



Crystal balls into the future: are global circulation and water balance models ready?

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Abstract. Variabilities and changes due to natural and anthropogenic causes in the water cycle always presented a challenge for water management planning. Practitioners traditionally coped with variabilities in the hydrological processes by assuming stationarity in the probability distributions and attempted to address non-stationarity by revising this probabilistic properties via continued hydro-climatological observations. Recently, this practice was questioned and more reliance on Global Circulation Models was put forward as an alternative for water management planning.

This paper takes a brief assessment of the state of Global Circulation Models (GCM) and their applications by presenting case studies over Global, European and African domains accompanied by literature examples. Our paper demonstrates core deficiencies in GCM based water resources assessments and articulates the need for improved Earth system monitoring that is essential not only for water managers, but to aid the improvements of GCMs in the future.

1 Introduction

Climate and direct anthropogenic change altering the water cycle has called into question the traditional water management planning that is based on past records of water resources as a means to characterize the likelihood of extreme conditions affecting water availabilities (Milly et al., 2008). The suggested alternative is relying on complex water balance simulations driven by projected climate forcings from global circulation models (GCM).

Hydrologists recognized long ago that the stationarity assumption is often violated due to changes other than climate (e.g. land cover and land use change, engineering alteration of the river channel, constructions of reservoirs, etc.). Water managers were very much aware of the need to test the statistical homogeneity of past observations (Lins and Cohn, 2011) and adjust the long-term characterization of the water

resources and extremes according to the anticipated changes in trends. The scientific challenge is if new techniques involving GCM simulations are indeed necessary or as Lins and Cohn (2011) expressed “humility may be more important than physics; a simple model with well-understood flaws may be preferable to a sophisticated model whose correspondence to reality is uncertain.”

A growing number of institutions run GCMs and use dynamical downscaling of GCM with Regional Climate Models (GCM-RCM) to produce large sets of projections for both present climate and future scenarios. The resulting datasets are expected to thoroughly sample the climate system phase space, where each simulation corresponds to different trajectory, starting from different initial conditions and determined by different choices of model parameters and structural uncertainties. Coordinated efforts such as the Coupled Model Intercomparison Project (CMIP) offers a collection of stan-

standardized GCM simulations that are the backbone of the regularly revised assessment reports of the Intergovernmental Panel on Climate Change (IPCC) (Allen et al., 2014).

Unfortunately, GCMs have difficulties properly reproducing contemporary climate casting doubts on their abilities in projecting future changes in key climate variables (e.g. air temperature and precipitation) (Maslin and Austin, 2012; Stevens and Bony, 2013). The discrepancy between representing present day climate are often handled via bias corrections (Hempel et al., 2013) assuming that the projected changes themselves are either correct by magnitude (delta method) or proportionally (scaling method) relative to observed contemporary simulations. Bias correction breaks the integrity of the original GCM simulation and often violates conservation principles, neglects feedback mechanisms, and their time-invariance under climate change is largely questionable (Maurer and Hidalgo, 2008). Although a debate on their applicability and effectiveness has recently arisen (Ehret et al., 2012), bias corrections are still a common practice.

It is generally assumed (without real scientific basis beyond very few empirical evidence) that multi-model averages outperform individual model projections, as individual biases are expected to at least partly cancel out. This expectation might have merit for a large number of truly independent models, but in reality GCMs share lot of commonalities (Masson and Knutti, 2011) due to their genealogy. The similarities in GCMs are not surprising since they are meant to represent the same physical processes after all. Nevertheless, given the usually small number of independent models (Pennell and Reichler, 2011) and model sensitivity to parameter choice, it is often difficult to assess the reliability of model ensemble averages and unambiguously quantify the associated uncertainties. Moreover, averaging is liable to reduce the variability in climate change analyses, especially for spatially heterogeneous variables (e.g. precipitation), while the apparent independence of the predicted change from the model skill in representing present day conditions undermines the hypothesis that reduced model spread in present day projections directly implies greater confidence in future scenarios (Knutti et al., 2010).

In addition to the inherent biases from GCM, their coarse resolutions prevents them from capturing regional spatial variability that is essential for water management applications. The coarse resolution GCM projections are either downscaled “statistically” considering spatial climate variability from observed records or dynamically by performing higher resolution regional climate model simulations forced by coarse resolution GCM as boundary condition. Just like bias correction, statistical downscaling carried out on multiple variables inevitably breaks their integrity resulting in forcing data sets that are inconsistent with the plausible states of the climate variables. The validity of dynamic downscaling is disputed as a viable strategy (Pielke Sr. and Wilby, 2012) since the skills of the high resolution RCMs resolving

fine scale processes are constrained by the erroneous GCM forcing. Since the main source of the GCM deficiencies originates exactly from their inability to represent the fine scale processes that RCMs intend to capture, the lack of feedbacks from RCM simulation into the GCM forcings puts a clear limit to the “improvement” from dynamic downscaling to the degree that some even question if RCMs have any added value (Kerr, 2013).

Impact assessment models designed for assessing the sensitivity of various economic sectors (e.g. water resources management, agriculture, human health, etc.) play a key role in translating the projected climatic changes into corresponding societal consequences. A growing number of hydrological models intended to support water managers and policy makers offer capabilities to assess water resources (Haddeland et al., 2011). Model inter-comparison exercises like Water and Global Change (WATCH) (Haddeland et al., 2011), Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) (Haddeland et al., 2014; Schewe et al., 2014) or Quantifying Projected Impacts under 2 °C Warming (IMPACT2C) shed lights on how these models in combination with state-of-the-art global circulation models perform.

Our paper presents a couple of examples applying a well established hydrological modeling framework based on the Water Balance Model introduced by Vörösmarty et al. (1989, 1998). While WBM itself was amongst the first in applying physical hydrological principles at continental and global scales its current implementation WBM_{plus} serve more as a modeling platform than a particular water balance implementation. We regard WBM_{plus} a modeling framework that can be configured on the fly to specific application both in terms of modeling domains and the complexity of simulated hydrological processes. WBM_{plus} can be configured with complex land surface processes that are in par with some of the hydrological models designed to resolve the energy and water balances simultaneously (e.g. Variable Infiltration Capacity, [VIC] model, Liang et al., 1994; Nijssen et al., 2001) and enabled to represent direct anthropogenic activities such as irrigation or reservoir operations.

The presented applications span the global and regional domains and show the challenges in applying GCMs for multi-decadal water resources management planning. Our paper intends to present a couple of case studies highlighting the limitations in applying GCMs and GCM driven RCM climate forcings for long-term water resources projections.

2 Lessons from WBM_{plus} simulations using GCM projected climate forcings

In the presented case study examples, WBM_{plus} was configured with a parsimonious representation of the vertical water exchange between the land surface and the atmosphere using a temperature driven estimation of the potential evapotranspiration (Hamon, 1963; Federer et al., 1996) and rudimentary

drying function (Vörösmarty et al., 1989). This configuration limits the climate variables needed to daily values of air temperature and precipitation and reduces the potential artifacts arising from the bias corrections.

WBM was criticized in the past for being too simplistic by neglecting the full energy balance in the vertical water exchange processes and lumping together various components of the evapotranspiration (evaporation from soil, from the canopy and transpiration through the stomates of the leaves). Our team resisted for years to apply the more elaborated water balance configuration in “production” experiments, where the uncertainties in forcing data and land cover parameterization appeared to outweigh the anticipated gain in more realistic representation of the hydrological processes. In recent years, a number of papers came to similar conclusion that added complexity does not necessary improve model performance (Perrin et al., 2001; van Griensven et al., 2006).

2.1 Global example

Impact model assessments rarely consider “raw” GCM climate forcings. Instead they either rely on a single GCM or an ensemble of multiple bias corrected GCMs as their starting points and expect the GCM community to characterize the discrepancies between GCMs. Fekete and Stakhiv (2013) carried out rudimentary comparison of three GCMs (CanESM2 from the Canadian Centre for Climate Modelling and Analysis, Canada; the MIROC5 model from the Atmosphere and Ocean Research Institute at the University of Tokyo, Japan; MRI-CGCM3 model from the Meteorological Research Institute, Japan) from the CMIP5 archive, which was at its early phase – at the time the Fekete and Stakhiv study was carried out – in assembling model result archive from the different modeling groups and only a few modeling team had completed all the model simulations (Fig. 1). The tested model scenarios were based on the most aggressive greenhouse gas emission trajectory following the RCP 8.5 representative concentration pathway.

Even without analyses (discussed in Fekete and Stakhiv, 2013), it is quite clear that the projected changes are well below the biases between runoff estimates based on “raw” GCM forcings versus observed climate data from the Climate Research Unit of East Anglia (New et al., 2000). Not only are the projected trajectories different from the different GCM projections but often the direction of their trends differs.

GCMs consistently project rising temperatures for the upcoming decades (although they have marked differences in the rate of change), but projected precipitation trends from different GCMs have a wide spread in the magnitude and direction of change. GCMs and their weather forecast model cousins are known to have deficiencies in representing cloud formation and precipitation processes for decades (WMO, 1975), and still remains their major shortcoming (Stevens and Bony, 2013).

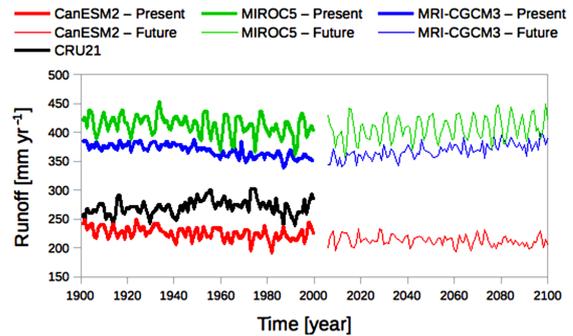


Figure 1. Annual estimates from GCM simulations under present and projected future conditions in contrast with observed climate forcings from the Climate Research Units, University of East Anglia.

The Inter-Sectorial Impact Model Intercomparison Project (ISI-MIP; (Warszawski et al., 2014) led by the Potsdam Institute for Climate Impact Research assembled an excellent compilation of GCM climate projections and applied consistent bias correction (Hempel et al., 2013) to five GCM/Earth System models: (1) HadGEM2-ES, Hadley Center, Met Office, United Kingdom (Jones et al., 2011); (2) IPSL-CM5A-LR, Climate Modelling Centre, Institut Pierre Simon Laplace, France (Dufresne et al., 2013); (3) MIROC-ESM-CHEM, Atmosphere and Ocean Research Institute, The University of Tokyo, Japan (Watanabe et al., 2011); (4) GFDL-ESM2M, Geophysical Fluid Dynamics Laboratory, NOAA, United States (Dunne et al., 2012) and (5) Norwegian Meteorological Institute, Norway (Bentsen et al., 2013) for four emission scenarios defined as representative concentration pathways (RCPs) and expressed in energy imbalances of 2.6, 4.5, 6.0 and 8.0 W m⁻² due to greenhouse gas effect.

Figure 2 shows the global terrestrial runoff estimates for contemporary and projected future climate conditions using the Water Balance Model (WBM_{plus}) (Vörösmarty et al., 1989, 1998; Wisser et al., 2010) global scale hydrological model. The bias correction removed some of the differences in the long-term mean under contemporary climate, but the seasonal variabilities according to the four models are still markedly different (Table 1, Fig. 2). The GFDL model in particular stands out with its rather hectic inter-annual variability in precipitation.

The projected linear trends in global air temperature (in °C per year), precipitation (in mm yr⁻²) and WBM_{plus} simulated runoff (in mm yr⁻²) are summarized in Table 2. Only the air temperature has consistent rising trends with considerable spread (0.04–0.08 °C yr⁻¹ for the RCP8.5 scenario). The precipitation trends vary regionally with increasing and decreasing trends for individual continents, with a global average increase of 0.21–1.04 mm yr⁻² for RCP8.5) during the 2006–2099 period. The predicted runoff trends (–0.49–0.13 mm yr⁻² for RCP8.5) are the results of the competition between the rising air temperature (leading to more evapo-

Table 1. Contemporary (1950–2006) global average air temperature, precipitation and runoff (estimated using WBM_{plus}) based on five bias corrected GCM hind-casts.

GCM	Air Temp [°C]		Precipitation [mm yr ⁻¹]		Runoff [mm yr ⁻¹]	
	Mean	SD	Mean	SD	Mean	SD
HadGEM2-ES	13.25	0.37	875	21	344	15
IPSL-CM5A-LR	13.25	0.45	853	23	335	16
MIROC-ESM-CHEM	13.19	0.29	876	20	335	15
GFDL-ESM2M	13.22	0.36	858	44	349	33
NorESM1M	13.21	0.35	871	15	331	12

SD = Standard Deviation

Table 2. Linear regression slope of the projected air temperature, precipitation and WBM_{plus} simulated runoff for the 2006–2099 period.

		RCP2.6	RCP5.4	RCP6.0	RCP8.5
Air Temp.	[°C yr ⁻¹]				
	HadGEM2-ES	0.01	0.04	0.05	0.07
	IPSL-CM5A-LR	0.01	0.03	0.04	0.07
	MIROC-ESM-CHEM	0.02	0.04	0.05	0.08
	GFDL-ESM2M	0.00	0.01	0.02	0.04
NorESM1M	0.01	0.03	0.03	0.05	
Precip.	[mm yr ⁻²]				
	HadGEM2-ES	0.18	0.35	0.53	0.21
	IPSL-CM5A-LR	0.13	0.59	0.39	0.96
	MIROC-ESM-CHEM	0.32	0.54	0.76	1.04
	GFDL-ESM2M	0.03	0.40	-0.03	0.27
NorESM1M	0.32	0.34	0.47	0.71	
Runoff	[mm yr ⁻²]				
	HadGEM2-ES	-0.02	-0.10	-0.02	-0.49
	IPSL-CM5A-LR	-0.02	0.14	-0.02	0.13
	MIROC-ESM-CHEM	0.04	-0.01	0.07	-0.10
	GFDL-ESM2M	-0.01	0.20	-0.21	-0.08
NorESM1M	0.17	-0.01	0.06	-0.01	

transpiration and hence less runoff) and more precipitation (that would lead to more runoff if there was no change in air temperature).

Perhaps, one of the most disturbing outcome of the ISI-MIP model intercomparison was the recognition that model uncertainties in the impact models were comparable to the uncertainties in the GCM forcings (Haddeland et al., 2011). While the true assessment of GCM uncertainties is probably better judged before bias corrections, the discrepancies amongst impact models (water balance models in the context of various applications such as water management, agricultural production, etc.) is disturbing given their relative simplicity compared climate models.

The large difference between global scale hydrological model simulations is not entirely new as the European Water and Global Change (EU-WATCH) program (a precursor to the ISI-MIP project) already came to the similar conclusions (Haddeland et al., 2011).

2.2 European example

IMPACT2C made use of the growing ensemble of high-resolution (~ 12 km resolution) simulations from the Coordinated Downscaling Experiment – European Domain (EuroCORDEX) and Med-CORDEX (Jacob et al., 2014). Climate projections for Europe are available through the CORDEX Climate Data Archive, while the bias corrected fields for hydrological impact studies are at present only available for internal use, and consist of a subset of five modeling GCM-RCM chains. A preliminary assessment of the robustness of the climate change signal for the RCP 4.5 scenario was performed on the original high resolution atmospheric temperature, precipitation and wind fields, following Tebaldi et al. (2011), although with more severe significance thresholds due to the small ensemble size (Fig. 3).

Robust signals could only be detected in temperature showing a 2 °C overall increase, a slightly weaker warming along the coasts of North-Western Europe in all seasons, and a more intense warming (up to +4 °C) in Northern and Eastern Europe in Winter and in Southern Europe in Summer (up

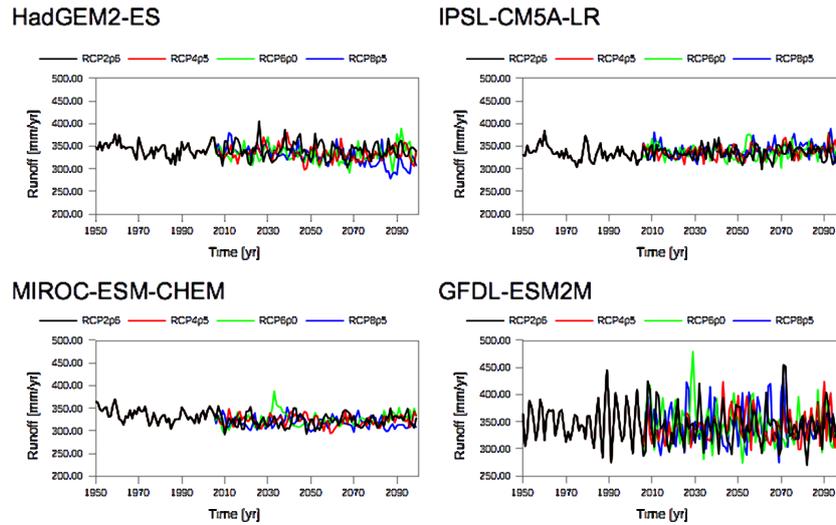


Figure 2. Global continental runoff estimates based on bias corrected present and projected future climate conditions using the ISI-MIP forcing data.

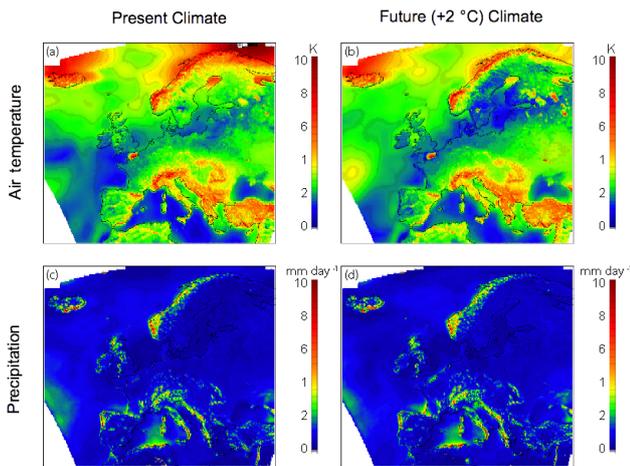


Figure 3. Ensemble spread (the difference between the minimum and the maximum from the ensemble members) of mean annual air temperature (a, b) and average precipitation (c, d) from uncorrected RCMs for present (1971–2000, a, c) and future (+2 °C, b, d) Climate considering RCP 4.5 scenario.

to +3 °C). Similar patterns are detectable in daily minimum and maximum temperatures, especially in wintertime daily minima over Scandinavia. Daily precipitation does not show clear changes in most of Europe, but exhibits general increases over Central and Northern Europe in winter and only over Northern Europe in summer, while precipitation seems to decrease in Central/Southern Europe in summer. Extreme precipitation exhibits scattered robust increases across Europe in both seasons. Extreme winds are not found to robustly increase/decrease.

It has been documented, however, that a winter positive bias in surface temperature and precipitation rates can be in-

duced in RCM simulations over Northern Europe through the prescribed large scale boundary conditions, which can lead to a too deep Icelandic low precipitation extending too far into the Nordic seas. Such feature also causes too low temperature and precipitation rates over Southern Europe. On the other hand, in summer warm and dry biases have been observed in RCMs simulations over Eastern Europe and to a lesser degree the Mediterranean, where too little simulated rainfall can dry out soil water reservoirs causing very high surface temperatures (Jacob et al., 2007). Therefore, there is definitely a need for thorough analyses of all the modeling chains before any conclusion can be reached (Jacob et al., 2014).

It is worth noting that the high resolution of the Med-CORDEX simulations might be expected to locally reduce the fraction of convective precipitation to total precipitation, therefore possibly reducing the summer warm and dry biases, thus improving both the spatial pattern and temporal evolution of precipitation. On the contrary, winter circulation being dominated by large scale features, it can mainly benefit from a finer representation of the flow-topography interactions in the domain interior (Rauscher et al., 2010).

Quite unfortunately, the bias correction procedures (in this case, quantile mapping) to the surface temperature and precipitation fields required the original RCM outputs to be up-scaled from 12 to 25 km resolution, in order to match that of the E-OBS gridded dataset selected for reference (Haylock et al., 2008). In addition, when further examined, the E-OBS dataset exhibits an even lower effective resolution, in particular over complex topography, as a consequence of spatial interpolation, and clear underestimation of orographic precipitation and overestimation of surface temperature over mountainous areas, even when compared to lower resolution data (WFDEI).

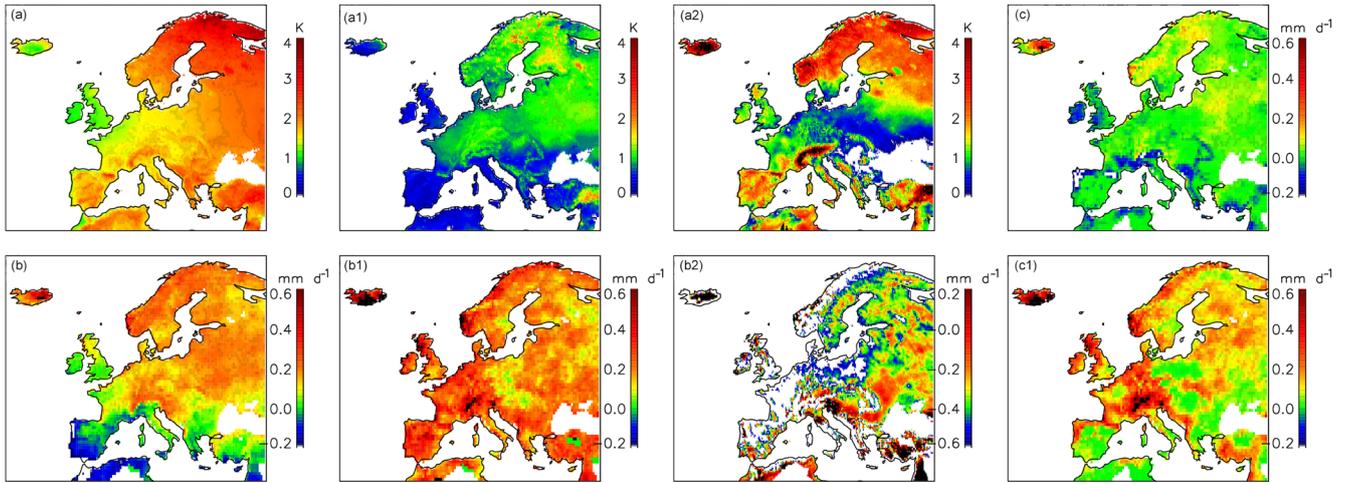


Figure 4. Predicted changes in mean annual temperature (a) average annual precipitation (b) and runoff (c) contrasted by their respective future climate bias-corrected spread (a1, b1, c1) and present climate bias-correction patterns for temperature and precipitation only (a2, b2).

When combined with the different representations of orography in the different RCMs, in vast areas this led to virtually correct altitude rather than intrinsic biases in the projected fields, as demonstrated by the comparison between the patterns of the uncorrected RCM ensemble spread in present and future climate for both precipitation and surface temperature, clearly carrying a stable topography signature, and between the correspondent average fields before and after bias correction (Fig. 4a2 and b2).

Such features are even more evident over specific regions, e.g. the Alps, over which individual model fields have been compared: single peaks can be identified and directly compared to high resolution geographic maps. The overall effect is a dramatic decrease and over-smoothing in precipitation projections and a similarly non-negligible increase in temperature at high altitudes, both severely inconsistent with the rest of modeled fields and, quite ironically, neutralizing just what is one of the major improvements expected from high resolution regional simulations.

Precipitation is the most critical input variable in hydrological modeling (Fekete et al., 2004; Biemans et al., 2009) and the main driver of river runoff. The corrected over-smoothed fields can therefore hardly be expected to produce accurate discharge projection when used to feed a hydrological model.

For four main European catchments discharging into the Mediterranean or the Black seas, WBM_{plus} generally underestimates total discharge when forced with the bias corrected regional P and T fields. Figure 5 shows the resulting seasonal cycle of basin integrated $P - E$ and total runoff, the black horizontal line representing the average total $P^* - E$ over the climatological time window (1971–2005), where P^* is the uncorrected precipitation. Evaporation is still derived from the corrected temperature field, as the correction ap-

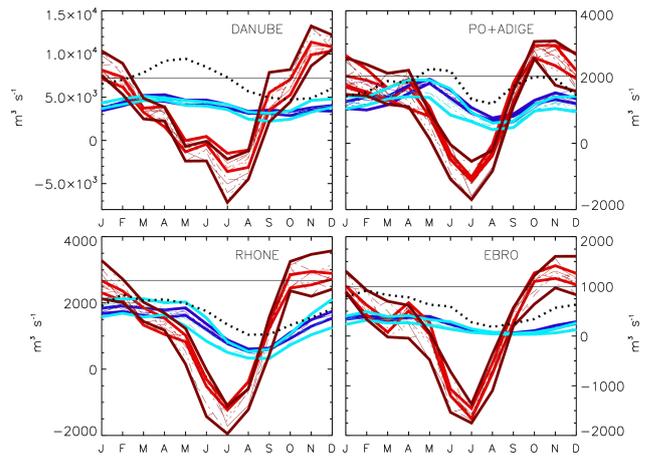


Figure 5. Basin-wide seasonal cycles of key water balance components ($P - E$: present – red, future $+2^\circ C$ – blue, runoff: present – orange, future $+2^\circ C$ – light blue). Thick lines outline the envelop of the five ensemble members, while thin lines correspond to single realizations. The black dotted line represent observed discharge. The black horizontal line represents average of the $P - E$ over the 1971–2005 period using uncorrected (supposedly biased) precipitation along with evapotranspiration estimates from the corrected temperature fields.

plied to precipitation largely dominates the final adjustment. Quite notably, the uncorrected precipitation appears to give a better estimate of $P - E$ for the Danube, while it has comparable (but opposite) bias for the Po+Adige and the Ebro basins in contrast to the bias corrected IMPACT2C simulations. Such overestimation is mainly attributable to spurious summer precipitation peaks in one (Po+Adige case) or more (Ebro case) model realizations. The Rhone constitutes an evident exception, where the overestimation of precipitation is

generally confined to the fall and winter months (except for one single ensemble member), when rainfall over the catchment is dominated by the large scale component rather than by local processes or interactions. Such bias is then probably attributable to systematic error propagation from the large scale GCM that the regional models are unable to correct, and that bias-correction techniques can only crudely mend in present day conditions.

By removing apparent systematic errors in the projected fields, bias correction effectively reduces model spread in control simulations, whereas it only partly succeeds in limiting noise in the projected water balance for the $+2^{\circ}\text{C}$ scenario realizations, due to the variety of different model responses. Therefore there is no clear indication of a significant climate change signal, while the summer drying problem appears to be worsened.

Figure 4 allows extension of such conclusions to the continental scale hydrological balance. The $+2^{\circ}\text{C}$ signal in the modelled precipitation climatological field appears as an increase over central eastern Europe and Scandinavia, and as a general decrease in southern Europe. On the other hand, evaporation likewise increases or decreases in the same areas, driven by rising temperatures and coupled to precipitation in wet regions via a soil-precipitation feedback amplification mechanism inducing more efficient extraction of moisture from the large scale atmospheric flow (Schar et al., 1999). It is elsewhere limited by water availability. A significant signal in total runoff can therefore only be detected over central eastern Europe and part of Scandinavia, where its magnitude is yet comparable to the relatively low local values, and numerical computations are possibly less accurate. It is difficult to quantify the role of upscaling, bias correction and ensemble averaging in determining the observed quasi-cancellation of signals in the atmospheric water balance, as all effectively act to decouple precipitation and soil moisture anomalies and to smooth out sub-grid variability.

The climate change signal in temperature alone also exhibits a definite meridional gradient, with the highest increments located over northern Europe, and southern countries experiencing lower though consistent warming. It is worth noting again, that both effects might originate in the reported model deficiencies, a hypothesis that is confirmed if the spatial patterns of both corrections to the data and model spread are considered. Under the assumption that model spread and correction magnitude together concur to give a rough estimate of uncertainties in model projections, if not as a disclosure of both model and data inadequacy, the climate change signal is in fact severely obscured by noise.

2.3 African example

For the African domain, the CORDEX community has produced a number of GCM-RCM combinations at a spatial resolution of 0.44° ($\sim 50\text{ km}$). A total of 16 of such combinations are currently available. For West Africa, a consistent

trend in temperature is visible (despite different magnitudes in the trends) in these models. The picture is less clear for precipitation owing to the difficulties of GCM in resolving the monsoon. The region has traditionally been one where climate models showed most disagreement (Giannini et al., 2008; Druyan, 2011). Despite some consistency in precipitation trends in the RCM ensemble, there are still large uncertainties in precipitation and it is not clear if wetter or drier conditions can be expected in the future (Fig. 6). Projected changes in annual precipitation from GCM indicate changes that are within the range of the observed variability of precipitation in the region (Fig. 7).

A change indicated by the majority of models is a delay in the onset of the rainy season together with a earlier cessation, leading to a total shortening of the wet period that lasts between 165 days in the South and only about 90 days in the Sahelian region in the North. With little change in precipitation this implies more precipitation falling on less days and generally more erratic rainfall.

Bias correcting the ambiguous climate model data in this region is likely not going to make the climate model for water balance modeling more meaningful. Despite the conceptual issues related to bias correction in general, the bigger problem is selecting the data sets on which the bias correction should be based on. For precipitation, for example, the observation network is very sparse and access to data is restricted by many national data sharing policies. Related to this, the satellite precipitation products (that rely on in-situ observations for calibration) in the region show large discrepancies that will translate through the bias correction chain and introduce further uncertainties.

3 Conclusions

Climate models are indispensable tools to understand atmospheric processes and the evolution of the Earth's climate regime, but they have clear shortcomings in providing climate projections for actual water management planning (Anagnostopoulos et al., 2010; Kundzewicz and Stakhiv, 2010). Hydrologist expressed concerns in the past about apparent inability of GCMs to reproduce contemporary climate conditions (Koutsoyiannis et al., 2008; Anagnostopoulos et al., 2010) with convincing fidelity. After decades of global circulation modeling research, the uncertainties in GCM projections are still increasing (Maslin and Austin, 2012).

In an anticipation that the computing power needed to enable GCM modelers to carry out computations at significantly higher spatial and temporal resolution (that are viewed as the key in improving GCM performance) is still decades away, some scientist are envisioning a possible alternative pathways by using supercomputers that are less accurate and don't necessary compute the same results from identical input data (Palmer, 2015). It is unclear, how such model can be

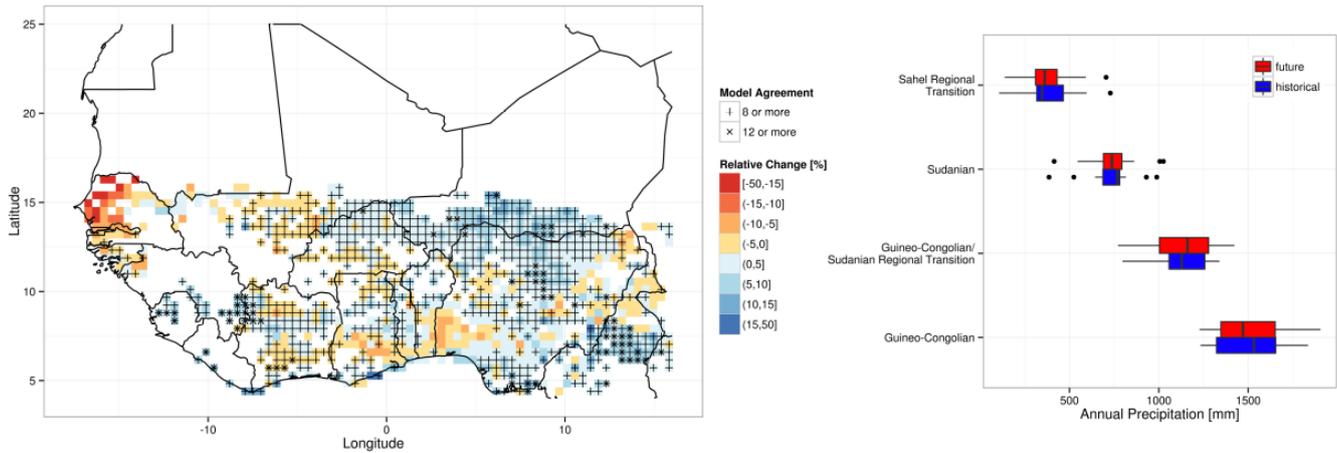


Figure 6. Relative change in ensemble median precipitation (left) and simulated absolute values of long term annual historical and future precipitation for 16 RCM/GCM combinations aggregated for 4 vegetation zones (right). “+” indicates an agreement of 8 or more models in the direction of change, “*” indicates an agreement of 12 or more models. Boxes extends from the 25th to 75th percentiles, whiskers indicate 1.5 times the interquartile range.

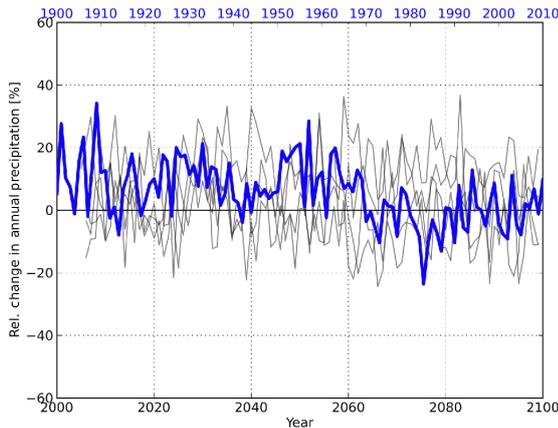


Figure 7. Projections of rel. changes in annual precipitation for West Africa, from 5 GCMs, randomly picked from ISI-MIP bias corrected data (grey). The blue line shows the observed variability in precipitation for the last 100 years (upper *x* axis) from UDEL data (Willmott et al., 1994).

tested if the model simulation results could vary randomly, and how random perturbation from numerical inaccuracy can lead to sufficiently dense sample of the system phase space. Furthermore, such a system would violate perhaps the most important basis of sciences that relies on the reproducibility of the experiments carried out by other scientists.

Considering the incredible increase in computational power (which was always viewed as the major roadblock in improving GCM performance) during the last three decades (since the climate change agenda rose to its current prominence in geophysical research), one has to wonder if it is indeed the lack of computing power that prevents major breakthroughs or there are fundamental obstacles in our ability to

predict the trajectories of the chaotic climate systems (Curry and Webster, 2011), and in our understanding and modeling of crucial processes (Held, 2005). Even if more detailed model simulations can improve model performance, the basic rule of computing “garbage in – garbage out” certainly will limit, how much improvement can be accomplished. Just like increased model complexity does not necessarily lead to better modeling skills processing more of the same poor quality data will only lead to more poor quality model results coming out.

The real improvements in our understanding of the Earth system processes will likely come only from better data that will need to come from improved Earth system monitoring both from in-situ and remote sensing sensors. A recent debate published in *Science* provided two distinct view about the role of in-situ monitoring (Fekete et al., 2015) and remote sensing (Famiglietti et al., 2015). While the right balance between putting sensors on the ground or in space is still up for scientific debate and ultimately might change over time as the various sensor technologies improve, but the debating papers were in full agreement in the need for both.

Given the demonstrated inefficiencies of both the Global Circulation Models and their operational cousins, the weather forecast models, in capturing the water cycle, better hydrological data are much needed. While remote sensing undoubtedly will play critical roles in monitoring precipitation and possibly soil moisture, river discharge, which is the most accurately monitored element of the hydrological cycle (Gutowski Jr. et al., 1997; Roads and Betts, 2000) will remain best monitored on the ground (Fekete et al., 2012). Data exchange of in-situ monitoring is often seen as an insurmountable obstacle, but surrendering to the difficulties in international data exchange amounts to nothing less than ac-

knowledging that acting on larger goals such as combating climate change is impossible.

The biggest obstacle to more monitoring is the lack of financial resources. One would think that cost of operating high performance computing centers to support GCM modeling pales in comparison to the investment needed to maintain in-situ observing networks. In reality, it is not the case, as an example the Earth Simulator built in Japan (which was the fastest computer between 2002–2004) had a USD 700 million price tag and needed a full overhaul by 2009 (Fekete and Stakhiv, 2013). In contrast, operating 5000 river discharge gauges globally at USD 20 000 per year (United States Geological Survey's costs) would require USD 100 million annual spending (Fekete et al., 2012). Similarly, the price of the Earth Simulator's is comparable to the costs of two Earth observing NASA satellites (Anthes et al., 2007).

The only way the investments in GCM and impact model assessment capabilities can reach their full potential is if robust and reliable Earth observation can aid their development and calibration and permit sustained validations. “*Historia est Magistra Vitae*” – and history remains the life's teacher in our changing world.

4 Code and data availability

The data used in the presented research are all publicly available listed under the assets tab of the electronic version of the paper. The water balance model results are available from the ISIMIP project of the Potsdam Institute for Climate Impact Research (Warszavszki et al., 2014; Hempel et al., 2013). Their hosting data portal is part of the Earth System Grid Federation. The results from the European water balance model experiments are accessible at the ENSEMBLES project under theme RT3. The modeling and spatial analysis tools used in the present study are available on GitHub. Updated version of Willmott et al. (1994) was retrieved from Willmott-Matsuura (2016).

The source code for the Water Balance/transport Model used in the presented studies are available on GitHub (Fekete, 2016).

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