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Effects of climate model radiation, humidity and wind estimates on hydrological simulations

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Abstract

Due to biases in the output of climate models, a bias correction is often needed to make the output suitable for use in hydrological simulations. In most cases only the temperature and precipitation values are bias corrected. However, often there are also biases in other variables such as radiation, humidity and wind speed. In this study we tested to what extent it is also needed to bias correct these variables. Responses to radiation, humidity and wind estimates from two climate models for four large-scale hydrological models are analysed. For the period 1971–2000 these hydrological simulations are compared to simulations using meteorological data based on observations and reanalysis; i.e. the baseline simulation. In both forcing datasets originating from climate models precipitation and temperature are bias corrected to the baseline forcing dataset. Hence, it is only effects of radiation, humidity and wind estimates that are tested here. The direct use of climate model outputs result in substantial different evapotranspiration and runoff estimates, when compared to the baseline simulations. A simple bias correction method is implemented and tested by rerunning the hydrological models using bias corrected radiation, humidity and wind values. The results indicate that bias correction can successfully be used to match the baseline simulations. Finally, historical (1971–2000) and future (2071–2100) model simulations resulting from using bias corrected forcings are compared to the results using non-bias corrected forcings. The relative changes in simulated evapotranspiration and runoff are relatively similar for the bias corrected and non bias corrected hydrological projections, although the absolute evapotranspiration and runoff numbers are often very different. The simulated relative and absolute differences when using bias corrected and non bias corrected climate model radiation, humidity and wind values are, however, smaller than literature reported differences resulting from using bias corrected and non bias corrected climate model precipitation and temperature values.

1 Introduction

Climate change is likely to have a significant impact on the global hydrological cycle and water resources (Bates et al., 2008). Due to large uncertainties it is hard to give precise predictions about how the hydrological cycle will change and how this will affect water availability. The estimates of these effects depend heavily on the meteorological input data used in hydrological model simulations. The impact of climate change on the global terrestrial water cycle is usually studied by using the output of climate models as input for hydrological models (e.g. Hagemann et al., 2011). However, due to larges biases in climate models outputs, they can often not be used directly as input for hydrological models. It is therefore needed to bias correct the output of climate models. Precipitation and temperature are likely the most important forcing variables in hydrological models, and bias correction of these variables has traditionally been given most of the attention (e.g. Wood et al., 2004; Piani et al., 2010; Themeßl et al., 2010). When hydrological models are used for assessing impacts of climate change, precipitation and temperature output from climate models are often bias corrected using the delta change method (e.g. Hay et al., 2000), or by a statistical bias correction method (e.g. Hagemann et al., 2011). However, other forcing variables (e.g. radiation, humidity, wind speed) can have significant biases in climate models. These biases subsequently influence evapotranspiration, runoff, snow accumulation and melt in hydrological simulations, which were also noted by Hagemann et al. (2011).

Climate model outputs other than precipitation and temperature have received moderate attention among hydrologists and in climate change impact studies. There is, however, a wide spread in the shortwave forcings reported for the models included in IPCC AR4 (Meehl et al., 2007), and Storelvmo et al. (2009) found that the different methods used to calculate cloud droplet number concentration from aerosol mass concentration is the main contributor to the spread. Wild and Liepert (2010) argued that inadequacies in the simulation of the surface radiation balance in climate models may contribute to the poor simulation of decadal variations in precipitation during the 20th century, and that improved knowledge of the surface radiation balance is key to our understanding of variations in the hydrological cycle. Sensitivity analyses using various datasets as input to hydrological models have shown that the resulting water fluxes are sensitive to radiation values, see e.g. Shi et al. (2010) and Nasonova et al. (2011); a result of evapotranspiration being highly dependent on the amount of available energy. Materia et al. (2010) concluded that, for the SSiB model, river flow is most sensitive to precipitation variability, but changes in radiative forcing affect discharge as well.

Sperna Weiland et al. (2010) looked at the spread in resulting discharge estimates before and after bias correcting GCM precipitation, temperature and potential evaporation, and found that bias correction resulted in discharge estimates closer to the baseline simulations. However, isolated effects on hydrologic simulations caused by differences in climate model output other than precipitation and temperature have to our knowledge not been quantified before. Also, a study on the implications for hydrologic control and projection results before and after bias correction of these input variables has not previously been conducted. The objectives of this study are to analyse how biases in radiation, humidity and wind influence resulting water fluxes in hydrological model simulations, and to analyse the impact of bias correction of these variables on control and projection periods. The baseline forcing dataset is the WATCH Forcing Data (WFD; Weedon et al., 2011), and the Hagemann et al. (2011) ECHAM and IPSL climate model forcings (control and projection periods) are used. Precipitation and temperature in the Hagemann et al. (2011) climate model forcings have been bias-corrected to match the WATCH Forcing Data (WFD; Weedon et al., 2011), whereas the other variables are taken directly from climate model output. In this study, the hydrological simulation results using WFD are hence considered the baseline simulations, and the results using ECHAM and IPSL forcings are compared to the WFD results. In addition, projections of evapotranspiration and runoff using bias corrected forcing variables are compared to projections using direct climate model outputs in the hydrological simulations.

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2 Method

2.1 Forcing datasets

The baseline forcing dataset used in this study is called the WATCH forcing data (WFD; Weedon et al., 2011). The WFD variables for the period 1958–2001 are taken from the ERA-40 reanalysis product of the European Centre for Medium Range Weather Forecasting (ECMWF) as described by Uppala et al. (2005). The one-degree ERA40 reanalysis product was interpolated to half-degree resolution on the CRU land mask, adjusted for elevation changes where needed and bias-corrected using monthly observations. Diurnal air temperature was bias-corrected with CRU data (New et al., 1999, 2000; Mitchell and Jones, 2005). Shortwave downward radiation (SW) was corrected using CRU cloud cover fractions, having found the grid-point specific correlations between monthly average SW and ERA40 cloud fraction. SW was also adjusted for the effects of tropospheric and stratospheric aerosol loading. Precipitation was adjusted using both a wet-day correction from CRU and precipitation totals from the GPCCv4 full data product (Rudolf and Schneider, 2005; Schneider et al., 2008; Fuchs, 2008), and corrected for undercatch (snowfall and rainfall separately) based on Adam and Lettenmaier (2003). For detailed information on the baseline forcing data, see Weedon et al. (2011).

The climate data are taken from the ECHAM and IPSL climate models, see Hagemann et al. (2011) for details. The time period is 1960–2100, and the same forcing variables as for WFD are available. Precipitation and temperature are bias corrected to WFD (Piani et al., 2010). The other variables (short- and longwave radiation, specific humidity, and wind speed) are interpolated from the spatial resolution of the climate model to 0.5 degree spatial resolution by a combination of bilinear and inverse distance interpolation (Waszkewitz et al., 1996). Figure 1 shows mean annual values of downward short- and longwave radiation, total downward radiation, specific humidity and wind speed for the period 1971–2000 for WFD, and climate model anomalies. Precipitation and temperature values are not shown since these variables, because of the

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bias correction, are very close for all datasets. Shortwave radiation shows large differences among the datasets, especially in Sub Sahara, South East Asia and at northern latitudes. The ECHAM and IPSL shortwave radiation values in some areas have opposite deviations from the WFD values, e.g. at northern latitudes (Fig. 1a). The relative differences among the datasets are lower for longwave than for shortwave radiation (Fig. 1b), but also this variable shows differences e.g. in the tropics. Compared to the WFD values, the climate model longwave radiation anomalies are in many places opposite to those of the shortwave radiation anomalies. Total radiation, i.e. shortwave and longwave radiation combined, is an important measure in evapotranspiration calculations, and mean annual total downward radiation is also included in Fig. 1. The climate model specific humidity and wind speed values are both fairly different in all areas of the world compared to the WFD values (Fig. 1d, e).

2.2 Hydrological models

Four hydrological models participating in the EU WATCH project (Harding et al., 2011) are included in this study. The models, their main characteristics, and simulation results using historical forcing data are presented in Haddeland et al. (2011). In the present study, the main focus is on evapotranspiration and runoff estimates. The evapotranspiration schemes implemented in the models are reflected in what meteorological forcing variables are needed by the models, see also Table 1. MPI-HM makes use of the Thornthwaite evapotranspiration scheme, meaning the model only depends on precipitation and temperature. WaterGAP and LPJmL have implemented the Priestley-Taylor equation for evapotranspiration, and hence also depend on radiation values. VIC has implemented the Penman-Monteith equation for evapotranspiration and is additionally dependent, as direct input or internally estimated, on humidity and wind speed.

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2.3 Bias correction and hydrological model simulations

As mentioned above, the original climate model precipitation and temperature data prepared for WATCH have been bias corrected to match the long-term statistics of WFD, but the other variables are raw climate model outputs. Despite the bias corrected precipitation and temperature values, the hydrological simulation results using WFD (Weedon et al., 2011) and the Hagemann et al. (2011) climate model forcings for the LPJmL, VIC and WaterGAP models are quite different for the period 1971–2000. The purposes of this study are to test whether a simple bias correction of forcing variables other than precipitation and temperature will yield more similar simulation results than before introducing the bias correction, and to analyze how it affects hydrologic projections. An underlying assumption is that the WFD forcing variables are closer to the true values than are the climate model outputs, although the method and analyses do not depend on this assumption. The bias correction was performed at daily time steps at the grid cell level as follows:

$$V_{bc} = V_{gcm} \cdot \frac{V_{wfd}\left(\overline{m}\right)}{V_{gcm}\left(\overline{m}\right)} \tag{1}$$

where V_{bc} is the resulting bias corrected variable (shortwave radiation, longwave radiation, humidity or wind speed) for any given day, V_{gcm} is the original climate model output value, V_{wfd} is the corresponding WFD variable, and $\overline{m}$ is the long-term mean monthly value for the variable and day in question. The long-term mean monthly relationships between the climate model outputs and WFD are hence used to correct the daily values in the climate model variables. The long-term mean differences in the period 1960–2000 are used for the entire period 1960–2100, and possible trends are not corrected. The LPJmL, VIC and WaterGAP models were rerun using the bias corrected variables as input forcings for the period 1960–2100 for the ECHAM and IPSL A2 projections. The MPI-HM model only makes use of temperature and precipitation data, and hence there was no need to rerun this model.

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The hydrological models are run for the entire periods for which the forcing datasets are available, but in this paper only results for 1971–2000 (control period) and 2071–2100 (projection period) are presented. An overview of the forcing datasets used and the hydrological simulations performed is presented in Table 1. Analyses are carried out on mean annual global terrestrial evapotranspiration and runoff estimates, as well as mean monthly simulated evapotranspiration and runoff for some study basins; see location in Fig. 2.

3 Results and discussion

3.1 Hydrologic effects of forcing differences; original results and results after bias correction (1971–2000)

Averaged over the period 1971–2000, mean annual simulated evapotranspiration is distinctly different when using climate model output directly to force the hydrological models than when WFD is used, see Fig. 3. The evapotranspiration differences appear despite the bias correction that was originally performed on input precipitation and temperature values, and is evident in all model results except for the MPI-HM model. The MPI-HM model only makes use of precipitation and temperature as input meteorological data, and hence the results are fairly similar for all forcing datasets used in this study. Simulated evapotranspiration using original ECHAM forcings are closer to the WFD results than are the original IPSL simulated evapotranspiration, which might be expected when looking at differences in the input data (Fig. 1). However, even when using ECHAM forcings the annual differences in simulated evapotranspiration are fairly high e.g. at northern latitudes and parts of the tropics.

Figure 3 shows that simulated evapotranspiration for the LPJmL, VIC and WaterGAP models after bias correction of climate model radiation, humidity and wind speed are much closer to the baseline WFD results than before bias correction was introduced. In a few high-elevation areas (e.g. Himalaya) and some dry areas (e.g. Sahara and parts of Australia) the evapotranspiration differences are still more than 20 %. In these areas even the MPI-HM results are different, indicating that temporal differences in precipitation and temperature values at least partly explain the somewhat deviating results for the other models. The choice of evapotranspiration scheme and input forcing variables used clearly results in sensitivity differences to the climate model outputs, which is demonstrated by the results for all four models.

In Figs. 4 and 5, mean monthly (1971–2000) simulated evapotranspiration and runoff for the study basins before and after implementing the bias correction (Eq. 1) are presented. The MPI-HM results are, again, fairly similar for all forcings used. However, also at the mean monthly level, the MPI-HM results indicate that differences in the precipitation and/or temperature characteristics cause slight differences in simulated water fluxes that are especially apparent when looking at runoff numbers (Fig. 5). Although precipitation and temperature are bias corrected, some differences in the correlation between the two variables before and after bias correction influence the results somewhat. The differences are hardly noticeable in the evapotranspiration estimates (Fig. 4), a result of the evapotranspiration numbers being higher than the runoff numbers and hence the relative evapotranspiration differences are smaller than the relative runoff differences.

For the LPJmL, VIC and WaterGAP models, the basin results after bias correction of the input variables are much closer to the WFD results than when using the original climate model forcings. The most profound changes are seen for the Amazon, Nile and Ganges-Brahmaputra river basins, where the ECHAM results after bias correction almost perfectly match the WFD results. The IPSL bias corrected results for LPJmL and WaterGAP match the WFD results in most basins; also in the Amazon, Nile and Ganges-Brahmaputra basins. The bias corrected VIC IPSL results for the Nile and Ganges-Brahmaputra basins are much closer to the WFD results than before the bias correction, but do not perfectly match them. It is likely that variability of, and between, the input variables cause the match not to be perfect, and a bias correction method based on the long-term monthly deviations will not match the baseline forcing variables

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in all aspects. For the results presented here, this effect is more evident the more variables are used as input meteorological data. When calculating the correction factors and simulating for a shorter period (1985–1999), the VIC IPSL results (not shown) are closer to the WFD results than when the bias correction is performed over a 40 yr time period. In the water limited Murray Darling river basin, the evapotranspiration differences are fairly small. However, for the VIC model differences appear in the runoff estimates, and the bias correction do not affect simulated runoff much. In this basin, monthly incoming radiation is similar in the climate models, and it is only humidity values that differ somewhat. The findings in Fig. 5 are similar to those of Sperna Weiland et al. (2010), although the Sperna Weiland et al. (2010) results also included the effects of bias correction on precipitation and temperature, and they used a slightly different bias correction approach (i.e. bias correction was performed on potential evaporation instead of directly on climate model outputs).

In the Ganges-Brahmaputra basin, the original IPSL evapotranspiration estimates are much higher than the ECHAM and WFD estimates during the Indian monsoon (Figs. 4 and 5). In this precipitation-rich period, total incoming radiation values are very different (not shown), mainly caused by lower shortwave radiation values in IPSL than in ECHAM and WFD. In general, it might be expected that radiation differences cause larger evapotranspiration differences in energy limited areas than in water limited areas. In order to investigate this issue further, the evapotranspiration fraction (here defined as mean annual evapotranspiration divided by mean annual precipitation) was used as a proxy for energy limitation, and differences in the originally simulated evapotranspiration values were compared for the cells in the model domain where total incoming radiation is more than 10 % higher in the climate model output than in WFD (see also Fig. 1c). The results are presented in Fig. 6, and shows that the models' sensitivity to differences in radiation is higher in areas with low evapotranspiration fractions than in areas with high evapotranspiration fractions. Hence, radiation differences in the forcing data have relatively larger effects on water fluxes in energy limited areas than in water limited areas. It should be noted, though, that small differences in water limited areas

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may be of higher societal and environmental importance than the larger differences in water rich areas.

3.2 Hydrological projections with and without bias correction (2071–2100 compared to 1971–2000)

Hagemann et al. (2011) showed that bias correction of precipitation and temperature can influence projected runoff changes profoundly (see e.g. Fig. 8 in Hagemann et al., 2011). A logical question for the study presented here is hence whether bias correction of radiation, humidity and wind speed influence projected changes in water fluxes. In order to answer this question, simulated runoff for the LPJmL, VIC and WaterGAP models with and without bias corrected forcings for the period 2071–2100 (projection period) are compared to simulated runoff for the period 1971–2000 (control period).

The mean annual relative runoff changes for the original and bias corrected simulations look similar in most areas of the world (Fig. 7; left and middle panels), when comparing simulated runoff for one climate model and one hydrological model. In Fig. 7 (right panels), the areas where the differences in the relative runoff changes are both (1) significant at the 5 % level and (2) more than 5 percentage points are also shown. These areas cover 0.14 to 0.26×10^8 km^2 for LPJmL ECHAM and IPSL results, 0.45 to 0.55×10^8 km^2 for the VIC ECHAM and IPSL results, and 0.25 to 0.44×10^8 km^2 for the WaterGAP ECHAM and IPSL results. This represents between 10 and 38 % of the global terrestrial area (equalling 1.46×10^8 km^2 for the land mask used in this study). Globally averaged, the projected changes without and with bias corrected climate forcings are presented in Table 2 and the leftmost part of Fig. 8. The bias correction of radiation, humidity and wind speed does not change the future relative predictions much at the global mean annual time scale, compared to using raw climate model outputs. However, the absolute runoff values for both the control and projection period results are considerably different. Table 2 also shows that there is a large spread in simulated water fluxes among the models; for more information on this topic see Haddeland et al. (2011) and Hagemann et al. (2011). Globally, the relative increase in runoff is slightly

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lower after introducing the bias correction; this is true for both climate model outputs and all hydrological models for which results can be compared (Table 2).

In the study basins, the effect on the hydrologic projections of the bias correction carried out in this study is in the order of a few percentage points, see Fig. 8. Figure 8 shows that in most basins, the direction of the change of the projection signal is fairly consistent among the models, although the magnitude is somewhat different. When comparing Fig. 8 to the results presented in Hagemann et al. (2011; Fig. 8), it appears that the effect of the bias correction of precipitation and temperature is higher than the effect of the bias correction of radiation, humidity and wind values. In the Hagemann et al. (2011) results, the differences in runoff projections before and after bias correction of precipitation and temperature in many basins are over 5 %, and in some basins up to 20 %. In this study, the differences are less than 5 % for most basins and models. The study of Materia et al. (2010) and the Hagemann et al. (2011) study in combination with the study presented here, have somewhat different focus and should not be compared directly, but they both indicate that precipitation variation influence runoff more than radiation variations do.

The cumulative distribution functions based on basin averaged monthly runoff values for the LPJmL, VIC and WaterGAP models using IPSL input data for the periods 1971–2000 and 2071–2100 presented in Fig. 9 show that for both periods, the absolute numbers can be very different with and without bias correction. Only some of the study basins are included in Fig. 9, but the results in these basins illustrate the general model performance well. In most basins the relative change (projection period compared to control period) in simulated runoff is not much different whether the bias correction is employed or not. Hence, the introduction of a bias correction does not change the predicted signal of the future changes much. Among the basins included in Fig. 9, it is only for the VIC model in the Nile River basin the relative changes are clearly different in all parts of the distribution function. There are, however, some basins not included in Fig. 9 where the projected changes do deviate, e.g. in the African basins Niger and Congo, in the European basin Volga, and in the Yukon and Mackenzie River

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basins in North America. Again, the largest deviations are found for the VIC model, but at the lower ends differences exist also for LPJmL in the Volga River basin (IPSL) and mid ranges in the Yukon River basin (ECHAM). Figure 9 clearly illustrates that the consequences of using raw climate model output in hydrological simulations, as compared to using bias corrected climate model output, are higher if simulated water fluxes are to be compared to absolute values (e.g. water requirements) than if the focus is on relative changes in water fluxes.

4 Conclusions

This study demonstrates that radiation, humidity and wind speed values have potentially large effects on simulated water fluxes, and that using these values directly from climate models can result in very different evapotranspiration and runoff estimates than when using values based on reanalysis and observational data. The differences are relatively largest in energy limited areas where estimated incoming radiation deviates much. The study also shows that after introducing a simple bias correction procedure on radiation, humidity and wind speed values, the simulated water fluxes are much closer to the baseline results.

Projected relative changes in mean annual runoff (2071–2100 compared to 1971–2000) are fairly similar using original and bias corrected forcings (radiation, humidity and wind speed). Hence, introducing a bias correction may not change relative hydrologic projections much. Sub-annual relative differences are somewhat larger, but only in a few areas have it been shown that the bias correction causes significant alterations in the relative projections. However, as for the control period, the absolute values of simulated runoff and evapotranspiration are very different before and after introducing the bias correction. These differences are seen at all ranges of the simulated runoff distributions, and hence may influence e.g. water scarcity analyses considerably. When comparing the findings of this study to other studies, it can be concluded that bias correction of radiation, humidity and wind affect hydrologic projections less than bias correction of precipitation and temperature.

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Table 1. Participating hydrological models and input forcing datasets.

Model name	Reference(s)	Model time step	Meteorological forcing variables*	Input forcing datasets and time periods included in analyses		
				WFD Baseline forcing data 1971–2000	ECHAM, IPSL Bias corrected precipitation and temperature 1971–2000, 2071–2100	ECHAM-BC, IPSL-BC Bias corrected precipitation, temperature, short- and longwave radiation, humidity and wind speed 1971–2000, 2071–2100
LPJmL	Bondeau et al. (2007), Rost et al. (2008)	Daily	P, T, SW, LWn	X	X	X
MPI-HM	Hagemann and Dümenil (1998), Hagemann and Dümenil Gates (2003)	Daily	P, T	X	X	
VIC	Liang et al. (1994)	Daily/ 3 h	P, T_{max}, T_{min}, SW, LW, Q, W, SP	X	X	X
WaterGAP	Alcamo et al. (2003)	Daily	P, T, SW, LWn	X	X	X

* P: Precipitation, T: Air temperature, T_{max}: Maximum daily air temperature, T_{min}: Minimum daily air temperature, SW: Shortwave radiation flux (downward), LW: Longwave radiation flux (downward), LWn: Longwave radiation flux (net), Q: Specific humidity, W: Wind speed, SP: Surface pressure.

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Table 2. Mean annual global terrestrial evapotranspiration (ET) and runoff (*Q*) numbers ($km^3\,yr^{-1}$) for all model simulations included in this study. Original and bias corrected (BC) results for the control (1971–2000) and projection (2071–2100) periods.

	WFD 1971–2000		ECHAM Cntrl 1971–2000		IPSL Cntrl 1971–2000		ECHAM A2 2071–2100		IPSL A2 2071–2100	
	ET	*Q*	**ET** ET-BC	***Q*** *Q*-BC	**ET** ET-BC	***Q*** *Q*-BC	**ET** ET-BC	***Q*** *Q*-BC	**ET** ET-BC	***Q*** *Q*-BC
LPJmL	64 787	62 023	**75 670** 64 125	**52 799** 63 842	**66 650** 63 205	**60 429** 63 860	**68 107** 65 033	**70 183** 73 240	**78 455** 66 665	**64 070** 75 275
MPI-HM	82 270	44 506	**81 612**	**46 340**	**81 881**	**45 183**	**101 004**	**42 979**	**111 602**	**41 128**
VIC	71 309	55 774	**84 417** 75 900	**44 051** 52 455	**75 838** 71 793	**51 592** 55 622	**78 591** 74 804	**59 908** 63 711	**91 049** 84 418	**51 182** 57 798
WaterGAP	73 210	54 720	**82 427** 73 147	**46 203** 55 458	**76 085** 72 266	**51 685** 55 465	**80 061** 76 514	**58 719** 62 242	**86 694** 77 094	**55 640** 65 239

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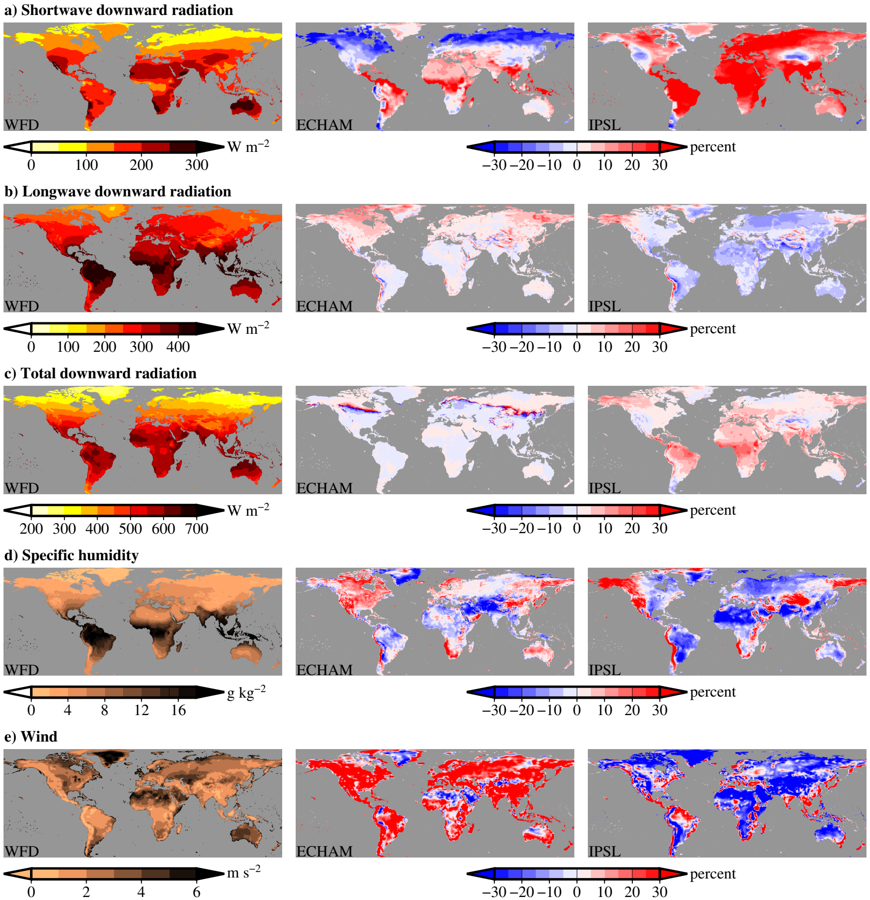

Fig. 1. Mean annual (1971–2000) WFD forcings and climate model anomalies. **(a)** Shortwave downward radiation, **(b)** longwave downward radiation, **(c)** total downward radiation, **(d)** specific humidity and **(e)** wind speed.

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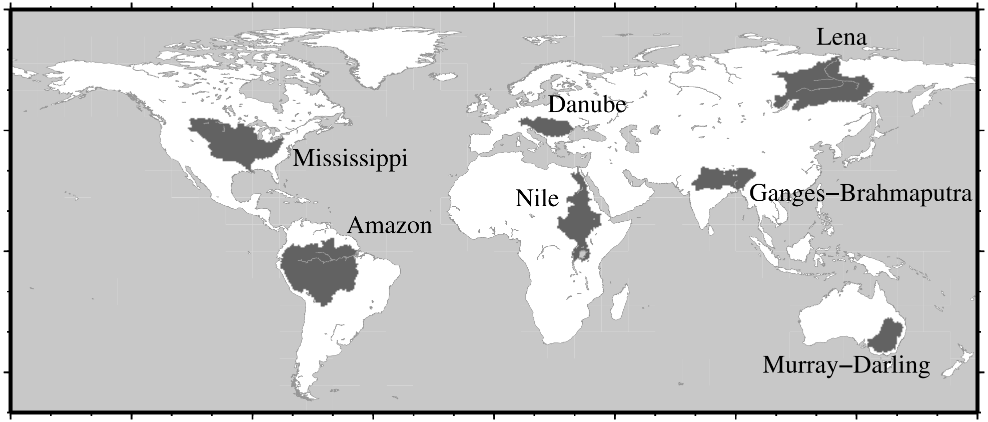

Fig. 2. Location of study basins.

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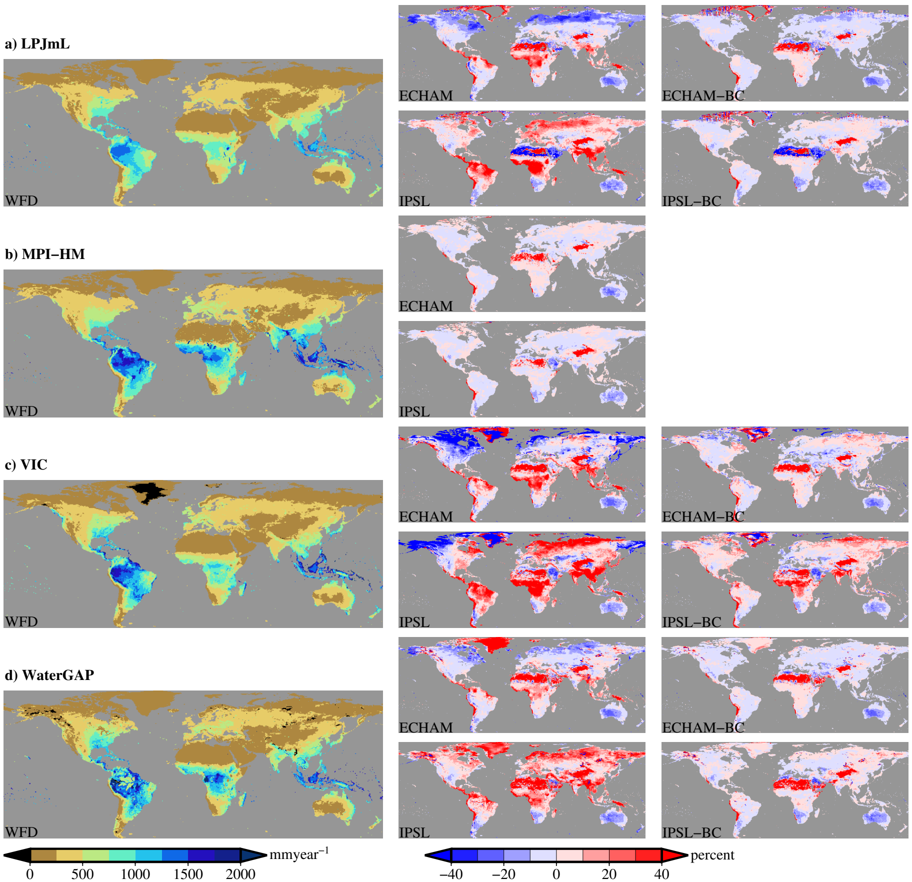

Fig. 3. Mean annual WFD evapotranspiration estimates for the **(a)** LPJmL, **(b)** MPI-HM, **(c)** VIC and **(d)** WaterGAP models, and climate model anomalies (original and bias corrected results when applicable).

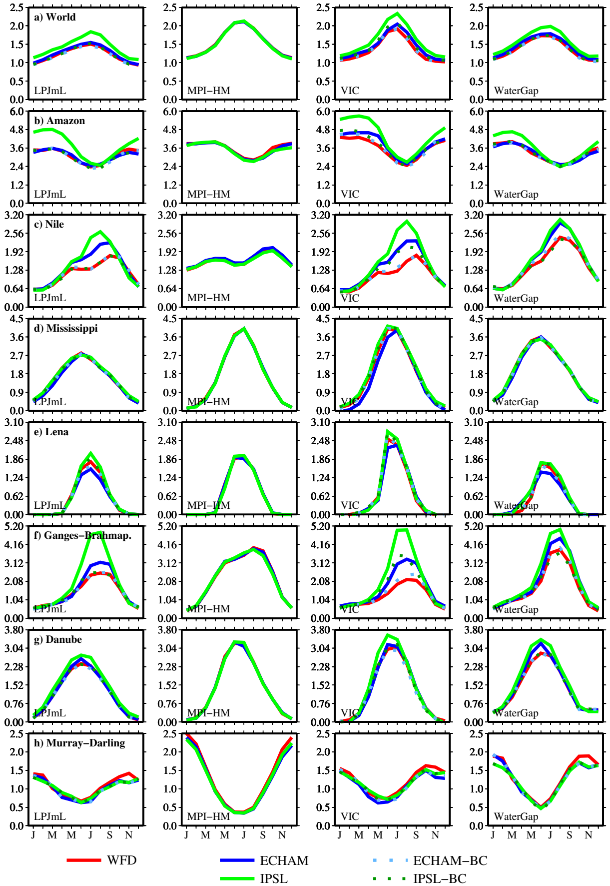

Fig. 4. Global terrestrial mean monthly simulated evapotranspiration (mm day^{-1}), and results for the study basins (control period; 1971–2000). Original and bias corrected results when applicable.

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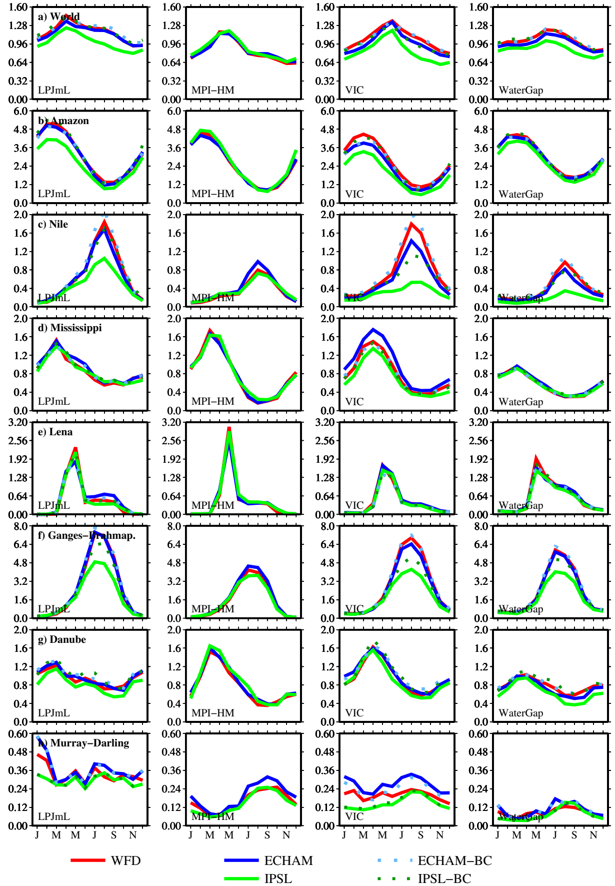

Fig. 5. Global terrestrial mean monthly simulated runoff (mm day^{-1}), and results for the study basins (control period; 1971–2000). Original and bias corrected results when applicable.

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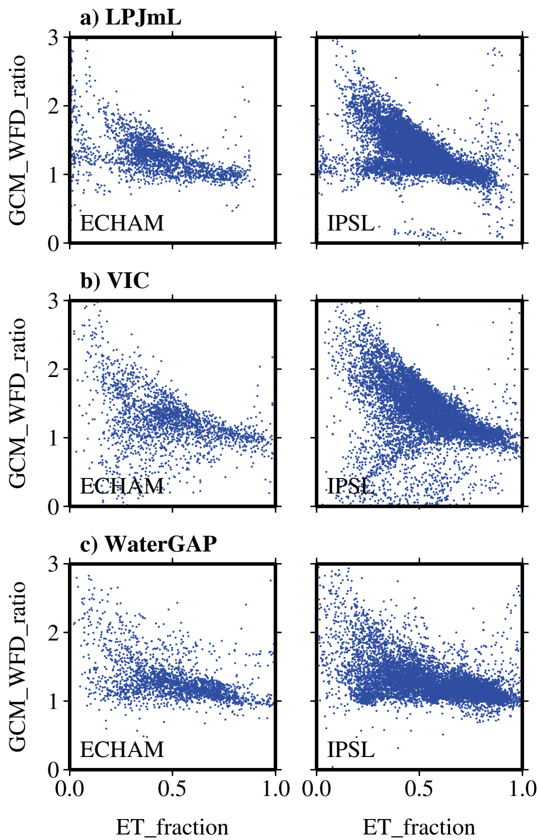

Fig. 6. Climate model evapotranspiration fraction divided by WFD evapotranspiration fraction (y-axis) plotted against the WFD evapotranspiration fraction (original results, control period, ECHAM to the left, IPSL to the right). Only cells where the climate model total radiation is more than 10 % higher than the WFD total radiation are included.

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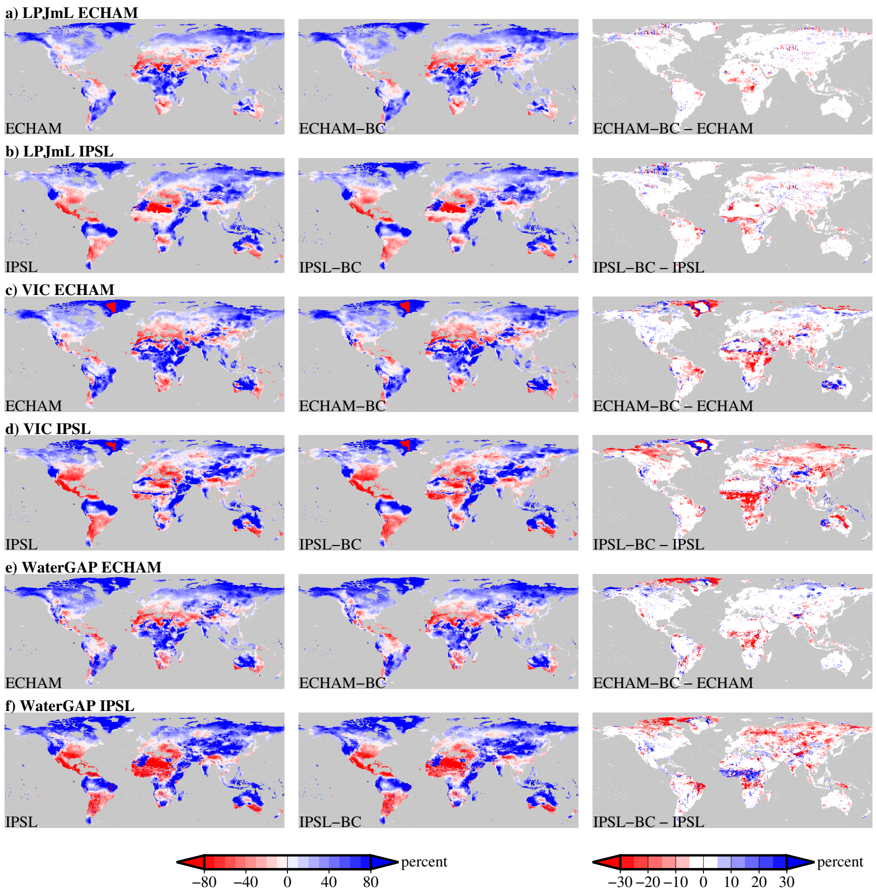

Fig. 7. Mean annual projected changes in simulated runoff; bias corrected results compared to original results. **(a)** LPJmL, **(b)** VIC, and **(c)** WaterGAP. BC denotes simulation results using bias corrected forcings.

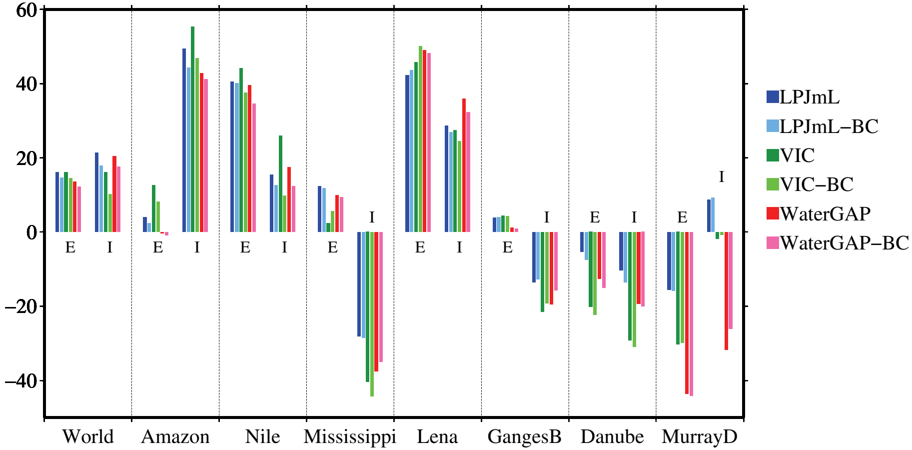

Fig. 8. Projected annual mean runoff changes (%), with and without bias correction (BC) in 2071–2100 relative to 1971–2000 for the LPJmL, VIC and WaterGAP models when using ECHAM (E) and IPSL (I) input datasets.

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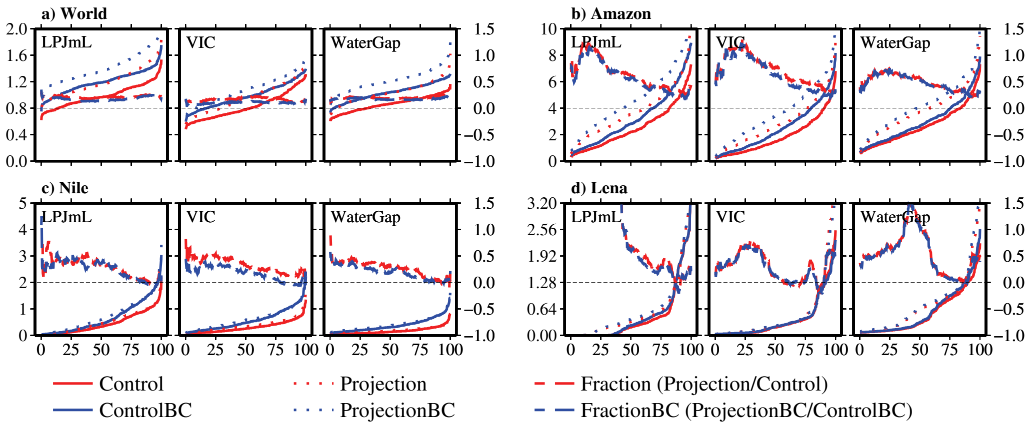

Fig. 9. World and basin cumulative distribution functions of monthly simulated runoff when using IPSL input data, 1971–2000 (control period) and 2071–2100 (projection period), with and without bias correction (left y-axis, numbers in mm day^{-1}). Included is also a comparison of the projection period results to the control period results (right y-axis, fraction).

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