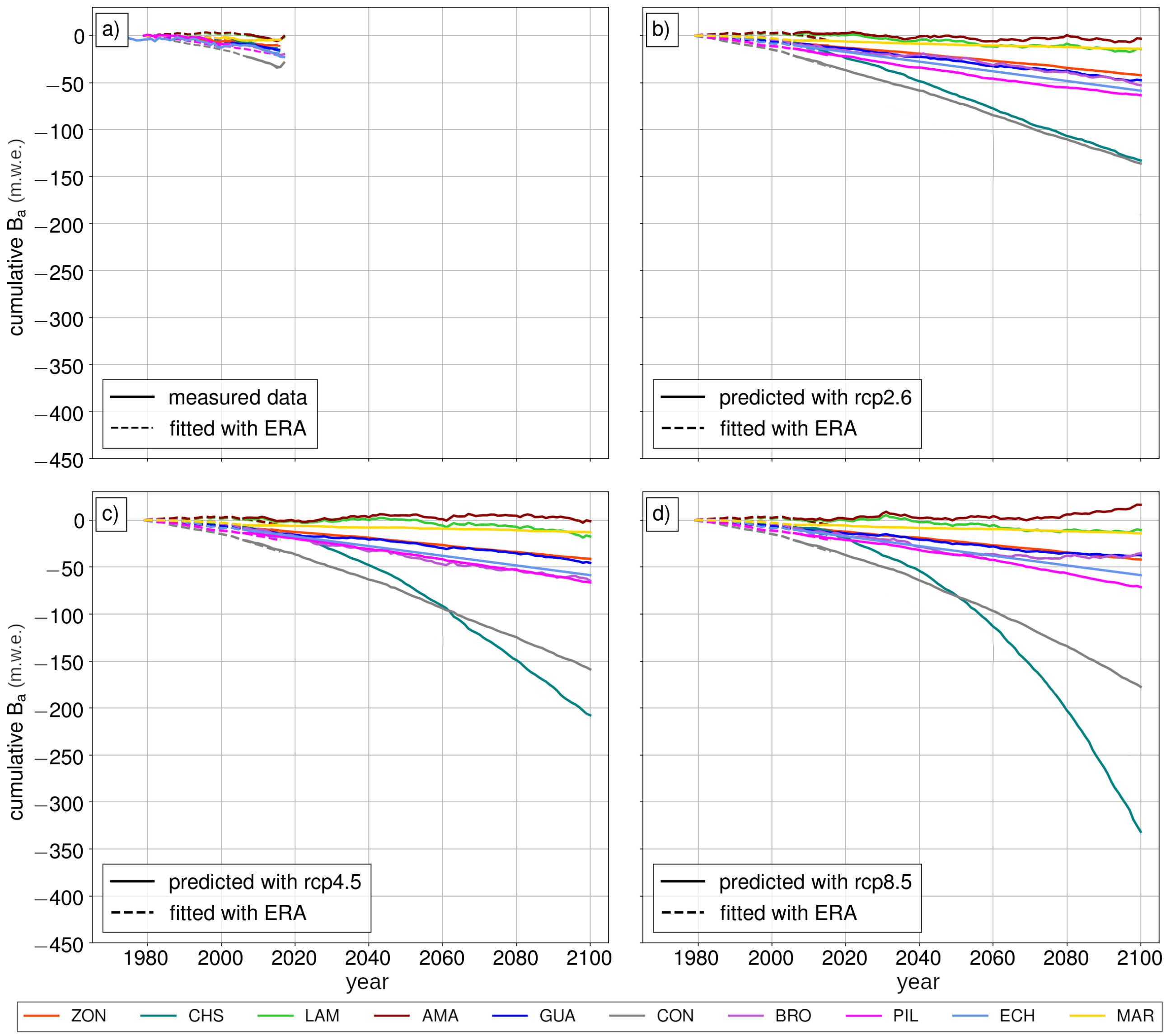

Fig. 1. Cumulative annual mass-balances of all glaciers until 2100. Dashed lines are the fitted values from ERA-Interim. Solid lines are a) measured mass-balance data and b-d) predicted values from the calibrated models forced with b) RCP2.6, c) RCP4.5 and d) RCP8.5 climate simulations. Predictions (for end-of-century positive mass balance in particular) are very likely biased as glacier dynamics and topographical feedback are not implemented in our EGMs.

promises predictions for the outer tropics in particular. Furthermore, our predictions (for end-of-century positive mass balance in particular) are very likely biased as glacier dynamics and topographical feedback are not implemented in our EGMs. The reader is advised to carefully consider these limitation and individual model performance scores before using the EGMs, and to treat our 21st century predictions as an example application rather than reliable predictions of the glaciological response to climate change in South America.

REFERENCES

Bellenger H, Guilyardi E, Leloup J, Lengaigne M and Vialard J (2014) Enso representation in climate models: from cmip3 to cmip5. *Climate Dynamics*, **42**(18), pages 1999–2018, ISSN 1999–2018 (doi: 10.1007/s00382-013-1783-z)

Buttstädt M, Möller M, Iturraspe R and Schneider C (2009) Mass balance evolution of Martial Este Glacier, Tierra del Fuego (Argentina) for the period 1960–2099. *Advances in Geosciences*, **22**, 117–124, ISSN 1680-7359 (doi: 10.5194/adgeo-22-117-2009)

Giorgetta MA, Jungclaus J, Reick CH, Legutke S, Bader J, Böttinger M, Brovkin V, Crueger T, Esch M, Fieg K, Glushak K, Gayler V, Haak H, Hollweg HD, Ilyina T, Kinne S, Kornblueh L, Matei D, Mauritsen T, Mikolajewicz U, Mueller W, Notz D, Pithan F, Raddatz T, Rast S, Redler R, Roeckner E, Schmidt H, Schnur R, Segschneider J, Six KD, Stockhause M, Timmreck C, Wegner J, Widmann H, Wieners KH, Claussen M, Marotzke J and Stevens B (2013) Climate and carbon cycle changes from 1850 to 2100 in MPI-ESM simulations for the Coupled Model Intercomparison Project phase 5. *Journal of Advances in Modeling Earth Systems*, **5**(3), 572–597, ISSN 1942-2466 (doi: 10.1002/jame.20038)

Marzeion B, Jarosch AH and Hofer M (2012) Past and future sea-level change from the surface mass balance of glaciers. *The Cryosphere*, **6**(6), 1295–1322, ISSN 1994-0424 (doi: 10.5194/tc-6-1295-2012)

Réveillet M, Rabatel A, Gillet-Chaulet F and Soruco A (2015) Simulations of changes to Glaciar Zongo, Bolivia (16° S), over the 21st century using a 3-D full-Stokes model and CMIP5 climate projections. *Annals of Glaciology*, **56**(70), 89–97, ISSN 0260-3055, 1727-5644 (doi: 10.3189/2015AoG70A113)

Schaefer M, Machguth H, Falvey M and Casassa G (2013) Modeling past and future surface mass balance of the Northern Patagonia Icefield. *Journal of Geophysical Research: Earth Surface*, **118**(2), 571–588, ISSN 2169-9011 (doi: 10.1002/jgrf.20038)

Taylor KE, Stouffer RJ and Meehl GA (2011) An Overview of CMIP5 and the Experiment Design. *Bulletin of the American Meteorological Society*, **93**(4), 485–498, ISSN 0003-0007 (doi: 10.1175/BAMS-D-11-00094.1) van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Hurtt GC, Kram T, Krey V, Lamarque JF, Masui T, Meinshausen M, Nakicenovic N, Smith SJ and Rose SK (2011) The representative concentration pathways: An overview. *Climatic Change*, **109**(1), 5, ISSN 1573-1480 (doi: 10.1007/s10584-011-0148-z)

Zheng F, Li J, Clark RT and Nnamchi HC (2013) Simulation and Projection of the Southern Hemisphere Annular Mode in CMIP5 Models. *Journal of Climate*, **26**(24), 9860–9879, ISSN 0894-8755 (doi: 10.1175/JCLI-D-13-00204.1)