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Discharge simulations performed with a hydrological model using bias corrected regional climate model input

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Abstract

Studies have demonstrated that precipitation on Northern Hemisphere mid-latitudes has increased in the last decades and that it is likely that this trend will continue. This will have an influence on discharge of the river Meuse. The use of bias correction methods is important when the effect of precipitation change on river discharge is studied. The objective of this paper is to investigate the effect of using two different bias correction methods on output from a Regional Climate Model (RCM) simulation. In this study a Regional Atmospheric Climate Model (RACMO2) run is used, forced by ECHAM-5 under the condition of the SRES-A1B emission scenario, with a 25 km horizontal resolution. The RACMO2 runs contain a systematic precipitation bias on which two bias correction methods are applied. The first method corrects for the wet day fraction and wet day average (WD bias correction) and the second method corrects for the mean and coefficient of variance (MV bias correction). The WD bias correction initially corrects well for the average, but it appears that too many successive precipitation days were removed with this correction. The second method performed less well on average bias correction, but the temporal precipitation pattern was better. Subsequently, the discharge was calculated by using RACMO2 output as forcing to the HBV-96 hydrological model. A large difference was found between the simulated discharge of the uncorrected RACMO2 run, the WD bias corrected run and the MV bias corrected run. These results show the importance of an appropriate bias correction.

1 Introduction

During the last few decades the world has become subject to a changing climate unprecedented in the last millennia. Temperature increase and other climate related changes will have large global impacts. According to IPCC (IPCC, 2007) climate projections for Northwest Europe one of the impacts is an increase in winter precipitation. This will increase the frequency and severity of extreme precipitation events. For the

Netherlands the KNMI ‘06 climate change scenarios foresee wetter winters and extreme precipitation amounts will increase (Hurk van den et al., 2006).

A large fraction of precipitation received by river basins is buffered in natural reservoirs, like soils, aquifers and lakes, and in artificial reservoirs. It is released only slowly. In a temperate climate such as is prevailing over the Meuse and Rhine basin, this generally results in a continuous flow of water. However, exceptional meteorological conditions can cause floods and longer periods of low flows (Wit de et al., 2001b). Occurrences in the past indicate that it is important to monitor and manage these rivers. As the Meuse is an almost purely rain-fed system, the seasonal and interannual variability of the hydrological regime of this river is more pronounced than that of the Rhine. It is also more likely to react stronger to the effect of global climate change (Uijlenhoet et al., 2001). Another aspect, which increases the variability of the system, is the substrate characteristics of the Meuse. The restricted dimension of the floodplain of the Ardennes Massif offers little room for natural flood retention areas, so water moves downstream relatively quickly.

By doing a statistical analysis of long observation records (1911–2002) for the Meuse basin, it was shown that the frequencies of wet days hardly changed, but the associated precipitation amounts have significantly increased since 1980 (Tu et al., 2005b). An average increase in extreme precipitation of 18% has been simulated by regional climate models over the recent history. The uncertainty of model simulations is significantly larger than the observed change. As different models, show the same trends (e.g. higher temperatures and more extreme precipitation) and there are no indications that these trends will change by abrupt climate change, the uncertainty does not completely overshadow the simulated change (Booij, 2002b). From recent simulations with (regional) climate models it appears that a large number of models, especially in summer, show dryness as a consequence of a strong hydrological feedback between the land surface and the atmosphere. This means that in these models the precipitation declines, which results in dehydration of the soil (STOWA, 2004).

The effect of climate change on the Meuse has been studied with different discharge models. The HBV-96 (hereafter HBV) model (Hydrologiska Byråns Vattenbalansavdelning; Hydrological Bureau Water balance-section; Bergström and Forsman, 1973) is, especially in Nordic countries, often used to simulate discharge response to a changing climate (Bergstrom et al., 2001).

Increased precipitation will lead to more frequent high flow conditions. This trend started in the second half of the 20th century, where an increased flooding probability has been observed (Pfister et al., 2004) and will probably continue during the 21st century (Wit de et al., 2001a; Wit de et al., 2007b). A significant increase since the beginning of the 80s of the 20th century has been demonstrated statistically (Tu et al., 2005a) This holds for the annual extremes, the winter high tides and discharges larger than 800 $m^3 s^{-1}$. De Wit (2001) states that simulations performed with a number of Global Climate Models (GCMs) suggest an increase in temperature, an increase in winter precipitation and a decrease in summer precipitation in the Meuse basin by the end of the 21st century. This results in a small decrease of the average discharge and a small increase of discharge variability and extreme discharges (Booij, 2005). It should be noted that simulations demonstrate that an extreme peak on the Meuse follows from a long period of moderate wet days instead of one or two extreme wet days (Aalders et al., 2004).

Also Regional Climate Model (RCM) simulations, driven by a range of Global Climate Model (GCM) projections, indicate a future with wetter winters and drier summers (Wit de et al., 2007a). On the occurrence of low flows in summer less research has been done. De Wit (2007a) studied the possible impact of climate change on the occurrence of low-flow generating meteorological conditions and on the impact of climate change on low-flows with HBV-model simulations. This research showed that it is challenging to project low flows for the future. In addition De Wit et al. (2007a) concluded that decrease of summer discharge does not necessarily mean that critical summer low-flows will become more severe and frequent. It was also found that the HBV-model, with a generally good performance, did not accurately simulate critical low-flows of the Meuse. So far, there is no ground to conclude that extreme low flows will occur more frequently (Warmerdam et al., 2001; Wit de et al., 2001b).

This paper will present the results a new high (25 km) resolution Regional Atmospheric Climate Model (RACMO2) forced by the a transient (1950–2100) simulation of the GCM ECHAM 5 using observed greenhouse gases for 1950–2000, and using the SRES A1B scenario for the 21st century. The RCM has been employed within the EU funded project ENSEMBLE (Lorenz et al., 2008). As such, the model uses a higher resolution than in earlier studies (Leander et al., 2007; Wit de et al., 2007a; Leander et al., 2008), presumably resolving the average and extreme discharges at the basin outlet better (Booij, 2005).

Another issue addressed in this paper is the use of bias correction methods. Bias corrections are applied because it has been shown that the simulated precipitation differs systematically from observed precipitation. Two non-linear bias correction methods were explored to correct the precipitation data generated by RACMO2. When linear corrections were made for the bias in the mean precipitation, it led to an underestimation of large quantiles of their distribution (Leander et al., 2007). It was found that a relatively simple nonlinear correction adjusting both the biases in the mean and variability led to a better reproduction of observed extreme daily and multi-day precipitation amount than the commonly used linear scaling correction. This also resulted in more realistic discharge extremes, suggesting that a correct representation of the variability of precipitation is important for the simulation of extreme flood quantiles (Leander et al., 2007). In this paper important details of non-linear bias correction methods will be shown. Two different bias correction methods will be applied to the RCM generated precipitation data. Subsequently, RCM output is used to drive the hydrological model HBV for the Meuse basin to investigate the effect of the bias corrections on the simulated discharges for present day and future climate conditions.

2 Meuse basin

The Netherlands is one of the smaller, highly populated countries in Europe. It forms the delta of a number of international river basins, including the Rhine and the Meuse. These rivers are used for multiple functions and have contributed to the prosperous development of Northwest Europe. The Meuse originates in France and flows through Belgium. Via the Netherlands it drains into the North-Sea. The Meuse is rain-fed and has a length of approximately 875 km. The basin has an area of 36 000 km^2, and covers parts of France, Belgium, Luxembourg, Germany and the Netherlands. Northwest Europe has a temperate climate, with frequent eastward moving Atlantic depressions, which results in a mean annual precipitation over the Meuse of 950 mm yr^{-1}. The spatial distribution patterns of rainfall in the Meuse basin are mainly the result of differences in altitude. The rainfall is highest in the Ardennes Massif (1500 mm yr^{-1}) and lowest in the lowlands (Pfister et al., 2004). The mean discharge of the Meuse at Liege for summer half year is 146 $m^3 s^{-1}$. In summer, flows are low and the evaporation rates are high. In the winter, it is 406 $m^3 s^{-1}$ with evaporation rates at the lowest level. The annual mean discharge for the Meuse at Liege is 276 $m^3 s^{-1}$ (Ashagrie et al., 2006). The Meuse has a relative fast response to rainfall, so it is relatively sensitive to both flooding and drought. The river flood waves do mainly occur during the winter half year.

3 Data and methodology

In this study the KNMI model RACMO2 (Lenderink et al., 2003) is used. The model is developed over the past few years and is the second version of a regional atmospheric climate model developed by KNMI. RACMO2 has been applied in the framework of PRUDENCE (Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects; e.g. Van den Hurk et al, 2005) and ENSEMBLES. The RACMO2 run used in this study is forced with output from a transient run conducted with ECHAM-5 GCM member 3, under the condition of the SRES-A1B emission scenario. ECHAM-5 is the fifth generation atmospheric general circulation model developed at the Max Planck institute for meteorology (Roeckner et al., 2003). The horizontal resolution of RACMO2 is approximately 25×25 km.

The changes in river discharges are estimated using both the direct and bias corrected output from RACMO2, to force the hydrological model. In studies using RCMs, systematic biases are considered, which result in under- or overestimation in precipitation or discharge. Leander et al. (2007) found that the simulated precipitation differed systematically from the observed precipitation. Both the temperature and the precipitation data created by RACMO2 are bias corrected in this paper. Temperature data are corrected using one method, and two bias correction methods are used to correct the precipitation data. The first bias correction method is developed by (Leander et al., 2007) for the Meuse. The second bias correction method is developed by Bakker (2008). Until now this latter method has only been applied to the Rhine river basin. The section below gives an overview of the used correction methods and the hydrological model used.

3.1 The HBV model

For this research the HBV model is used, to simulate discharge until 2100 with use of RACMO2 input. The HBV model is a rainfall-runoff model, which includes conceptual numerical descriptions of hydrological processes at the catchment scale. It was originally developed by Swedish Meteorological and Hydrological Institute (SMHI) in the early 70s to assist hydropower operations. An advantage of the HBV model is the large number of applications in more than 40 countries world-wide. Its applications cover basins in different climatological and geographical regions, ranging in size from less than one to more than 1 792 000 km^2 (Bergström et al., 1994; Bergström, 1995). In comparison, the Meuse basin has a surface area of 36 000 km^2.

The model consists of subroutines for meteorological interpolation, snow accumulation and melt, evapotranspiration estimation, soil moisture, runoff generation and a simple routing procedure between sub basins considering lakes. The processes infiltration excess overland flow, saturation excess overland flow and subsurface storm flow are represented by one fast flow component. Several sub basins can be combined to obtain the appropriate spatial scale (Booij, 2005).

The model used for this study is the HBV-96. For hydrological simulations, the Meuse basin is divided in 15 sub basins (Fig. 1). RACMO2 covers the basin by 15 grid boxes. The simulated area-average precipitation for each of the sub basins was obtained as a weighted average over the grid boxes covering the sub basin. The weights were determined as the fraction of the sub basin area falling within a specific grid (Leander et al., 2007). The HBV model is run with both bias corrected data, the uncorrected dataset and observed data.The input for the HBV model is temperature (T), precipitation (P) and potential evapotranspiration (PET). These values are simulated by RACMO2, or observed. The model is run for the period 1951–2100, and different time-slices will be used in the results.

3.1.1 Performance HBV model

In order to assess the performance of the HBV model, a run with observed temperature and precipitation data was executed. The output was compared to the measured river discharge data. The results are shown in Fig. 2.

As can be seen in Fig. 2 the measured discharge is slightly lower than the simulated discharge for nearly every month. The cause of this deviation is not known and may have multiple sources like the stage-discharge relationship, model calibration and the limited number of temperature and precipitation observations.

Table 1 gives more insight in the performance of the HBV model. The table shows a number of relevant statistics. For instance, the number of days with a discharge above 1500 $m^3 s^{-1}$ reflects the risk of flooding events (van Schrojenstein Lantman, 2004). Values below 60 m^3/s induce problems for shipping and other water supply functions (Wit de et al., 2007a). In this table it can be seen that, especially, discharge during spring and summer is overestimated. The observed value of the summer-half year mean is much higher than the measured value. The number of days below 60 $m^3 s^{-1}$ is almost twice as high for the measured values. This confirms that the HBV model has difficulties in simulating low flows.

3.2 Bias correction methods for RACMO 2 data

3.2.1 Temperature

For temperature, observed records from the Meuse basin were available from the period 1969–1998. See Fig. 1 for locations of observation stations. 30 years of output during the control period (arbitrarily taken to be the same years 1969–1998 in the forecast) of this run was compared to the observed values and showed a systematic bias. A non-linear bias correction was applied involving shifting and scaling to adjust the mean and variance.

The corrected temperature T^* can be obtained by:

$$T^* = \overline{T}_m + (\sigma\overline{T}_{o,s}/\sigma\overline{T}_{m,a})(\overline{T}_m - T_m) + (\overline{T}_{o,s} - \overline{T}_{m,a}) \quad (1)$$

where T_m is the uncorrected daily temperature from RACMO2, $T_{o,s}$ is the average of observed temperatures and $T_{m,a}$ is the corresponding basin average temperature from RACMO 2. An overbar denotes the 30 year average, subscript o the observed values, m the modeled values and σ the standard deviation

The 30 year average and the standard deviation were separately determined for each five-day period of the year as the ratio between the average observed and RACMO2 temperature in a 65-day running time window around the considered five-day period, following (Leander et al., 2007).

3.2.2 Precipitation

For precipitation observational records were available from the period 1969–1998 and a similar control period was created from the RACMO2 data. The bias for precipitation was corrected using two different methods. In the first method, a two-step correction

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was executed to correct for the wet day frequency (F_{wet}) and the wet day average (M_{wet}). A correction for F_{wet} is carried out by eliminating or creating wet days. M_{wet} is corrected by decreasing of increasing the wet day average. In the remainder of this report this procedure will be referred to as the "Wet Day (WD) bias correction".

The second correction method uses a non-linear method which corrects the coefficient of variation (CV) as well as the mean. Each daily amount of precipitation P is transformed to a new amount P^* using:

$$P^* = aP^b \tag{2}$$

The parameters $a$and b were estimated for each five-day period using a similar running time filter as for temperature. The value of b is determined such that the CV of the corrected daily precipitation matches that of the observed daily precipitation. a is calculated subsequently in order to match the mean of the corrected values to the observed mean. This bias correction will be referred to as the "Mean Variance (MV) bias correction". It is also described by Leander (2007, 2008).

Daily values of Potential Evapotranspiration (PET) for the RACMO2 run were calculated using daily values of PET for Belgian sub basins. Similar values for French basins were not available, and therefore the area-weighted average of the Belgian basins was used for this part. PET was derived for each of the sub basins from the daily temperature T using the relation:

$$\mathrm{PET} = [1 + \alpha_o(T - \overline{T}_o)]\overline{\mathrm{PET}}_o \tag{3}$$

With $\overline{T}_o$ the mean observed temperature (°C) and $\overline{\mathrm{PET}}_o$ the mean observed PET (mm/day) for calendar month m in the period 1969–1998. The proportionality constant α_m was determined for each calendar month by means of a regression of the observed values of PET for the Belgian part of the basin on the observed daily temperatures (Leander et al., 2007).

4 Result of bias corrections

4.1 Temperature

Bias corrections for temperature were performed on the RACMO2 data according to the methodology described in the previous section. The corrections are performed on each basin separately and are averaged for all 15 sub basins. Figure 3 shows monthly averages for the period 1969–1998 of the uncorrected and bias corrected temperature data for the Meuse basin.

In Fig. 3 the calculated absolute temperature bias for the period 1969–1998 can be seen. The graph shows the difference of RACMO2 data with the observational data before the non-linear bias correction and after correction. Figure 3 shows that the bias of the uncorrected data set is quite large, up to more than one degree in August and December. The bias is very variable between months. After correction the bias is reduced. The average reduction of the bias is 45% and especially the large biases are reduced, together with a decrease in variability. A stronger reduction of temperature bias could be achieved when the bias correction method is improved. The impact of further temperature bias reductions on simulated extreme flows is probably low (Leander et al., 2008).

4.2 Precipitation

For precipitation data two different bias correction methods were applied as described before. The corrections were performed on each sub basin and subsequently averaged for all basins. The MV method corrects for mean and variance, while the WD method corrects the wet day frequency and wet day average. All series shown are corrected for the period 1969–1998.

In Fig. 4 it is shown that the precipitation bias before correction is highly variable and overall quite large, with an average bias of around 25%. In summer the bias is lower than in winter, spring and fall.

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The WD correction reduces the bias largely. While the original bias varied between almost zero and 43%, the corrected data show a consistently low average bias of 1%. It seems that this correction method is very well capable of reducing the average bias. The MV bias correction method shows more variability and a larger remaining bias, with an average of 6%. This is still quite a reduction in comparison with the original bias of 25%. Only the basin and monthly averaged values are shown.

Table 2 gives more information about the bias correction methods. Some statistics of daily precipitation are shown for comparison of both methods with the uncorrected data. A distinction is made between winter and summer half-year. The coefficient of variation (CV) is calculated as the ratio between the standard deviation (St.Dev) and the mean.

The differences between observed values (OBS) and the RACMO2 control uncorrected data for winter half-year are larger than the differences for the summer-half year. Again the reason for these smaller differences in summer could be that the total amount of precipitation and the extremes are smaller in this period. Table 2 shows that RACMO2 overestimates the amount of precipitation in all seasons. M_{wet} is estimated quite well by uncorrected RACMO2 data, while F_{wet} is overestimated for both winter and summer half year (see also Fig. 4). It means that the simulated amount of wet days is too large, while the mean amount of rainfall on these wet days is estimated fairly well. After both bias correction methods the average values are corresponding much better with observed winter and summer values. For both corrections this is approximately the same. The standard deviation and coefficient of variation (CV) are estimated better by the MV method, but also the WD method results in a reduced CV. The M_{wet} and F_{wet} are clearly estimated better by the WD bias correction method. This is not very remarkable, because the WD bias correction is aimed to produce correct values of M_{wet} and F_{wet}.

As mentioned in the introduction, extremes in discharge are often preceded by multiple days of heavy rainfall. A realistic simulation should represent this temporal signature. To check whether this is the case, the yearly maxima of the ten-day precipitation totals are calculated and displayed for both bias correction methods and the observed rainfall in Fig. 5 as function of the reduced Gumbel variate.

Figure 5 shows that the WD bias correction gives substantially lower results than the observed data. The uncorrected model output and MV bias correction resemble the observed data set better. This graph shows that the WD bias correction reduces the number of successive rainy days, which are generally responsible for high discharge levels. The WD bias correction produces less high flood peaks which has an impact on modelled future extreme discharges. Figure 6 shows the observed period in comparison to the RACMO2 scenario period 2071–2100. The MV bias corrected data simulates increase of the number of successive rainy days for the scenario period than present in the observed data. This implies that more high discharges will be simulated by the HBV model.

Figure 7 shows the relative change in the annual cycle of precipitation between the control period and the end of the 21st century using both bias correction methods. The data are basin and monthly averaged. For the end of this century it is projected that the winter precipitation will increase and the summer period will be drier. The average change in summer (April–September) is −10% for the WD bias correction method and −7% for the MV bias correction method. The average change in winter is +19% for WD and +29% for the MV method. The summer change is fairly similar for both corrections, but the MV bias correction shows a much larger average change for the winter period. This is probably related to the wet day fraction corrected by WD, and the small change of the mean precipitation on wet days.

5 Results HBV model

Figure 8 displays the average monthly discharges of calculated observed values and the RACMO2 runs. The simulated discharges for 2071–2100 are higher than the current discharges, but there is a large variability between the different RACMO2 runs. The original RACMO2 run overestimates the discharge, which is related to the temperature and precipitation bias. The difference between the two bias corrections is not very large. The MV bias correction estimates the discharge to be slightly higher than the WD bias correction. Summers are expected to become drier and the results on low flows seem to confirm this. The number of days with less than 60 $m^3 s^{-1}$ is higher for the RACMO2 runs than simulated for the control period 1969–1998.

The results of the discharge simulation runs with the HBV model are displayed in Table 3. The HBV-CTL values are simulated from the observed temperature and precipitation data. These values are compared to the control period of RACMO2 uncorrected and the control and scenario period of RACMO2 bias corrected statistics.

Table 3 shows that the annual mean of the control period 1969–1998 is overestimated by all RACMO2 runs. The higher values are also visible in winter and summer half-year mean. The overestimation of the annual mean is similar for the WD bias correction method (7%) and for the MV bias correction method (5%). The difference in average precipitation between the observed values and both correction methods was less than 1%. The table also shows that the number of days with more than 1500 $m^3 s^{-1}$ discharge is reduced by both bias correction methods. This indicates that extremes are not simulated accurately and could be underestimated.

In Table 3 the scenario period of both RACMO2 bias corrected runs are also shown. Both bias corrected runs show an increase of discharge for the simulated 30 year scenario period at the end of this century, compared to their control simulations. RACMO2 WD shows an increase of almost 9% between the future and control simulations. RACMO2 MV results in a much larger increase of 20%. For the number of days above 1500 $m^3 s^{-1}$ the WD correction method shows only a small increase, while RACMO2 MV has a very large increase. Note however that Fig. 5 showed that the WD method overcorrects the number of successive precipitation days. This effect is also visible in the maximum discharge, which is considerably lower than the HBV-CTL maximum and the values of the other RACMO2 runs. The future scenario of RACMO2 WD even has a lower maximum than the present day climate. In Fig. 6, it was also shown that the MV method yields higher values for the 10-day precipitation amounts. This effect could

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result in a higher extreme discharge. The number of days with a moderately high discharge between 800 and 1500 $m^3 s^{-1}$ is higher for the both RACMO2 runs. Overall, in spite of the large differences, the RACMO2 data do indicate that with the A1B scenario, used in the RACMO2 ECHAM 5 run, the river Meuse will have substantial higher peak discharges at the end of this century.

For low flow the threshold value is 60 $m^3 s^{-1}$. A sensitivity analysis shows that the discharge below and above this threshold decreases or increases linearly with days. Table 3 shows that the number of days below 60 $m^3 s^{-1}$ almost doubles for both bias corrected scenarios. The summer half-year mean decreases with almost 17% for the WD bias correction and with almost 13% for the MV bias correction method. This is consistent with the expectations of drier summers: the precipitation decrease for WD method was 10% and for MV 7%. As evaporation rates are much higher in the summer, it is expected that the decrease in discharge is higher.

6 Discussion

A problem with the use of RCMs for hydrological purposes is that the simulated precipitation differs systematically from the observed precipitation. This is observed in multiple studies (Jacob et al., 2007; Leander et al., 2007; Leander et al., 2008). Two different bias correction methods are used to correct the precipitation records. The results show large differences between these correction methods. The WD bias correction method shows almost no remaining bias in Fig. 4, but Fig. 5 shows that this method removes too many successive precipitation events. The HBV model hardly simulates extreme discharges with input of the WD bias corrected RACMO data. The bias of the MV method compared to the observed data is a little larger, but the average is simulated well and the standard deviation and CV are simulated better than the WD bias correction method. The yearly maxima of the ten-day precipitation totals are well simulated.

For the WD bias correction the mean increase in winter discharge is 23%, which is higher than the relative increase in precipitation. For summer discharge the decrease in discharge is 17%, which is also higher than the relative decrease in precipitation. For the MV bias correction the same applies, with a mean increase in winter discharge of 38% and a mean decrease in summer discharge of 13%. In winter the increase in precipitation is somewhat lower than the increase in discharge, which means that the water storage changes in the winter. In summer the decrease in precipitation is lower than the decrease in discharge, due to increased evaporation rates in summer.

The maximum discharges of the WD bias correction are not higher than the maximum discharge of the historical period. This was expected, because the method corrected for the days with successive heavy rain, which is needed for high discharge (see Fig. 5). The uncorrected and MV corrected discharge shows higher values than the observed period 1969–1998. This was expected from Fig. 6, which shows that the scenario period of MV has more successive rainy days than the period 1969–1998.

It is projected that winters will become wetter and extreme precipitation amounts will increase (KNMI, 2006). The results of this study, using a high resolution A1B RACMO2 scenario, show that HBV simulates higher discharges for the Meuse at the end of this century. This confirms results from previous studies on discharges (Wit de et al., 2001a, 2007b; Booij, 2005).

Only the SRES scenario A1B is used in this study, and the results need to be confirmed by using a more comprehensive set of GCM simulations (Leander et al., 2008) as changes in mean precipitation, change in the CV of 10-day precipitation amount are controlled strongly by the driving GCM.

The HBV model seems to have systematic biases, which result in over- or underestimations of the discharge. Research did point out that is not quite clear how well HBV can describe flood peaks (Booij 2005; Leander et al. 2005). De Wit (2007b) observed some deviations in the HBV model for the 1985–1998 record. The HBV model simulates monthly average discharges well for the months with the highest (January) and lowest (August) discharge, but they are generally overestimated during spring and underestimated during autumn. It also appears that in HBV most of the summer precipitation infiltrates the surface, whereas in reality summer precipitation often results in small but fast responses in river discharge. Leander et al. (2005) stated that the model does not consider the possibility of inundations upstream of Borgharen. This may limit the amount of water that can reach the Netherlands.

For the critical low discharge this research only partly confirmed the results of De Wit (2007). The HBV model does simulate substantially more low flows for the end of this century. However, the HBV model overestimates the discharge in the summer period. Reason for this could be that refill from groundwater aquifers compensate for the reduced precipitation and increased evapotranspiration. Another reason could be that HBV has problems with simulation of low flows. If the model is validated specifically against low-flow indices the performance could be improved (Wit de et al., 2007a).

The results of this study emphasize the importance of an adequate bias correction method. The bias corrections are developed using data from the period 1969-1998 and are applied on the whole RACMO2 run of 1951–2100. Here the assumption is made that the corrections done for the historical period can also be applied to the period 1998–2100. It is important that these methods are tested when more historical records are available.

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Table 1. Statistics of modeled and observed values over period 1969–1998 at Borgharen. HBV-CTL values are model calculations using observed temperature and precipitation records.

	Modeled values (HBV-CTL)	Observed values
Annual mean (m^3/s)	257	227
No of days >=1500 $m^3 s^{-1}$ (%)	0.4	0.5
No of days 800 < >1500 $m^3 s^{-1}$ (%)	4.6	4.2
No of days <=60 $m^3 s^{-1}$ (%)	15.7	29.0
Maximal discharge (m^3/s)	2837	2959
Minimal discharge (m^3/s)	8.5	0
Winter half-year mean (m^3/s)	329	320
Summer half-year mean (m^3/s)	183	132

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Table 2. Statistics of both correction methods. OBS means observed values for the period 1969–1998. St.Dev. means standard deviation and CV means coefficient of variation. M_{wet} [>=0.3] are the number of days with an average of more than 0.3 mm precipitation. F_{wet} [>=0.3] refers to the percentage of wet days. The statistics are averages over all sub-basins. Winter half-year is from October to March, summer half-year is from April to September. No-corr means uncorrected RACMO2 data. WD or MV refer to the bias correction methods applied to the RACMO2 data.

1969–1998	**OBS Winter**	No-corr	WD	MV	**OBS Summer**	No-corr	WD	MV
Average	**2.78**	3.60	2.79	2.77	**2.43**	2.81	2.44	2.42
St. Dev	**4.78**	4.89	4.61	4.77	**4.42**	4.55	4.51	4.42
CV	**1.73**	1.36	1.66	1.72	**1.82**	1.63	1.85	1.84
M_{wet} [>=0.3]	**4.97**	4.93	4.99	4.49	**4.85**	4.66	4.90	4.32
F_{wet} (%) [>=0.3]	**55.3**	72.2	55.2	61.1	**49.9**	59.8	50.1	55.7

Table 3. Statistics of the various HBV runs using observations (CTL) and uncorrected and corrected RACMO runs for the control and future periods. The HBV-CTL values reported in Table 1 are repeated here for comparison reasons.

	HBV-CTL	RACMO2 uncorrected	RACMO2 WD		RACMO2 MV	
	1969–1998	1969–1998	1969–1998	2071–2100	1969–1998	2071–2100
Annual mean ($m^3 s^{-1}$)	256	413	274	298	271	325
No of days >=1500 $m^3 s^{-1}$ (%)	0.4	1.4	0.2	0.3	0.3	1.5
No of days 800< >1500 $m^3 s^{-1}$ (%)	4.5	13.6	4.6	9.0	4.9	11.5
No of days <=60 $m^3 s^{-1}$ (%)	15.7	7.3	13.5	25.7	15.1	26.7
Maximal discharge ($m^3 s^{-1}$)	2836	3224	2384	2069	2868	3017
Minimal discharge ($m^3 s^{-1}$)	8.4	29.6	23.8	3.2	18.5	2.8
Winter half-year mean ($m^3 s^{-1}$)	329	546	354	433	347	478
Summer half-year mean ($m^3 s^{-1}$)	182	412	194	161	194	169

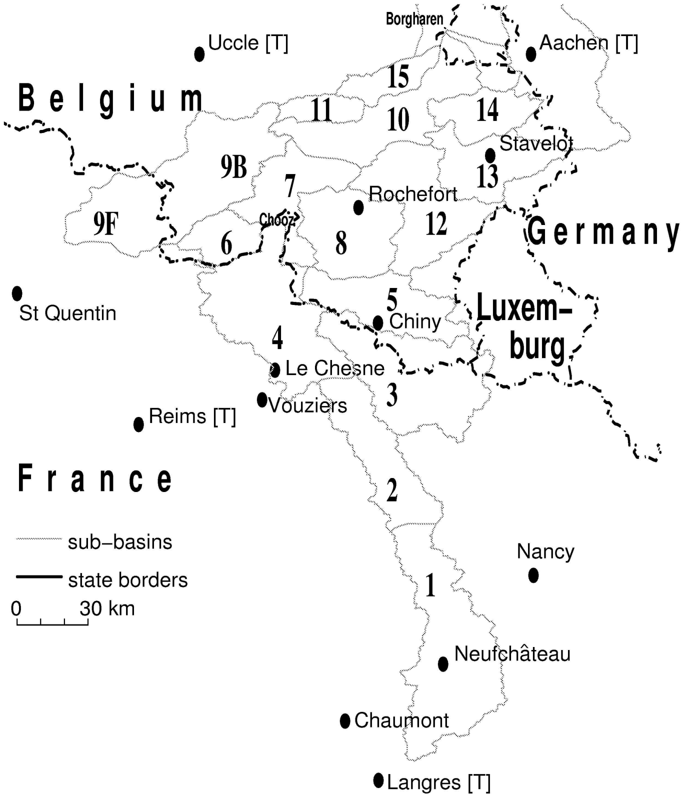

Fig. 1. Meuse Basin and observation stations.

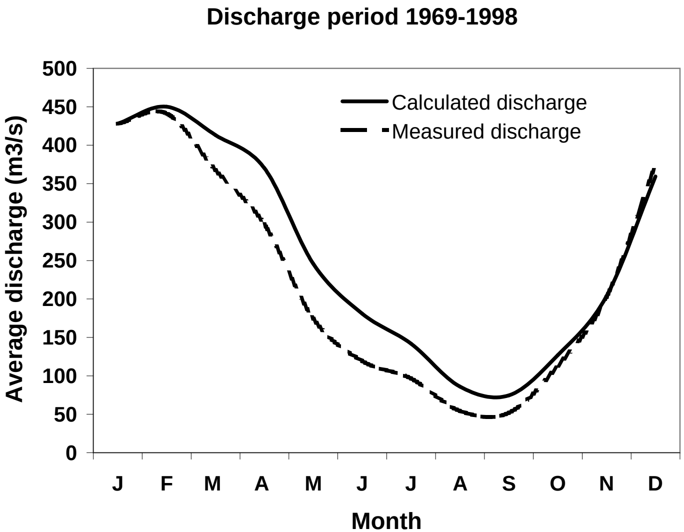

Fig. 2. Performance of the HBV model. Shown are the mean annual cycle of calculated discharge with use of observed temperature and precipitation and measured discharge at Borgharen for period 1969–1998. The discharge is averaged over 30 years.

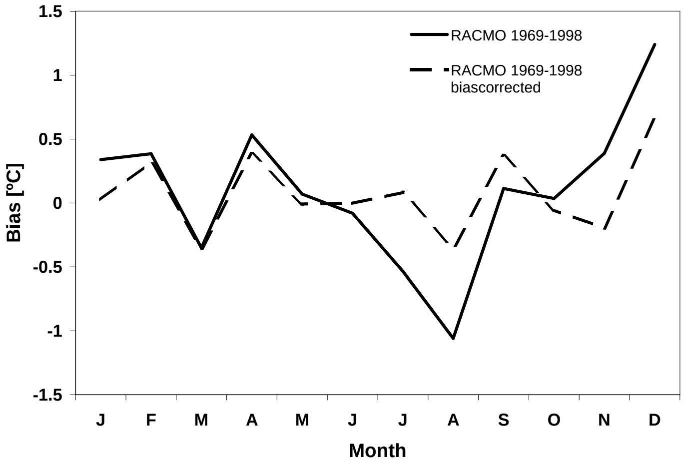

Fig. 3. Absolute temperature bias of RACMO2 data compared to observed data for the period 1969–1998, before and after bias correction. The bias is shown per month, averaged over all 15 sub basin and 30 years

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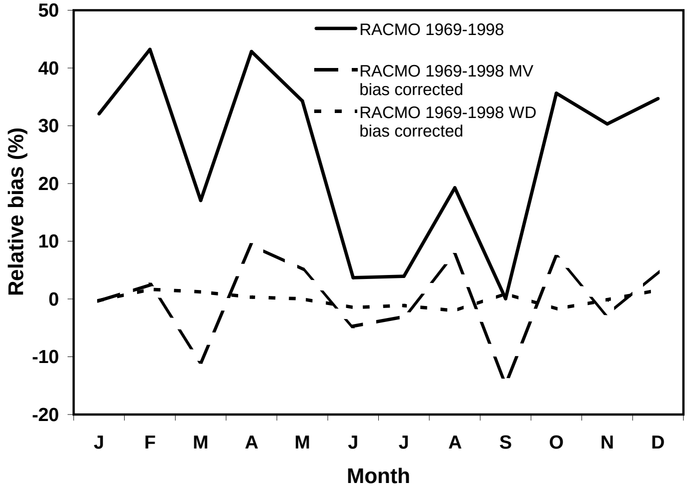

Fig. 4. Relative bias of RACMO2 data compared to the observed data for the period 1969–1998, before and after bias corrections. The bias is shown per month, averaged over all 15 sub basins and 30 years

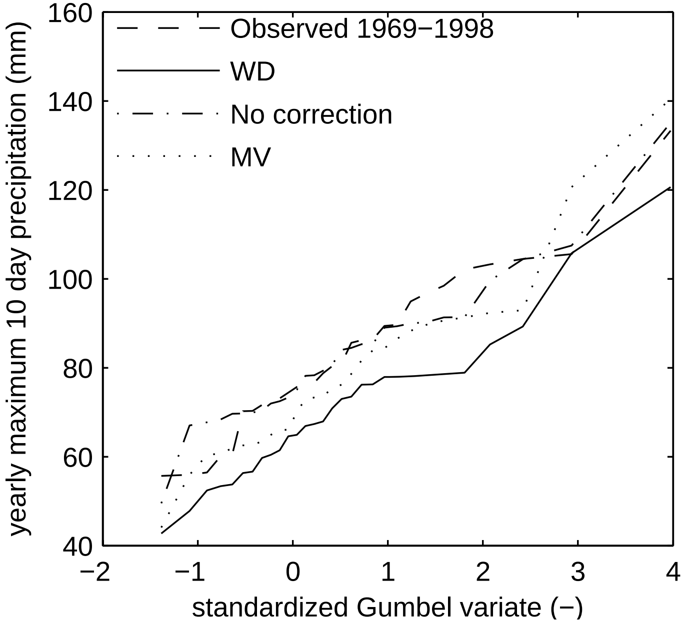

Fig. 5. Gumbel plot with ten-day precipitation amounts. Both observed and modeled values are shown, including RACMO2 data with no bias correction, WD bias correction and MV bias correction. All data refer to the period 1969–1998.

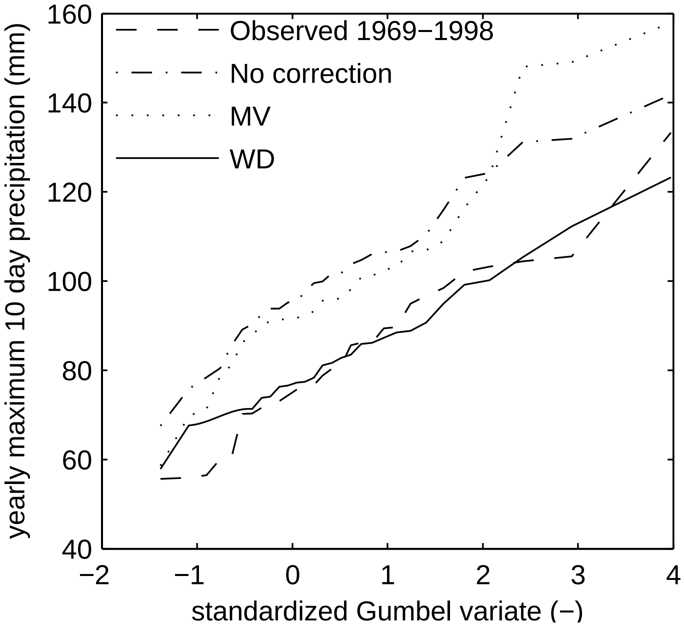

Fig. 6. As Fig. 5, for the scenario period 2071–2100.

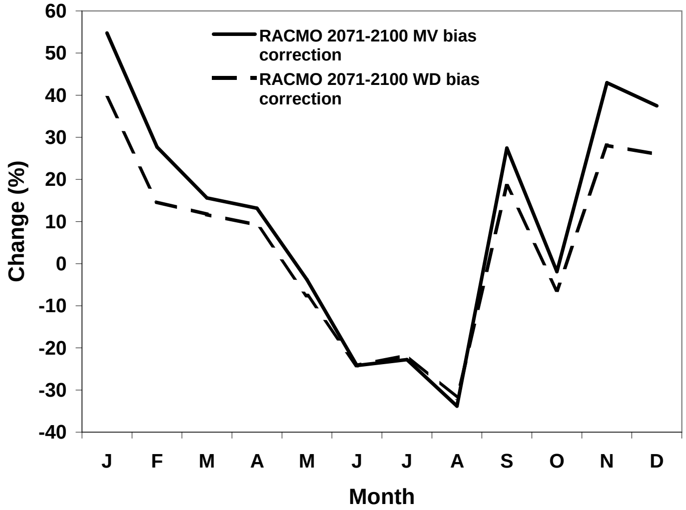

Fig. 7. Relative change of precipitation in the Meuse basin. The simulated scenario period 2071–2100 of RACMO2 MV and WD bias corrections is compared to the RACMO2 control period 1969–1998.

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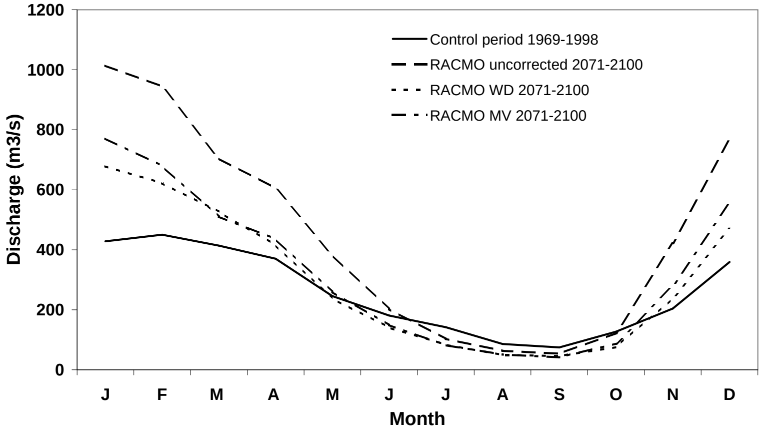

Fig. 8. Discharge at Borgharen calculated by the HBV model. The input was the observed precipitation and temperature values for the control period, as well as simulated precipitation and temperature values of the three RACMO2 runs.

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