Hydrological and climatic uncertainties associated with modeling the impact of climate change on water resources of small Mediterranean coastal rivers

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This paper investigates the uncertainties associated with using regional climate models and one hydrological model calibrated from non-stationary hydroclimatic time series to simulate future water resources of six Mediterranean French coastal river basins. First, a conceptual hydrological model (the GR2M model) was implemented in order to reproduce the observed river discharge regimes. Climatic scenarios were then constructed from a set of Regional Climate Models (RCMs) outputs and fed into the hydrological model in order to produce water discharge scenarios for the 2071–2100 period. At last, an assessment of uncertainties associated with the hydrological scenarios is given.

With respect to the 1961–1990 period, RCMs project a mean annual temperature increase of 4.3–4.5 °C (3.1–3.2 °C) under the IPCC A2 (B2) scenario. Precipitation changes, although more variable, indicate a decrease between −10% and −15.6% for A2 and between −6.1% and −11.6% for B2. As a result, the GR2M model simulates a general water discharge decrease between −26% (−14%) and −54% (−41%) for the A2 (B2) scenario, depending on the basin of interest.

Sensitivity tests on the hydrological modelling revealed that the hydrological scenarios are sensitive to the choice of the *PE* formulation, although this climatic input is negligible in the model calibration. Also, a slight but significant drift between the modelled and observed time series was detected for most basins, indicating that the hydrological model fails to adapt to non-stationary discharge conditions. A simple correction method based on a dynamical parametrization of one model parameter with temperature data considerably reduces the model drift in half of the investigated basins. When extrapolated this new parametrization to the future climate scenarios, decrease of water discharge is found to be twice as great as estimated from the standard parametrization. Our results suggest that the uncertainties stemming from hydrological models with fixed parametrizations should be further addressed in any climate change impact study.

1. Introduction

It is now largely recognized that the Mediterranean region is particularly sensitive to future climate change. Simulations made by General Circulation Models (GCMs) project a high temperature increase combined with a general precipitation decrease over the 21st century (IPCC, 2007; Giorgi and Lionello, 2007). The projections are robust and consistent between simulations, which identifies this region as one of the most prominent "hot-spots" in the context of climate change (Giorgi, 2006).

Many studies showed that changes in climate conditions have played a major role on the trends detected in hydrological time series in this area. Liquete et al. (2005) reported decreasing trends in water discharge time series of many rivers in Andalusia (southern Spain), which they attributed mainly to climatic factors (temperature increase and precipitation decrease). Lòpez-Moreno et al. (2008) demonstrated that changes in precipitation, temperature, snow accumulation together with an increase in vegetation density led to a marked reduction in water resource in the southern Pyrenees. Lespinas et al. (2009) analysed the hydroclimatic evolution of six Mediterranean coastal rivers located in southern France over the 1965–2004 period. They showed that changes of climatic conditions have contributed to reduced water resources by about 20% in this region. At larger spatial scales, Ludwig et al.

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(2003, 2009) performed trend analyses on 37 Mediterranean and Black Sea rivers for which 20 years of observed discharge data were available. They showed that most of the Mediterranean rivers reveal strong negative trends since the early 1960s, indicating that the decrease in freshwater discharges is a general phenomenon in the Mediterranean drainage basin. The authors also found that precipitation decreased and contributed to reduced water resources in this area (Ludwig et al., 2010). GCM simulations indicate that this trend will continue in the future, associated with more frequent droughts (Lehner et al., 2006), leading to an increase in water demands for irrigation (Döll, 2002). This will in turn affect the ecological, social and economic systems in this region. An assessment of the future evolution of water resources in the Mediterranean drainage basin is complicated due to the fact that most modelling studies are large scale evaluations (e.g. Arnell, 2003; Milly et al., 2005; Ludwig et al., 2009, 2010). Very few studies have focused on the effects of future climate change on small coastal basins, mainly because of the incapacity of current GCMs to provide reliable hydroclimatic information at the local scale (Elguindi et al., 2011). Small coastal river basins are however very abundant in this part of the world (Milliman, 2001), often characterized by highly variable morphologies and contrasted runoff patterns. Omitting these basins in general evaluations may considerably bias estimates of future freshwater fluxes to the Mediterranean Sea.

There are many uncertainties related to the climatic models, scenarios and the hydrological model used in climate change impact studies (Chen et al., 2011; Arnell, 2011). These uncertainties are usually assessed via combinations of GCMs and hydrological models (Booij, 2005; Jiang et al., 2007), assuming that the range of the different projections between GCMs and hydrological models is representative of their respective uncertainties. This can even allow ranking the different sources of uncertainty relative to variability of their outputs (Wilby and Harris, 2006). Most often, the uncertainties from climate scenarios and downscaling of different GCMs are considered as the major uncertainty sources (Wilby and Harris, 2006; Chen et al., 2011; Teng et al., 2012). For these reasons, most studies focus mainly on the uncertainties related to climate modeling, notably in our study area (Quintana Segui et al., 2010).

However, these conclusions have to be taken with care. First, the number of GCMs used is usually more important than the number of hydrological models, which prevents the ability to compare statistically both uncertainty sources. Second, it is commonly assumed that the uncertainties in hydrological modeling can be fully represented by using different hydrological models. However, it is now well established that, in non-stationary conditions, additional uncertainties exist coming from the parameter instability due to the possible changes in the physical catchment characteristics and in the dominant processes (Brigode et al., 2013). Furthermore, many studies showed that the model parameters are highly dependent on the climatic characteristics of the period used to calibrate the hydrological models (Vaze et al., 2010; Merz et al., 2011; Coron et al., 2012). These additional uncertainties are mostly ignored in the climate change impact studies.

This paper addresses these problems. In complement to the retrospective study of Lespinas et al. (2009) it proposes future scenarios on the water resources of six French Mediterranean coastal rivers by the end of the 21st century. A conceptual hydrological model was implemented for these river basins for recent years and then forced by future climate scenarios constructed from an outputs set of Regional Climatic Models (RCMs). The fact that water discharge of the investigated rivers followed a general negative trend over the last decades allows testing the ability of the hydrological model to reproduce non-stationary conditions.

The choice of the hydrological model is crucial and mainly depends on the available data and study objectives. In our case, the studied rivers have strong intra-annual flow variability due to both intense flash-flood events that occur mainly in spring and autumn as well as low water periods in summer. Moreover, the discharge values are influenced by presence of dams and thus are not representative of the natural variability of the considered rivers. Lastly, the regional climate models still suffer from large uncertainties regarding the expected changes in precipitation extremes, especially in the investigated area (Boberg et al., 2009; Buonomo et al., 2007). These observations make studying the effects of climate change on extreme flows in the investigated basins difficult. For these reasons we focused our study on the general evolution of the overall water availability, which is generally well represented by a monthly time step conceptual hydrological model. The GR2M model was chosen because it was previously adapted in a region encompassing the studied basins. Our specific objectives were to: (i) test whether the model implementation allows reproducing the hydrological regimes and trends observed over the 1965–2004 period, (ii) produce estimates of the expected changes in water resources by the end of the 21st century and (iii) evaluate the uncertainties related to these estimates.

2. Data and regional settings

2.1. Observed hydrometeorological data

As input climate variables, the GR2M model only requires monthly values of precipitation (P) and potential evapotranspiration (PE) averaged over the drainage basins of interest (Fig. 1). P values were estimated from spatialization of station observations while PE values were estimated from temperature (T) data because of the very limited availability of PE observations in our study region. These data were obtained for the 1960–2004 period from the Climathèque database server (http://climatheque.meteo.fr).

Specific attention was given to collection and treatment of climatic data in order to obtain a dataset as complete and homogeneous as possible. Only meteorological stations that contained less than 20% gaps were taken into account, which led to the selection of 117 precipitation and 44 temperature stations (see Lespinas et al., 2009 for a location map of the meteorological stations). All climatic data series were submitted to a homogenization procedure before being interpolated via a Kriging-based method in order to produce spatial grids covering the entire study area (see Lespinas et al. (2009) for more details). The spatially averaged monthly values of P and T were then extracted for each of the six drainage basins. PE values were estimated from T using the empirical formulation developed by Folton and Lavabre (2004) for synoptic stations located in southern-eastern France. This formulation was developed from monthly T and PE (calculated according to the Penman–Monteith equation) values recorded at 68 meteorological stations and has the following form:

$$PE\ (\text{mm}) = a \cdot \left(\frac{T+20}{10}\right)^{b} + \left(\frac{Z}{100}\right)^{c} \quad (1)$$

T is the monthly mean temperature (in °C), Z the mean elevation (in m) of the basin and a, b and c three coefficients (without units; Table 1) that were adjusted by maximising the Nash–Sutcliffe efficiency (NSE; Eq. (2) in Section 3.2 but replacing $\sqrt{Q}$ by PE). It can be noted that the a coefficient values differ significantly between months, with the greatest values in spring and summer and the lowest values in autumn and winter. This indicates that temperature has the greatest influence on PE in the warm season. Folton and Lavabre (2004) showed that the b parameter could be fixed at the same value for two 6-month periods without reducing the accuracy of the PE estimates. They also observed that the PE values were underestimated for elevated stations if only the coefficients a and b

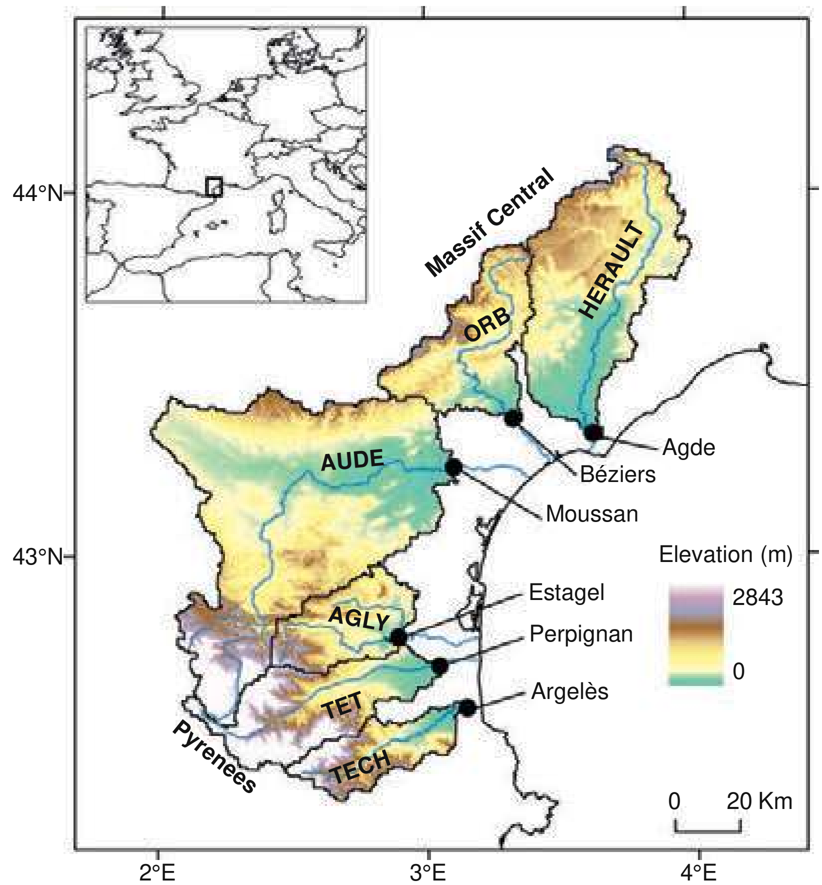

Fig. 1. Location map of study basins (black contours) with the associated gauging stations (black circles). A Digital Elevation Model constructed from the last Shuttle Radar Topography Mission (Jarvis et al., 2006) is included as background.

Table 1
Values of the coefficients a, b and c of Eq. (1) used to calculate the monthly *PE* values.
Source: Folton and Lavabre (2004).

Month	*a*	*b*	*c*
January	0.21	4.70	1.00
February	0.29	4.70	1.00
March	2.54	3.10	1.30
April	2.65	3.10	1.30
May	2.62	3.10	1.30
June	2.19	3.10	1.30
July	1.96	3.10	1.30
August	1.73	3.10	1.30
September	0.16	4.70	1.30
October	0.15	4.70	1.00
November	0.15	4.70	1.00
December	0.18	4.70	1.00

were considered. They therefore added a supplementary term that reflects elevation (Z) and a third coefficient (c) in order to correct this bias.

The choice of the *PE* formulation used, although potentially well adapted for the study area, constitutes a non-negligible uncertainty source for the hydrological scenarios in the future. In fact, many studies concluded that the results of climate change impact studies can be quite sensitive to *PE* formulation (Kay and Davies, 2008; Gosling and Arnell, 2011). To take into account this uncertainty source, sensitivity tests based on other commonly applied temperature-based *PE* formulations will be presented in the Section 5.2.1.

Monthly discharge data (Q) were obtained from the HYDRO database hosted at the French Ministry of Environment. They were acquired for the hydrological stations located at the outlet of each drainage basin which contained less than 15% of missing values (except for the Argelès gauging station which has 30% of missing values). Some missing data could be reconstructed from neighbouring stations when correlation between both series was highly significant ($r^2 > 0.97$; see Lespinas et al. (2009) for more details on the selection and processing of the discharge data).

2.2. Basins characteristics

The rivers considered in this study are the Hérault, Orb, Aude, Agly, Têt and Tech rivers (Fig. 1). All are situated in southern France, between the Rhône River to the north-east and the Spanish border to the south-west. The first two rivers originate in the southern slopes of the Massif Central north of the study area. The others have their sources in the Pyrenees to the southwest, except the Agly River which originates in the Corbières, a less elevated limestone massif between both mountainous chains. After leaving the mountains, all rivers flow through alluvial plains before entering the Mediterranean Sea. Average morphological characteristics are very different in the investigated river basins (Table 2). The Têt is on average the steepest and the highest basin, while Hérault is the lowest basin and has much lower average slope.

Mean annual P over the period 1965–2004 was between 780 and 1089 mm depending on the basin (Table 3). Most basins are influenced by a Mediterranean climate characterized by mild and humid winters, warm and dry summers and heavy precipitation events in autumn. The Aude and the upstream parts of the Agly, Têt and Tech basins however are under the influence of more

Table 2
Main physiographic characteristics of study basins. *Data sources*: Columns 2–4: Jarvis et al. (2006); Columns 5–8: IFEN (2007).

Basin	Morphology			Land-use			
	Area (km^2)	Mean elevation (m)	Mean slope (°)	Natural vegetation		% Cultivated	% Urban
				% Forest	% Other		
Hérault at Agde	2576	367	9.0	28.0	36.5	32.6	2.5
Orb at Béziers	1323	444	12.7	56.5	16.9	24.3	2.0
Aude at Moussan	4957	462	8.5	34.9	15.9	47.1	2.0
Agly at Estagel	905	508	12.8	40.5	33.5	24.7	1.1
Têt at Perpignan	1357	1061	16.0	45.9	25.6	24.7	3.4
Tech at Argelès	730	778	15.9	56.5	20.9	19.6	3.0

Table 3
Main hydroclimatic characteristics of study basins.

Basin	Mean annual *P* (mm)	Mean annual *PE* (mm)	Mean annual *Q* (mm)	RR	Complete years for *Q*
Hérault	1089	971	547	0.48	34
Orb	1019	948	641	0.63	39
Aude	848	941	267	0.32	37
Agly	824	972	224	0.26	38
Têt	780	851	263	0.32	34
Tech	879	919	425	0.47	28

Column 'RR': mean Runoff Ratio (=Annual *Q*/Annual *P*) calculated for the hydrological years (September to August).

oceanic conditions characterized by a relatively homogeneous distribution of precipitation throughout the year. There is a significant precipitation gradient both from upstream to downstream and from north to south, ranging from approximately 600 mm/year near the coast to about 1600 mm/year in the upstream part of the Hérault basin. A more detailed description of the morphological and climatic characteristics of the drainage basins can be found in Lespinas et al. (2009).

As a result of these climatic conditions, the river flow regime in the studied rivers is characterized by a strong intra-annual variability with a high water period in late autumn to spring and a low water period in summer (Fig. 2). The two exceptions are the Têt and Tech rivers where the river flow regime is marked by a strong nival component characterized by a high water period in spring due to snow melting. The mean annual discharge varies from 224 to 641 mm and the mean annual runoff ratio (RR = Annual *Q*/Annual *P*) from 0.26 to 0.63 (Table 3). Such a large variability in water yields can at least partially be explained by the climatic and geologic context as well as by the influence of human activities (Lespinas et al., 2009). For example, water abstractions by irrigation channels in the Têt River and water losses through karstic geological formations in the Agly River largely explain the low values of RR in these basins. In the case of the Têt River, the abstracted water volumes represent approximately one third of the mean annual water discharge measured at Perpignan. Furthermore, the presence of a major dam (Vinca, built in 1976) slightly modifies the seasonal river flow regime. Water is stored in the reservoir during spring and summer and then released in early autumn to sustain base-flow (see Ludwig et al., 2004; Garcia-Esteves et al., 2007, for more details). Inversely, the Orb River has additional water inputs in the upstream part via water deviation from the Vèbre River, a tributary of the Adour-Garonne River basin located west of the study area. Although this artificial water input occurs mainly in winter, it contributes to about 15% of the mean annual discharge measured at Béziers, which explains the high value of RR in the Orb basin (DIREN, 2004).

2.3. Recent hydroclimatic evolution

Mean annual temperature increased over the 1965–2004 period by 1.5 °C in the entire study area (Lespinas et al., 2009). Warming was unevenly distributed over the seasons, with a maximum temperature increase in spring and summer. Temperatures also increased in winter with a lower magnitude while they remained stationary in autumn. Annual and monthly precipitation were highly variable over this period but did not follow a clear evolution in any of the investigated river basins, except a decreasing trend in January and February in the elevated areas of Hérault and Orb. Also no significant change in the tails of daily precipitation distribution was observed (Lespinas, 2008).

Time series of the mean annual discharge near the outlets of the six coastal rivers follow a decreasing trend over the past decades (Fig. 3), although this trend is significant (p-value < 0.1) only for the Hérault and Aude rivers according to the Mann–Kendall (MK) test (Mann, 1945; Kendall, 1975). A decreasing trend was also observed for Orb at Béziers, but with a lower significance level (p-value = 0.16). The mean annual time-series of discharge has been calculated for the civil years but the trends are similar when they are calculated for hydrological years (September to August). Note that the years for which at least one monthly discharge value was missing have not been considered, which represented only a few years and had little influence on this non-parametric test.

Lespinas et al. (2009) demonstrated that the general reduction of water resources in this region was characterized by two main features. First, a clear signal of decreasing trends was detected in the most elevated subbasins of the Pyrenees. They contribute significantly to the total water discharge of the Aude River measured at the Moussan station, which explains its negative trend reported here. Also, the Têt River receives part of its water from the upper Pyrenees but this contribution is not sufficient to induce a significant negative trend of the mean annual discharge measured at Perpignan (Fig. 3). There is strong evidence that reduced snowfall in winter and early spring in response to the global warming is responsible for the water resource reduction. Second, the discharge time series of the lowland stations of the Hérault and Orb rivers also followed a significant decreasing trend, which seems to be related to reduced base flow and groundwater contributions. Multiple factors can explain this evolution, especially the temperature increase, winter precipitation reduction upstream of these river basins and a possible increase of the abstracted water volumes due to groundwater mining (Lespinas et al., 2009).

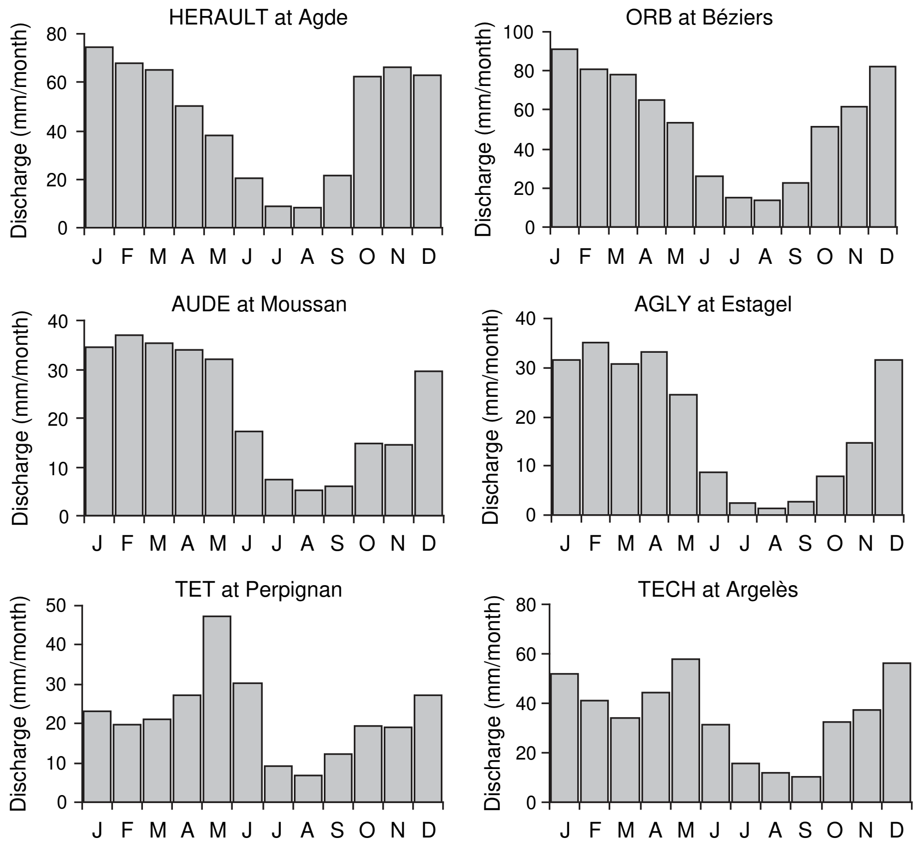

Fig. 2. Mean monthly discharge (in mm/month) over the period 1965–2004.

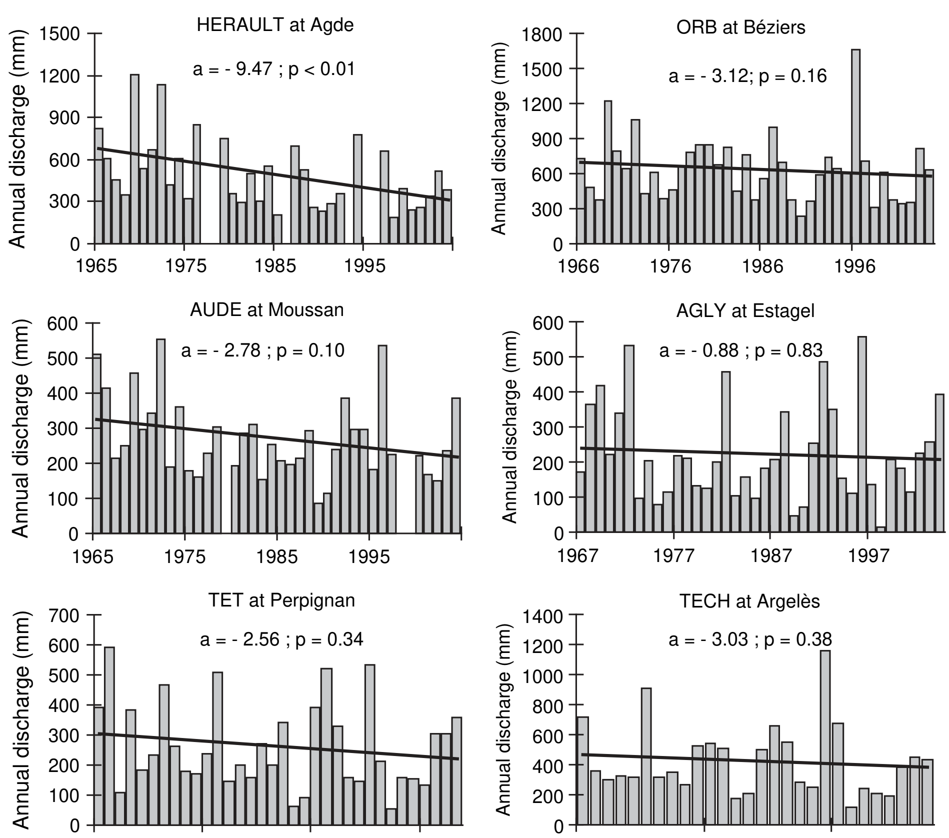

Fig. 3. Evolution of the mean annual discharge (bar chart) along with the associated linear trend (black line) over the period 1965–2004. Slopes of the trends (a) as well as significance of the trends according to the Mann–Kendall test (p) are also shown.

2.4. Future climate scenarios

Information on climate change predicted for the 2071–2100 period was obtained from the precipitation and temperature outputs of several RCMs developed by different institutes that contributed to the Prediction of Regional scenarios and Uncertainties for Defining European Climate change risks and Effects (PRUDENCE) project. This project aimed to provide dynamically downscaled high-resolution climate change scenarios for Europe at the end of the 21st century and to explore the uncertainty of these projections (Christensen et al., 2007). Each PRUDENCE experiment consisted of a control simulation for the 1961–1990 period and one or two future scenario simulations for the 2071–2100 period. These latter simulations were realized from hypotheses based on future development paths in various sectors such as energy and converted into GreenHouse Gas (GHG) emissions (Nakićenović and Swart, 2000).

Two GHG scenarios were considered in the PRUDENCE project. First the A2 scenario that describes a very heterogeneous world for which the underlying theme is self-reliance and preservation of local identities. It is characterized by a continuous increase of global population and a regional orientation of economic development. The B2 scenario describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is characterized by a lower population increase than A2 and by intermediate levels of economic development. In both scenarios the technological changes are slower and more diverse than in other scenarios. This explains why they correspond, in terms of GHG concentration range, to only about 50% of the range of the nine GHG scenarios proposed by the Intergovernmental Panel on Climate Change (IPCC).

Most simulations used the same driving data (from the Hadley Centre Atmospheric Model (HadAM3H) for the A2 scenario) in order to provide a detailed understanding of the uncertainties on the regional model. Some simulations were also produced under the B2 scenario and with driving data from two other GCMs and from ensemble members. Most climatic simulations were produced with a resolution grid close to 50 km (grid spacing of 0.44–0.5° resolution), but some of them were also performed with a 25 km resolution grid. However, comparison of the outputs between both resolutions shows very little differences (Christensen and Christensen, 2007). We therefore considered that simulations produced at a 50 km resolution grid were sufficient to construct the climate scenarios for the investigated basins. Related information and used datasets can be freely downloaded from the web site of the PRUDENCE project http://prudence.dmi.dk.

The climatic simulations used in this study are reported in Table 4. These were selected on the basis of the availability of simulations for the control and the two future (A2, B2) GHG scenarios. The simulations produced with the driving data provided by the GCM ECHAM4/OPYC3 were also taken into account to evaluate uncertainty related to the global climate forcings. All in all, 16 pairs of control and scenario simulations were considered in this study. All data were re-interpolated onto a common 0.5° by 0.5° grid (corresponding to the Climatic Research Unit (CRU) grid) in a spatial domain encompassing the entire study area.

3. Model adjustments

3.1. The GR2M model

The monthly time step model GR2M was first developed by Makhlouf and Michel (1994) on various river basins located in France and showed better performance compared with many other hydrological models in this area. Since then, it was largely used to estimate water resources in many river basins in south-eastern France (Lavabre et al., 1999, 2002) and even in Western Africa (Paturel et al., 1995; Niel et al., 2003; Mahé et al., 2005). This model employs a spatial, temporal and conceptual lumping of hydrometeorological processes.

The structure of GR2M used in this study is the recent version of Mouelhi et al. (2006) that benefited from the experience gained during the development of the daily GR4J model (Perrin et al., 2003). Mouelhi et al. (2006) first built a Parent Model Scheme (PMS) that encompassed the most efficient components of the existing hydrological models. These latter were selected after a trial-and-error process showing their relevance and efficiency. Using a stepwise approach, the authors then made systematic attempts to improve the performance of the PMS while reducing its complexity. This procedure led to a new structure of the GR2M model shown in Fig. 4.

The GR2M model describes each basin as having two reservoirs, a soil reservoir denoted as S that controls the production function with a maximal capacity X_1 (mm; the first free parameter of the model) and a routing reservoir denoted as R that controls the transfer function with a capacity of 60 mm. The former is intended to reproduce hydrological processes in soils and their interfaces while the second reflects transfer of water to the river, notably groundwater exchanges. At each modelling time step, precipitation is channelled either towards the soil reservoir by infiltration (Eq. (1) in Fig. 4) or directly towards the routing reservoir as surface flows (P_1 (mm); Eq. (2) in Fig. 4). The soil reservoir reaches the level S_1 (mm) and then loses part of its moisture by evapotranspiration (Eq. (3) in Fig. 4). Consequently it reaches a new level S_2 (mm). Part of soil moisture P_2 (mm) is then transferred to the routing reservoir by percolation (Eq. (4) in Fig. 4). P_3 (mm), the net precipitation (sum of P_1 and P_2; Eq. (5) in Fig. 4) enters the routing reservoir that reaches the level R_1 (mm; Eq. (6) in Fig. 4). Part of water is then gained or lost by the routing reservoir as lateral water exchanges between the underground part of the river basin and its outside environment (Eq. (7) in Fig. 4). If X_2 (without units; the second free

Table 4
PRUDENCE simulations selected in this study.

Institute	RCM	Boundary data	Acronyms A2, B2
Danish Meteorological Institute (DMI)	HIRHAM	HadAM3H	HS1, HB1
		ECHAM4/OPYC	ecsA2, ecsB2
Haldey Centre (HC)	HadRM3P	HadAM3P	adhfa, adhfd
Swedish Meteorological and Hydrological Institute (SMHI)	RCAO	HadAM3H	HCA2, HCB2
		ECHAM4/OPYC	MPIA2, MPIB2
Universidad Complutense of Madrid (UCM)	PROMES	HadAM3H	a2, b2
International Center for Theroretical Physics (ICTP)	RegCM	HadAM3H	A2, B2
Centre National de Recherches Météorologiques (CNRM)	Arpège	Observed SST	DE6, DE5

RCM: Regional Climatic Model.
Boundary data: GCM used to drive the RCM.
Acronyms A2, B2 are for the A2 and B2 GHG scenarios.

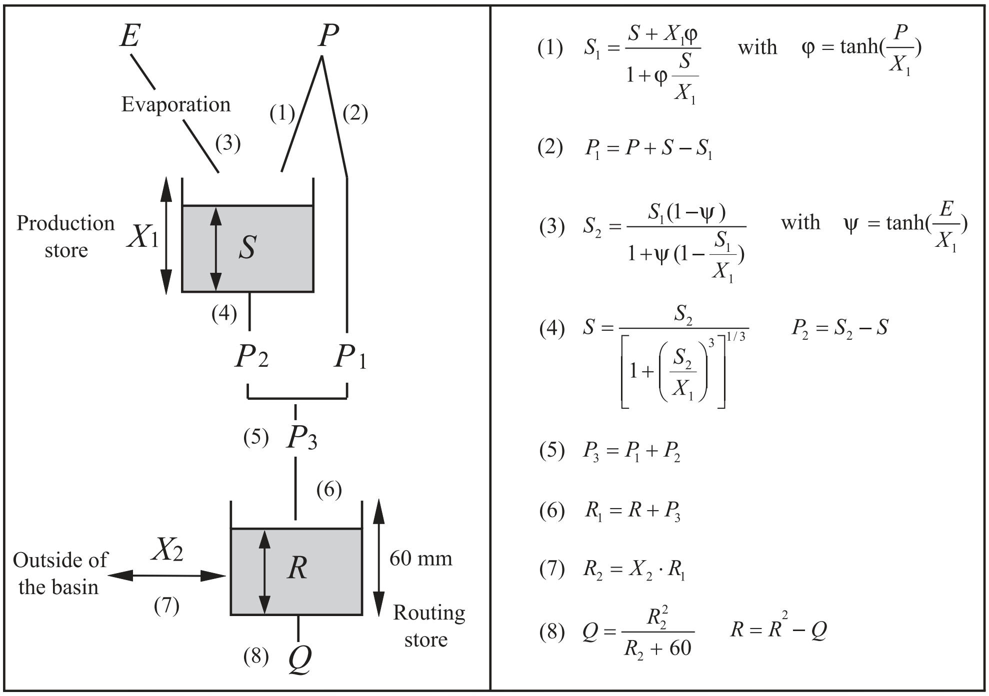

Fig. 4. Structure of the GR2M model (adapted from Mouelhi et al., 2006).

parameter of the model) is greater than 1, there is a water supply from the outside of the basin; otherwise there is a loss. Finally, the routing reservoir provides the riverine water discharge Q (Eq. (8) in Fig. 4).

An important specificity of this new version of the GR2M model is the introduction of the parameter X_2. From a modelling point of view, this parameter corrects possible biases in climatic and discharge time series in order to correct errors in water balance (Eq. (7) in Fig. 4). Mouelhi et al. (2006) also indicated that this parameter allows better representation of lateral water exchanges between the underground part of any topographic basin and its external environment (through permeable geologic layers). They also found that the best performances of the model are obtained when X_2 acts on the level of the routing store.

3.2. Optimization and assessment criteria

The most common approach in hydrological modelling studies consists of adjusting the free parameter values to obtain the best fit between the simulated and observed discharge time-series (hereafter standard calibration). The parameters of the model are optimized over a calibration period and then maintained constant over an independent validation period for which the efficiency of the model is evaluated. The calibration was done using a ''quasi-Newtonian'' local optimization algorithm that starts from an initial set of parameters and then uses a gradient search procedure to evolve in the parameters space toward the optimum values. Lespinas (2008) showed that this algorithm is not very sensitive to choice of the initial set of parameters and that the GR2M model does not have major optimization problems since only two parameters have to be optimized. The default values proposed by Mouelhi et al. (2006) i.e. [X_1 = 300 (mm); X_2 = 1 (no unit)] were therefore selected as set of initial parameters.

The contents in stores at the beginning of the calibration period can also affect the modelling results even if this effect tends to be reduced with time. Special care was therefore taken to prevent problems linked to inappropriate initial conditions. Firstly, the initial levels in production and routing stores were set to half of their respective maximum values (i.e. 150 for S and 30 for R). Secondly, the first year of calibration was ignored in the computation of the objective function, as proposed by Edijatno et al. (1999) and Perrin et al. (2001).

One objective function was used to calibrate the GR2M model and three criteria were used to assess its efficiency both on the calibration and validation periods. The objective function used for calibration was the Nash and Sutcliffe (1970) efficiency (NSE) criterion calculated on square root transformed discharge:

$$NSE(\sqrt{Q}) = 1 - \frac{\sum_i \left(\sqrt{Q_{obs,i}} - \sqrt{Q_{sim,i}}\right)^2}{\sum_i \left(\sqrt{Q_{obs,i}} - \overline{\sqrt{Q_{obs}}}\right)^2} \quad (2)$$

where $\sqrt{Q_{obs,i}}$ and $\sqrt{Q_{sim,i}}$ represent the observed and simulated discharge on month i and $\overline{\sqrt{Q_{obs}}}$ the mean of square root transformed observed discharge over the calibration period. $NSE(\sqrt{Q})$ index varies between $-\infty$ and 1 for perfect simulation. It quantifies the ability of the model to explain discharge variance, i.e. the improvement achieved by any model in simulating discharge compared to a basic reference model simulating a constant discharge equal to the observed mean discharge. In this study, NSE calculated on square root transformed discharge was chosen instead of the classical NSE calculated on raw discharge because the latter tends to emphasize large errors associated with flood events. Using square root transformed discharge yields into more all-purpose criterion (Oudin et al., 2006).

The first criteria to assess efficiency of the GR2M model both on the calibration and validation periods is the standard NSE calculated on raw discharge (replace $\sqrt{Q}$ by Q in the Eq. (2)). The second is the NSE criterion calculated on square root transformed discharge (Eq. (2)). $NSE(Q)$ puts more emphasis on flood simulation while $NSE(\sqrt{Q})$ gives a more balanced image of the overall hydrograph fit. The third criterion is the mean cumulative error of the model:

$$CE = 100 \cdot \left(\frac{\sum_i Q_{sim,i}}{\sum_i Q_{obs,i}}\right) \quad (3)$$

CE measures the ability of the model to correctly reproduce the total water volume observed over the simulation period. It equals 100% when the water balance is perfectly simulated, and is greater than 100% (lower than 100%) when it is overestimated (underestimated).

4. Simulations of water discharge

4.1. Present water discharge

The investigated basins experienced significant changes in climate conditions for the 1965–2004 period, suggesting that the choice of the period used to calibrate the model could have significant impact on hydrologic simulations produced both for present and future climate. Indeed, it is well-known that different time periods can lead to different optimized parameter sets, especially when they are quite different in terms of climate conditions (e.g. Vaze et al., 2010). In our study, the 1965–2004 period is characterized by some contrasting conditions between a "cold" period in the beginning and a "hot" period in the ending, any relative notion being kept in mind. Despite this climate evolution, sensitivity tests on the calibration period did not lead to significantly different results both in terms of optimized parameter set and in the hydrological simulations produced for present and future climate (Section 5.2.2). Therefore, we present here only results obtained on a calibration period and an independent validation period, this in order to give insights for the model's performance over the entire available data.

For each basin, data-time series were splitted into two independent (non-overlapping) periods of equal length. Then the model was calibrated on the first period and evaluated on the second period (respectively 1965–1984 and 1985–2004 when all data are available). Hereafter the parameter set obtained from the model calibration over the 1965–1984 period is defined as the reference parameter set. The values taken by the efficiency criteria reveal that the discharge series modelled by GR2M fit rather well with the observed ones. The NSE criterion calculated on square root transformed discharge ranges between 0.65 and 0.89 in calibration and between 0.69 and 0.87 in validation (Table 5). The best results are obtained for the Aude River, with a NSE criterion of 0.86 and 0.87 in calibration and validation, respectively, while the worst results are obtained for the Têt River, with a NSE criterion of 0.65 and 0.69 in calibration and validation. The NSE criterion calculated on raw discharge ranges between 0.58 and 0.90 in calibration and between 0.67 and 0.89 in validation. The best results are obtained for the Orb River, with a NSE criterion of 0.86 and 0.89 in calibration and validation, and the worst results are again obtained for the Têt River, with a NSE criterion of 0.58 and 0.67 in calibration and validation. The low quality of hydrological simulations for the Têt River is mainly due to the non-representation of the snow-induced effects on discharge regime in the GR2M model (Lespinas, 2008). The influence of the snow is strongest in this basin while it is very limited in the other basins.

Table 5
Performance of the GR2M model for calibration and validation.

Basin	$NSE(\sqrt{Q})$		$NSE(Q)$		CE (%)		Parameters	
	Cal.	Val.	Cal.	Val.	Cal.	Val.	X_1 (mm)	X_2
Hérault	0.89	0.77	0.90	0.75	99	121	458	1.11
Orb	0.83	0.85	0.86	0.89	100	120	550	1.33
Aude	0.86	0.87	0.85	0.85	98	104	544	0.98
Agly	0.87	0.80	0.87	0.76	89	87	249	0.79
Têt	0.65	0.69	0.58	0.67	92	103	779	1.03
Tech	0.77	0.76	0.75	0.67	95	108	232	1.14

In terms of simulated water volumes (*CE*) the model behaviour is more contrasted between calibration and validation periods. The *CE* values indicate that the model tends to underestimate the observed water volumes in the calibration period and to overestimate them in the validation period (Table 5). The only exception is the Agly River for which the water volumes are underestimated both in calibration and validation. These results suggest that the GR2M model does not reproduce the discharge trends observed over the 1965–2004 period. Fig. 5 allows confirming this assumption. It shows the time-series of the differences between the simulated and observed mean annual discharge. It can be noted that these differences follow a significant positive trend ($p < 0.1$; according to the Mann–Kendall (MK) test) for all drainage basins except the Agly basin. Note, lastly, that annual discharge for the two years 1996 and 1997 are strongly underestimated by the GR2M model in the Tech River, this because of the presence of two major floods during both these years that were insufficiently captured by the precipitation stations network.

Regarding the parameter values, it is very interesting to notice the high value of the parameter X_2 for the Orb River and its low value for the Agly River (1.33 and 0.79 respectively; Table 5). For these basins, it is very likely that the model algorithm compensates for artificial additional water inputs in the Orb River and for the karstic losses in the Agly River to balance the water budget (see Section 2.2).

4.2. Implementation of future climate scenarios

The direct use of the RCMs outputs as inputs to the GR2M model was rejected because they could considerably deviate from observations in the control simulations (1961–1990). Averaged over all RCMs, these biases could reach ±1.5 °C for annual temperature and ±25% for annual precipitation, depending on the drainage basin (Lespinas, 2008). Biases are even greater at the monthly scale, especially for precipitation over the Pyrenees, which underlines the difficulty for the RCMs to correctly reproduce the intra-annual distribution of precipitation over areas with complex morphologies (Lòpez-Moreno et al., 2007).

We applied instead the classical perturbation method, which is the most frequently used to construct climatic scenarios for hydrologic impact studies (e.g. Arnell and Reynard, 1996; Kamga, 2001; Caballero et al., 2007). For each grid-point and for each selected RCM we calculated the differences in mean monthly temperature (ΔT_m) and precipitation (ΔP_m; in relative changes because of larger uncertainties on this climatic variable) values between the A2/B2 GHG concentration scenarios (2071–2100) and the control (1961–1990) simulations. ΔT_m and ΔP_m were then interpolated by kriging in order to produce spatial layers covering the entire study area and finally the average differences were extracted for each drainage basin. For each climate scenario and for each drainage basin, the perturbed climatic time-series for 2071–2100 were constructed as follows:

$$T_{scenario,j,m} = T_{obs,i,m} + \Delta T_m \quad (4)$$

$$P_{scenario,j,m} = P_{obs,i,m} \times (1 + \Delta P_m) \quad (5)$$

where j corresponds to the years 2070, 2071,...,2100, i corresponds to the years 1960, 1961,...,1990 and m to the month of the year. $T_{obs,i,m}$ and $P_{obs,i,m}$ refer to the observed temperature and precipitation values for the month m of the year i. The monthly T time-series were then used to generate the monthly PE time-series using Eq. (1).

The perturbed time-series were used for the hydrological simulations. For each drainage basin, a first simulation (called hereafter "reference simulation") was made by running the GR2M model with the observed climate data for the 1961–1990 period. Then,

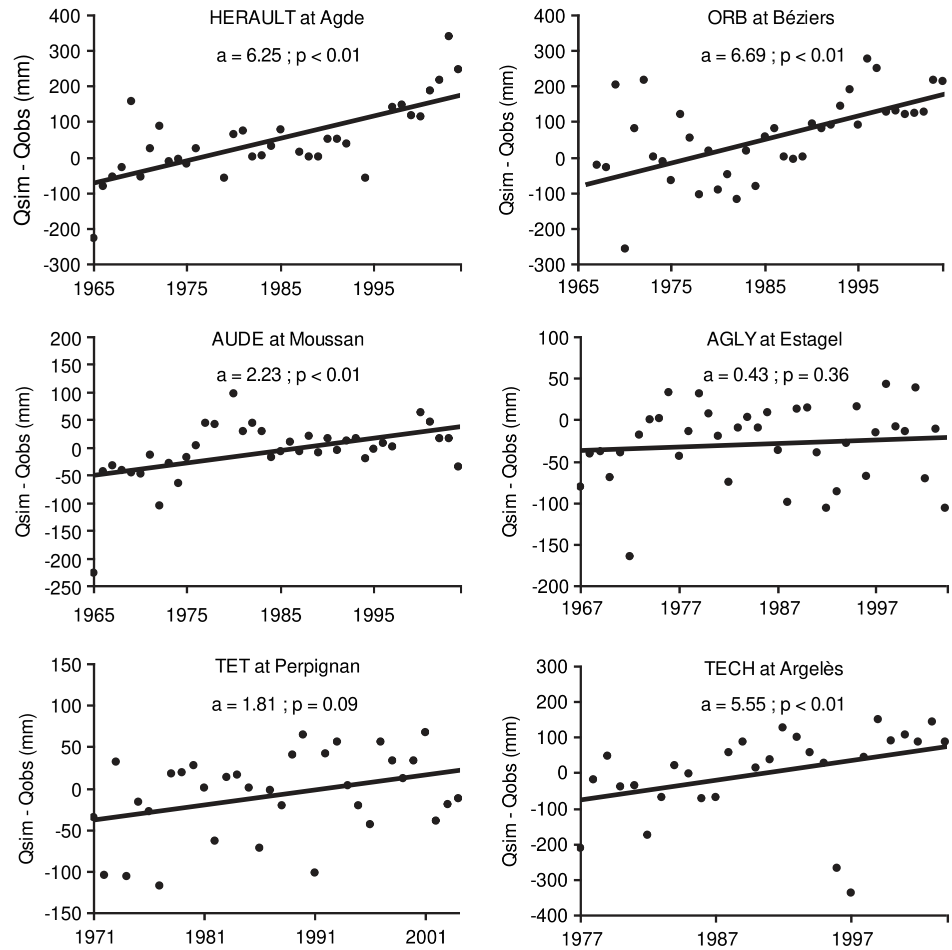

Fig. 5. Time-series of differences (in mm) between the mean annual discharge simulated by the GR2M model calibrated over the 1965–1984 period (reference parameter set) and observations over the period 1965–2004. Slopes of the trends (*a*) as well as significance of the trends according to the Mann–Kendall test (*p*) are also shown.

the 16 perturbed climatic time-series were used as inputs into the GR2M model, thus providing 16 monthly discharge time-series representing the 2071–2100 period. Finally, the average monthly discharge changes between each of the 16 future simulations and the reference simulation were calculated.

Notice that the GR2M model was run for all hydrological simulations with the reference parameter set obtained after calibration over the 1965–1984 period (see Section 4.1). These simulations are therefore based on the implicit and strong assumption that the hydrological functioning of the basins remains unchanged under future climate.

4.3. Future water discharge

Table 6 presents, for each drainage basin, the range of changes in mean annual temperature and precipitation between the reference simulation and the future scenarios. Averaged over all RCMs outputs (in the following "multi-model average"), the future scenarios project a mean annual temperature increase between 4.3 °C (3.1 °C) and 4.5 °C (3.2 °C) for the A2 (B2) scenario, depending on the basin of interest. Note that the differences between RCMs can be important. For instance mean annual temperature is projected to increase between 3.5 °C and 5.8 °C under the A2 scenario for the Hérault basin. Such large differences are mainly caused by the uncertainties from driving data, the greatest warming being projected when the RCMs are forced by ECHAM4/OPYC3 (not shown). Seasonally temperature increase is greatest in summer with a mean temperature increase of about 6 °C for the June–July–August months. This result is in agreement with Christensen and Christensen (2007) who, based on simulations made in the PRUDENCE framework, indicate that Southern France along with Iberian Peninsula could experience the greatest temperature increase in summer compared to the rest of Europe. In spring and autumn the temperature increase is also important but lower while in winter it is about 3 °C under the A2 scenario (not shown).

Despite a greater uncertainty regarding precipitation, almost all climate scenarios project a decrease of annual precipitation, with a multi-model average between −10% and −15.6% for A2 and between −6.1% and −11.6% for B2, depending on the basin of interest (Table 6). The annual precipitation decrease is more important for the Agly, Têt and Tech drainage basins than for the Hérault and Orb basins. Some climate scenarios project no change, even a slight increase. The most pessimistic scenarios indicate that annual precipitation could be reduced by more than 25% compared to present-day conditions. Seasonally, in multi-model average, precipitation is projected to decrease by about 20% in spring and by more than 40% in summer but remains stable in autumn and winter. Seasonal changes in temperature and precipitation under the B2 scenario are qualitatively similar to those obtained for the A2 scenario, although smaller in terms of magnitude, as already noted by other studies (Giorgi et al., 2004; Raïsanen et al., 2004). All the climate scenarios, whatever the basin considered, show an increase in potential evaporation for all seasons and a decrease of precipitation in spring and summer.

Fig. 6 shows changes in mean annual discharge for the A2 and B2 GHG concentration scenarios. Most climate scenarios lead to a decrease in mean annual discharge, with multi-model average

Table 6
Changes in mean annual temperature (°C) and precipitation (%) between 1961–1990 and 2071–2100 projected by the 16 climatic scenarios considered in this study. Min and Max are calculated from the absolute values of changes.

Variable	GHG Scenario	Statistic	Hérault	Orb	Aude	Agly	Têt	Tech
T	A2	Mean	4.3	4.3	4.5	4.4	4.4	4.3
		Min	3.5	3.6	3.6	3.5	3.6	3.5
		Max	5.8	6.0	6.3	6.1	6.0	5.8
	B2	Mean	3.1	3.1	3.2	3.2	3.2	3.2
		Min	2.3	2.3	2.3	2.3	2.3	2.3
		Max	4.4	4.6	4.7	4.6	4.5	4.4
P	A2	Mean	−10.0	−11.9	−15.5	−14.6	−15.6	−14.9
		Min	−3.1	−3.2	−6.6	−6.9	−8.7	−5.6
		Max	−20.9	−22.9	−25.9	−25.7	−27.8	−28.9
	B2	Mean	−6.1	−7.9	−11.0	−10.9	−11.6	−10.7
		Min	1.5	−1.2	−0.1	0.4	−1.6	−1.4
		Max	−13.9	−17.4	−25.1	−22.6	−23.0	−21.9

ranging between −26% and −54% under the A2 scenario and between −14% and −41% under the B2 scenario, depending on the basin of interest. Note the important dispersion between the hydrological simulations. For instance mean annual discharge is projected to decrease between −32% and −68% under the A2 scenario and between −5% and −58% under the B2 scenario in the Aude River. Few climate scenarios suggest an increase in mean annual water discharge as for instance the B2 scenario of DMI for the Agly River. In general, the Aude, Agly, Têt and Tech basins are more affected by a discharge reduction than the Hérault and Orb basins because of larger precipitation decreases. Notice that the uncertainties caused by the external forcing of the RCMs seem to be very large: the climate scenarios built from the RCMs forced by ECHAM/OPYC3 indicate a greater temperature increase and hence lead to a greatest evapotranspiration increase, which lead to a larger discharge decrease.

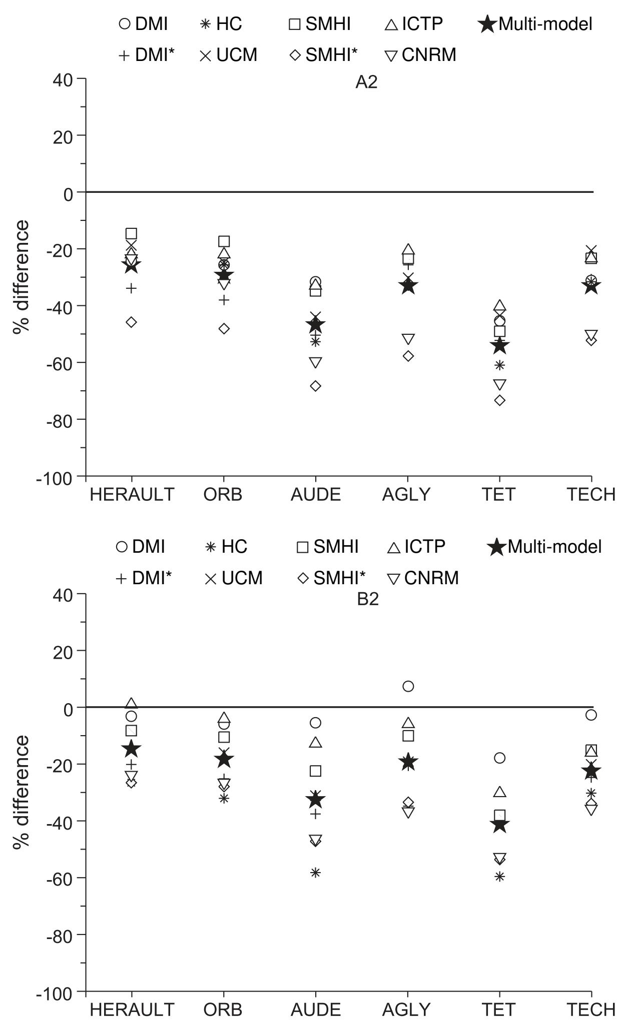

Fig. 6. Changes (in%) in the mean annual discharge simulated by the GR2M model calibrated over the 1965–1984 period (reference parameter set) between the periods 1961–1990 and 2071–2100. The RCMs marked with an asterisk were forced by the outputs of the GCM ECHAM4/OPYC3.

Seasonally, all climate scenarios lead to a discharge reduction more significant in summer than in the other seasons (about −55% averaged over all basins and all RCMs under the A2 scenario; Fig. 7). The discharge reduction is also considerable in spring (−38%) and autumn (−45%) but lower in winter (−32%). The changes in mean water discharge are similar for the B2 climate scenarios but are systematically lower in magnitude than for the A2 climate scenarios (the discharge reduction, averaged over all drainage basins and all RCMs, is projected to be about −46%, −39%, −16% and −23% in summer, autumn, winter and spring, respectively). Note that the UCM model produces some noticeable outliers far above the other simulations, notably in September for the Aude and Têt Rivers. These outliers correspond in fact to artefacts/model errors in the climate series simulated by the RCM and the resulting hydrological scenarios should therefore be considered with caution (Lespinas, 2008).

5. Modelling uncertainties

5.1. Climate scenarios

The RCMs of the PRUDENCE project indicate a significant increase in temperature associated with a decrease in precipitation by the end of the 21st century. The change of the regional climate towards warmer and dryer conditions is strong among all models in late spring and summer, while there are more uncertainties amongst the other seasons. This indicates that the hydroclimatic trends already observed in this region (Lespinas et al., 2009) will likely continue in the future. It must, however, be kept in mind that the climatic scenarios of the PRUDENCE project involve a limited number of RCMs that were forced by the outputs of only two GCMs (HadAM3H and ECHAM4/OPYC3). These climate models simulate changes in large-scale circulation rather atypical compared to most climate models included in the last IPCC report (Déqué et al., 2007). A larger choice of coupled RCMs and GCMs as well as a more important number of GHG concentration scenarios should be considered to better quantify the uncertainties due to climate forcings.

It should also be emphasized that the perturbation method assumes that the statistical distribution of climatic parameters – except the mean monthly value – remains unchanged in future

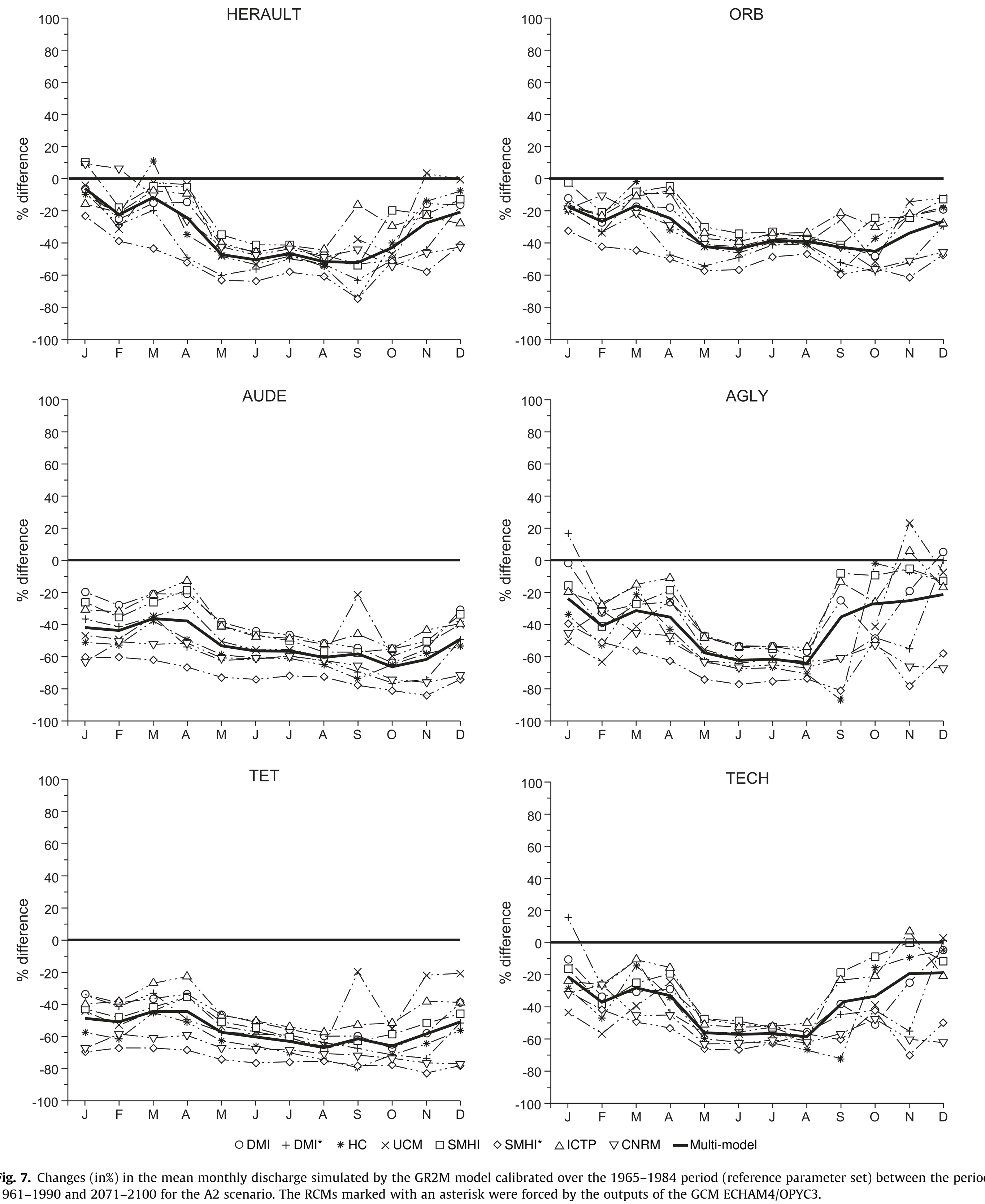

Fig. 7. Changes (in%) in the mean monthly discharge simulated by the GR2M model calibrated over the 1965–1984 period (reference parameter set) between the periods 1961–1990 and 2071–2100 for the A2 scenario. The RCMs marked with an asterisk were forced by the outputs of the GCM ECHAM4/OPYC3.

climate. In other words, the perturbation method cannot produce new precipitation/temperature patterns, with variation coefficients and/or extreme values that significantly differ from the present climate conditions. This hypothesis is obviously very simplistic from a climatological point of view, particularly in the PRUDENCE scenarios that simulate changes in variability of temperature and precipitation (Beniston et al., 2007). The perturbation method therefore does not allow for the studying of the impacts on water discharge related to changes in climatic variability, which can be important in Mediterranean area.

5.2. Hydrological modelling

Uncertainty about climate modelling is not the only factor that affects the hydrological simulations produced for the recent and future periods. The choice of the hydrological model used and the way it is implemented can also have a significant impact on the model's performance, and therefore on the hydrological simulations. More specifically, use of the parameters values calibrated for the present period for simulating discharge under future climate conditions can be very questionable. Although this is the classical approach in any climate change impact study, it is based on the hypothesis that the relationship of precipitation-runoff in the investigated drainage basins does not significantly change between both periods. It is therefore needed to ensure that the hydrological model is able to work efficiently in non-stationary climate conditions, at least over the observed period.

In this study, there is strong evidence that the GR2M model does not reproduce the general decrease in water resources observed over the 1965–2004 period (Section 4.1). Although the statistical significance of the model drift is limited by the weak number of the investigated basins, it can be noticed that each of them differs largely from the others by the morphological characteristics, average climate conditions, land-use and direct human influence on water discharge as well as the evolution of each of these factors (Lespinas et al., 2009). For the Orb, the only river for which naturalized discharge series were also found in the Hydro database (corrected for anthropogenic impacts), the trend towards overestimated discharge still persists when using the corrected discharge values. These observations indicate that the systematic deviation between the modelled and observed discharge has climatic origins and is not only related to evolution in human water use, as already suggested Lespinas et al. (2009).

The systematic drift of the GR2M model suggests either that the model is not sensitive to changes in climate conditions or that the basins have experienced changes in their hydrological responses to climatic inputs. Although the exact causes of the model drift are not clearly identifiable, this problem would imply that on the long term, the model outputs might be strongly biased when projected far into the future. From a modeling point of view, the model drifts towards overestimated discharge, suggesting a mis-representation of the evaporation computation in the GR2M model, which could come from errors in the input *PE* data, model parameterization or model structure (Brigode et al., 2013).

Some sensitivity tests were therefore made in order to estimate uncertainties in hydrological modeling, and to better identify origins of the model drift and to possibly correct it. First, the choice of the *PE* formulation as well as the period used to calibrate the model was investigated. Both choices affect optimization of the free parameter values of the GR2M model and therefore the hydrological scenarios produced for future climate. The corresponding uncertainties are evaluated in the Sections 5.2.1 and 5.2.2. Second, we investigated whether the model drift is due to errors in the model structure that do not efficiently take into account the input data. Indeed, if the detected trends are solely produced by changes in *P* and *T*, they should be accounted for in future climate projections. This point will be examined by using a dynamical calibration approach of the GR2M model (Section 5.2.3.).

5.2.1. Choice of PE formulation

The *PE* formulation used is crucial since it partly controls the production function through evapotranspiration in the GR2M model (Section 3.1). *PE* is calculated monthly in the model, and influences the model parameterization and consequently the hydrological simulations.

A wealth of methods for the estimation of *PE* exist and are well documented in the hydrological literature (e.g., Jensen et al., 1990; Xu and Singh, 2002). These methods differ by the climatological areas where they are built, the available data and the formulation of the underlying physics. Although the *PE* formulation we used led to satisfactory modelling results, other *PE* formulations may still improve the model performance and lead to differences in the hydrological simulations both for present and future periods. In order to evaluate the associated uncertainties we tested other commonly used *PE* formulations based on temperature and radiation data. These were the formulations of Thornthwaite (1948), Hamon (1961) and Oudin et al. (2005). The first two are based on temperature and day-length while the *PE* formulation proposed by Oudin et al. (2005) is based on temperature and extraterrestrial radiation, the latter parameter being computed following the method proposed by Allen et al. (1998). The Oudin et al. (2005) formula is very close to the more commonly used Jensen and Haise (1963), and McGuinness and Bordne (1972) *PE* formulations and appears to be a good choice for its use together with climate model data. All equations are outlined in Oudin et al. (2005).

The left panel of Fig. 8 shows the monthly averages of the *PE* estimates over the 1965–2004 period for the different *PE* formulations for the Hérault basin. It shows that, although the seasonal cycle is similar between the four formulations, with maxima in summer and with minima in winter, the monthly average values are quite different, with the lowest *PE* values obtained for the Oudin formulation and the highest *PE* estimates obtained with the Thornthwaite formulation. On an annual basis, the *PE* estimates range from 778 mm (Oudin) to 1758 mm (Thornthwaite), with intermediate values of 971 mm (Folton–Lavabre) and 979 mm (Hamon).

Table 7 presents average performance of the GR2M model over all studied basins for the different *PE* formulations. It can be noted that performance is very similar for most *PE* formulations, confirming results of previous studies that indicate a lack of sensitivity of hydrological models to *PE* inputs (Parmele, 1972; Paturel et al., 1995). Note however, that the Oudin *PE* formulation appears slightly more efficient, whereas Thornthwaite gives the worst modeling results. Also, the model parameter values are somewhat different between the *PE* formulations, suggesting that the GR2M model compensates for the different estimates of *PE* by adjusting the parameter values. Especially the X_2 parameter values seem to be related to the *PE* estimates. Indeed, whatever the basin considered, the highest values of X_2 are found for the Thornthwaite formulation, which gives the highest *PE* values, and the lowest values of X_2 are found for the Oudin formulation, which gives the lowest *PE* values. This suggests that errors in the modelled discharge could be linked to the errors in evaporation estimates. This point will be further studied in the Section 5.2.3.

The right panel of Fig. 8 shows the monthly averages of changes in *PE* for the different *PE* formulations in the Hérault basin for the A2 scenario. It shows that, although seasonal changes are similar between the four formulations, with maximum increase in summer and minimum increase in winter, the lowest *PE* changes are obtained for the Oudin formulation and the largest *PE* changes with the Folton–Lavabre formulation. On an annual basis, increases of the mean *PE* values range from 185 mm (Oudin) to 505 mm (Folton–Lavabre), with intermediate values of 362 mm (Hamon) and 495 mm (Thornthwaite).

For each *PE* formulation, the reference simulations for the 1961–1990 period and future simulations for the 2071–2100 period were produced following the protocol described in Section 4.2. Most hydrological scenarios produced from the different *PE* formulations indicate a decrease in mean annual discharge between the

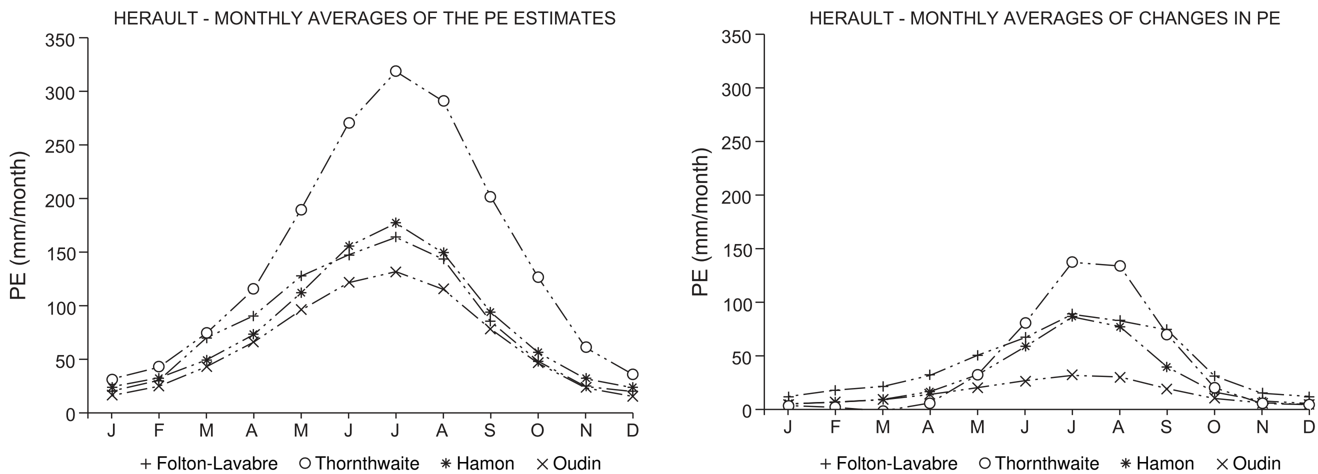

Fig. 8. Mean monthly *PE* over the period 1965–2004 and changes for the period 2071–2100. Left panel. monthly averages of the *PE* estimates over the period 1965–2004 for the Hérault River Basin with different *PE* formulations. Right panel: changes (in mm/month) between the periods 1961–1990 and 2071–2100 for the Hérault River Basin with different *PE* formulations for the A2 scenario.

Table 7
Average performance of the GR2M model calibrated over the 1965–1984 period (reference parameter set) for different *PE* formulations.

PE formulation	$NSE(\sqrt{Q})$		$NSE(Q)$		CE (%)		Parameters	
	Cal.	Val.	Cal.	Val.	Cal.	Val.	X_1 (mm)	X_2
Folton–Lavabre	0.81	0.79	0.80	0.76	95	107	469	1.06
Thornthwaite	0.80	0.77	0.78	0.73	96	105	317	1.23
Hamon	0.82	0.79	0.81	0.77	96	109	398	1.05
Oudin	0.82	0.79	0.81	0.77	95	109	451	0.97

two periods, although less significant in magnitude compared with the Folton–Lavabre *PE* formulation. Mean annual discharge reduction averaged between all RCMs and for all basins in the A2 scenario is about −37% (Folton–Lavabre), −15% (Thornthwaite), −28% (Hamon) and −28% (Oudin). Note that the values of change in mean annual discharge are not related to the changes in annual *PE*; the Thornthwaite *PE* formulation gives the larger increase in annual *PE* while it leads to the lowest discharge decrease. The changes in mean annual discharge seem to be more dependent on seasonal changes in the *PE* values, which underlines the complexity of the uncertainties from the *PE* formulation on the hydrological modelling results. Seasonally the patterns of changes in mean monthly discharge are, however, very similar between the different *PE* formulations (Fig. 9). The same patterns are observed when the *PE* formulations are used with the scenario B2.

5.2.2. Choice of the calibration period

Another source of uncertainties comes from the fact that the hydrological scenarios were produced with the reference parameter set obtained by calibrating the GR2M model over the 1965–1984 period (Section 4.2.). Although this is the classic approach of most impact studies on climate change, the choice of the calibration period has a strong impact on the free parameter values of the GR2M model, and thus also on the hydrological scenarios.

In order to evaluate the uncertainties associated with the calibration period used to calibrate the GR2M model, this latter was calibrated and validated according to the full split-sample test proposed by Klemeš (1986). This means that when the data time series covered the whole 1965–2004 period, the model was first calibrated for the 1965–1984 period and evaluated on the 1985–2004 period (parameterization P1–P2, which is the reference parameterization used in Section 4) then it was calibrated on the 1985–2004 period and evaluated on the 1965–1984 period (parameterization P2–P1). A third parameter set was obtained by calibration of the GR2M model on the whole available record (parametrization ALL).

Table 8 presents the average performance of the GR2M model over all study basins for the different parameterization's periods. Only the results for the *PE* Folton–Lavabre formulation are shown but similar results are obtained with the other *PE* formulations. It can be noted that the performance is very similar for all parameterization periods, indicating that the model algorithm is rather robust over the whole modelling period. Note however, that when the calibration and validation periods are reversed, the *CE* values are inversed as well; in the validation period, the modeled water balance is overestimated in the P1–P2 parameterization and is more largely underestimated in the P2–P1 parameterization.

The average parameter values are similar enough between the different parameterization periods, suggesting that the choice of the calibration period has a limited influence on the hydrological scenarios. Note however, that the X_2 parameter value is higher when calibrating the GR2M model on the 1965–1984 period than when calibrating the model on the 1985–2004 period. The decrease of the X_2 values between these two periods indicates that the water losses are larger over the recent years, and that the optimization of the model adjusts this parameter to likely simulate an increase in water loss by evapotranspiration. This hypothesis will be studied in the Section 5.2.3.

For each parameterization period and for each *PE* formulation, the reference simulations for the 1961–1990 period and future simulations for the 2071–2100 period were produced following the protocol described in Section 4.2. The results show that for each *PE* formulation the mean annual discharge reduction averaged for all RCMs and for all basins differs only within ± 1% between the different parameterizations. Also the patterns of changes in mean monthly discharge are very similar (Fig. 10).

5.2.3. Dynamical parameterization of the GR2M model

The sensitivity tests on the *PE* formulation (Section 5.2.1) and the calibration period (Section 5.2.2) have revealed a lack of strength in the hydrological modeling. They showed indeed that the X_2 parameter value seems to be dependent on the *PE* formulation and the calibration period used, while the model drift towards overestimated discharge still persists independently of these modeling choices (not shown). These results are in agreement with other studies that showed that the parameters of the hydrological

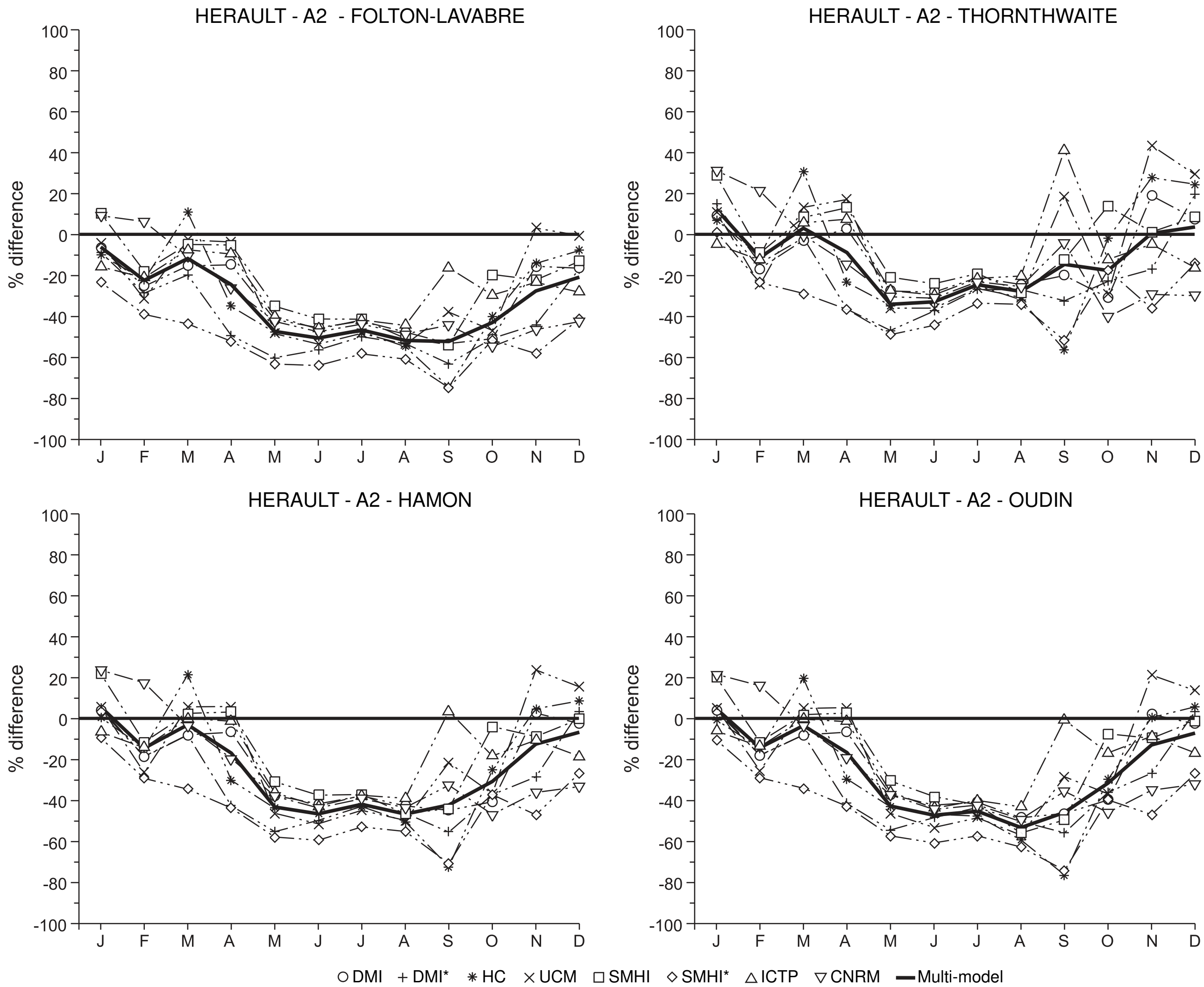

Fig. 9. Changes (in%) in the mean monthly discharge simulated by the GR2M model calibrated over the 1965–1984 period (reference parameter set) between the periods 1961–1990 and 2071–2100 for the Hérault River with different *PE* formulations for the A2 scenario. The RCMs marked with an asterisk were forced by the outputs of the GCM ECHAM4/OPYC3.

Table 8
Average performance of the GR2M model for different parametrization periods.

Parameterization	$NSE(\sqrt{Q})$		$NSE(Q)$		CE (%)		Parameters	
	Cal.	Val.	Cal.	Val.	Cal.	Val.	X_1 (mm)	X_2
P1–P2	0.81	0.79	0.80	0.76	95	107	469	1.06
P2–P1	0.82	0.78	0.78	0.77	94	84	455	0.99
ALL	0.81	X	0.78	X	94	X	465	1.03

models and their performance are relatively dependent on the climatic variables used to calibrate the model (Merz et al., 2011; Vaze et al., 2010; Coron et al., 2012). But they also suggest that the errors in modeled discharge could at least be partially attributable to the errors in evaporation estimates by the production function of the GR2M model, and that the X_2 parameter values may likely be adjusted to correct these errors. As both the different *PE* formulations and the calibration periods vary largely with respect to temperature, one can furthermore expect that this adjustment is possible by linking the X_2 parameter value with temperature.

To check this hypothesis, we followed the approach proposed by Merz et al. (2011); the GR2M model was calibrated on much shorter time periods to test whether the calibrated parameter values systematically change over time and whether these trends can be explained by climatic variability. The GR2M model was hence calibrated on successive, independent 4-year periods from the available discharge record. This means that when the discharge data was complete, the model was firstly calibrated on the 1965–1968 period, then on the 1969–1972 period, etc., and finally on the 2001–2004 period. The corresponding T and P average values for these 4-yr periods were also extracted. This allowed testing on whether possible shifts in model parameter's values can be correlated with climate conditions, and eventually corrected in order to evaluate their impact on the model performance.

When calibrating the GR2M model on successive 4-year periods, we found that the optimized values of X_2 follow a systematic trend to lower values in all drainage basins, except for Agly. We also noticed that the successive values of X_2 follow the interannual variability of T in most basins, with a significant negative correlation found between both parameters for the Hérault, Orb and Têt rivers (Fig. 11, left panels). Also negative correlations between X_2 and T were found for the Aude, Agly and Tech Rivers but they were statistically not significant. No relationship was found between the successive values of X_2 and P and the optimized X_1 values did not show any links with climatic parameters.

The negative relationship found between X_2 and T in most basins confirms that the model drift is due to errors in evaporation

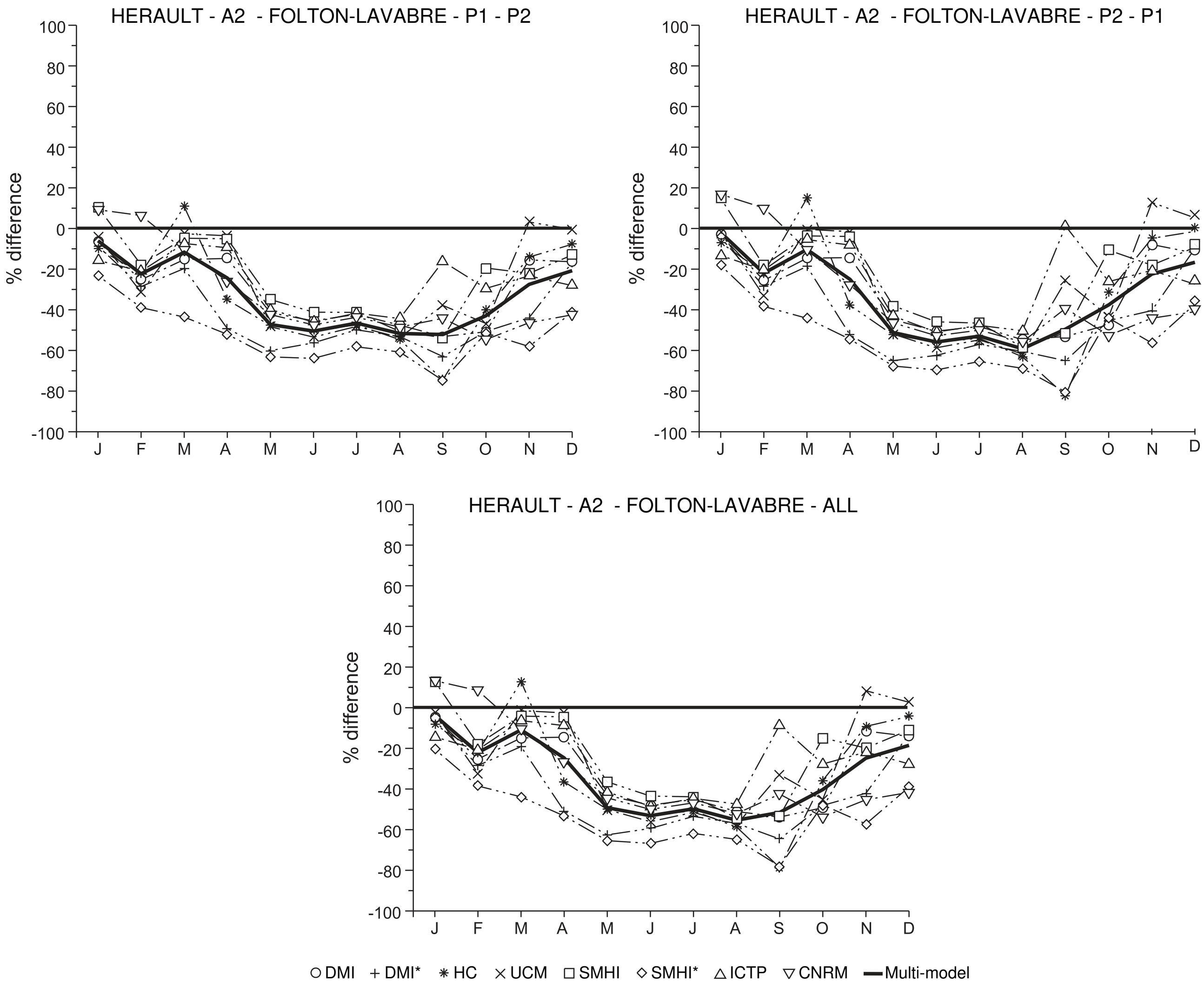

Fig. 10. Changes (in%) in the mean monthly discharge simulated by the GR2M model calibrated on different periods according to the full split-sample test of Klemeš (1986) between the periods 1961–1990 and 2071–2100 for the Hérault River for the A2 scenario. The RCMs marked with an asterisk were forced by the outputs of the GCM ECHAM4/OPYC3.

estimates, and that this parameter could compensate for these errors. Indeed, from a modelling point of view, X_2 corrects possible biases in climatic and discharge time series in order to correct errors in water balance (Mouelhi et al., 2006). X_2 does not therefore only control some unknown sources or losses of water in the basin but it can also compensate for errors in the evaporation computation. Although this approach might be questionable from a physical point of view, one should not forget that the GR2M model is not a physical but a conceptual model built from an empirical approach. Therefore, due to the simplistic representation of the hydrological processes in the structure of the GR2M model, any physical interpretation of the model parameters should be taken with extreme caution. As the other *PE* formulations also lead to negative relationships between X_2 and T (not shown), one can furthermore argue that this problem comes from the model structure; in the original version of the model, the water loss by evaporation is indeed estimated from the level of the soil reservoir and the *PE* formulation chosen; this computation has the advantage to be very simple but it is obviously too simplistic with respect to the real world.

For the Hérault, Orb, Têt and Tech rivers we established simple linear models of the type $X_2 = f(T)$ on the basis of the optimized X_2 values and the corresponding T values. This allowed us to produce another set of hydrological simulations with X_2 derived at each modelling-step from the T values averaged over the preceding 12 months (in order to have a moving-averaged annual value for T). The values of X_1 were maintained equal to the values optimized in the standard calibration (see Section 3.2).

Table 9 presents the modelling results with the X_2 parameter values fixed (parameterization P1–P2) and derived from temperature. The model performance is similar between the two parameterizations in terms of the optimization criteria in calibration. The NSE criterion shows, however, higher values in validation for the parameterization with X_2 derived from T, with the largest increase recorded for the Hérault River (+0.07). In terms of *CE*, the model performance tends to be slightly deteriorated over the calibration period, with increased differences between the observed and simulated water volumes. These differences are, however, negligible. In validation, the model performance is significantly improved, in particular for the Hérault and Orb Rivers where differences in the *CE* values between calibration and validation are strongly reduced compared to the parameterization P1–P2.

The right hand panels of Fig. 11 finally confirm that the correction method allows in most cases for the drift of the model outputs to be reduced. Time series of the differences between the simulated and observed mean annual discharges show no significant trend ($p > 0.1$) except for the Hérault River, where a drift persists

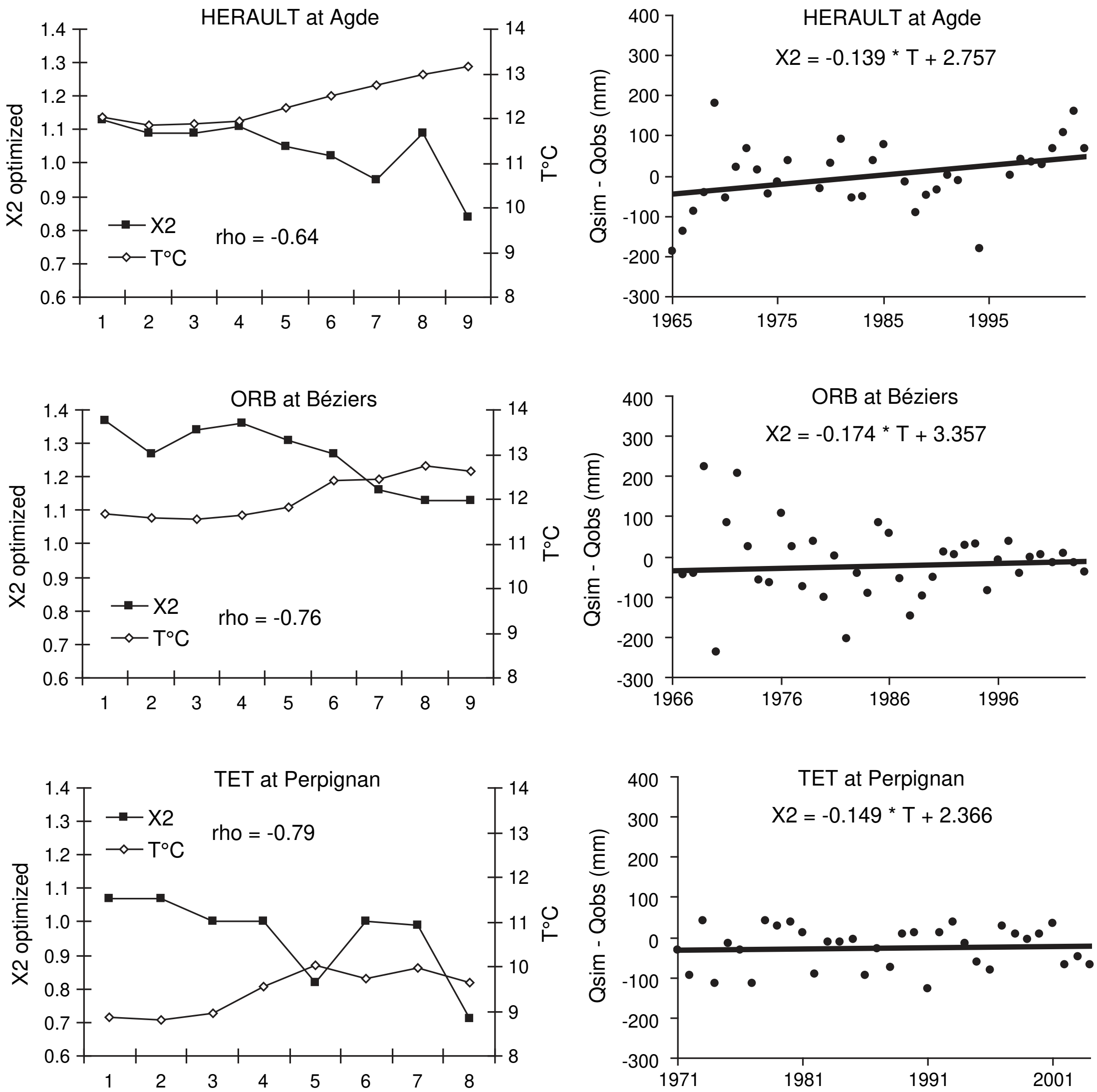

Fig. 11. Correction of the GR2M model drifts for the Hérault, Orb and Têt rivers. Left panels: Evolution of the optimized X_2 parameter value and mean annual temperature over the successive calibration periods. The rho values are the Spearman's correlation coefficients calculated between both time-series. Right panels: Time-series of differences (in mm) between the mean annual discharge simulated by the GR2M model with temperature-varying X_2 values and observations over the period 1965–2004.

Table 9
Performance of the GR2M model for X_2 fixed and varying with T.

Basin	Model version	$NSE(\sqrt{Q})$		$NSE(Q)$		CE (%)	
		Cal.	Val.	Cal.	Val.	Cal.	Val.
Hérault	X_2 fixed	0.89	0.77	0.90	0.75	99	121
	X_2 varying with T	0.88	0.84	0.89	0.84	97	100
Orb	X_2 fixed	0.83	0.85	0.86	0.89	100	120
	X_2 varying with T	0.81	0.90	0.85	0.92	99	97
Têt	X_2 fixed	0.65	0.69	0.58	0.67	92	103
	X_2 varying with T	0.63	0.70	0.56	0.64	90	90

Column 'Model version': 'X_2 fixed' refers to the P1–P2 parametrization of the GR2M model (see Table 4) and 'X_2 varying with T' to the parametrization with temperature-varying X_2.

but is clearly reduced compared to the parameterization P1–P2. Note that the parameter values of the $X_2 = f(T)$ relationships are comparable between the different basins, meaning that the same changes in T approximately lead to similar changes of X_2. This indicates a spatially coherent influence of T on the basins, which supports the hypothesis of the impact of climate change on the decreasing discharge trends.

For the three basins for which the X_2–T relationships were significant, hydrological scenarios for future climate were produced by running GR2M with the parameter X_2 values derived from T. The results are shown in Fig. 12 for the A2 scenario and can be compared with those obtained from the parameterization P1–P2 (Fig. 7). The differences between both outputs are important, with a much greater discharge reduction in the hydrological simulations

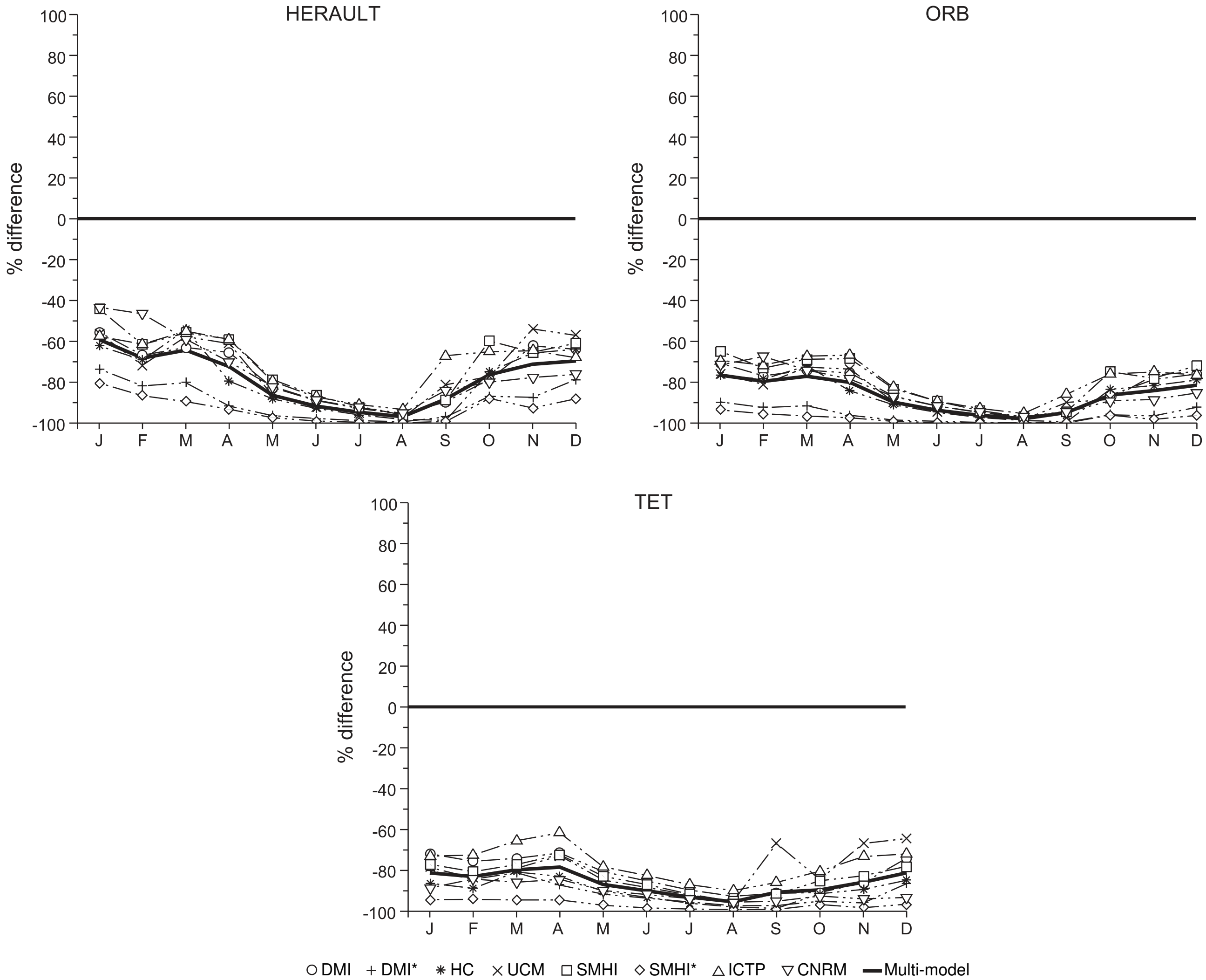

Fig. 12. Changes (in%) in the mean monthly discharge simulated by the GR2M model with temperature-varying X_2 between the periods 1961–1990 and 2071–2100 for the A2 scenario. The RCMs marked with an asterisk were forced by the outputs of the GCM ECHAM4/OPYC3.

when the X_2 parameter values are derived from T. In multi-model average, for the A2 climate scenario, mean annual discharge is decreased by about −71%, −83% and −85% for the Hérault, Orb and Têt rivers, respectively. The reductions are −54%, −66% and −71% for the same basins with the B2 scenarios. Seasonal patterns of discharge changes remain very similar to those obtained with the parameterization P1–P2, with the greatest discharge reduction simulated in summer. Note that similar results are obtained when using the other *PE* formulations (Section 5.2.1).

6. Discussion

The low sensitivity of the *PE* formulation on the GR2M model performance is in agreement with the results of Oudin et al. (2005) who suggested that the choice of *PE* formulation is not critical for the performance of rainfall–runoff models. The authors compared the performance of four conceptual rainfall–runoff models when given by (bias-corrected) *PE* data derived using 27 alternative formulae for 308 catchments spread over three countries. They found that most of the *PE* formulations performed similarly in terms of fit between observed and simulated flows. The temperature-based formulae, in particular, were often found to perform as good as (or even better than) much more complex formulations.

Our results are also in agreement with other studies indicating that climate change impact studies can be quite sensitive to *PE* formulation (Kay and Davies, 2008; Gosling and Arnell, 2011). Note that the Oudin *PE* formulation gives the best results in terms of model performance and leads to hydrological scenarios that are very close to those produced with the Lavabre–Folton *PE* formulation. This gives some confidence in the regional *PE* formulation used in this study. Inversely, the Thornthwaite formulation gives the less satisfactory results in terms of model performance and produces the most optimistic hydrological scenarios for future climate. These results indicate that only the most efficient *PE* formulations should be used within climate change impact studies, as recommended by Bormann (2011). One can note, however, that the *PE* formulations are calibrated for present climate conditions and are used far beyond the conditions under which they were calibrated, which naturally constitute another uncertainty source in hydrological modeling.

Other physically-based *PE* equations could have been used in order to best evaluate the uncertainties coming from the *PE* formulation on the model outputs. This study is, however, limited by the availability of climatic data. Only a few synoptic stations, most situated near coasts and outside the investigated basins, report some meteorological variables as humidity required to calculate physically-based *PE* estimates. It would be therefore not obvious to produce gridded data sets of *PE* estimates for the investigated watersheds. Furthermore, it is not likely that they give values beyond the range of the *PE* values used in this study, notably because the other physical variables such relative humidity did not significantly change over the investigated period, as far as recorded by the only three synoptic stations recording this parameter in our study area (not shown).

In half of study basins, the model drift could be largely corrected by an alternative parameterization of the GR2M model based on temperature, indicating that the increased temperature could have an important role on the model drifts. This is in agreement with other studies which showed that freely adjustable parameters in hydrological models can be dynamically calibrated according to the climate conditions (Wagener et al., 2003; Vos et al., 2010; Merz et al., 2011). It is therefore interesting to note that the best corrections of the model outputs were obtained for the Hérault and Orb rivers. This supports the hypothesis from Lespinas et al.(2009) that reduction of groundwater recharge in these basins played a major role in the discharge decrease and was triggered by increased evaporative water losses, either directly via reduced infiltration and/or indirectly via increased groundwater mining.

There are many limitations regarding the choice of the hydrological model used in this study. First, the monthly time step of the model leads to a spatio-temporal aggregation of hydrological processes. This largely limits the physical interpretation of the correcting method in discharge modeling and also its validity when extrapolated to future climate conditions. It can, however, be noticed that most studies that reported statistical relationships between the calibrated parameters of the hydrological models and the climatic variables focused on daily time-step hydrological models (Vaze et al., 2010; Merz et al., 2011; Coron et al., 2012). Our results therefore support that the uncertainties in hydrological modeling coming from the time resolution are negligible compared with those coming from the model structure. Also, the production function of the GR2M model depends only on *PE*, precipitation and soil water contents, which obviously constitutes an important simplification of the physical processes that influence the runoff production in drainage basins. It does not account for other factors such as land use changes and/or anthropogenic water extractions, which often play an important role too. These factors were studied in detail by Lespinas et al. (2009) who concluded that they alone cannot explain the observed changes in discharge time-series. Anthropogenic water use is very unevenly distributed in the different drainage basins and does not show clear trends over the last decades, at least as far as the surface water extractions for irrigation are concerned (which are the most important in the Têt basin). At last, the production function of the GR2M model does not specifically take into account snow processes, which play a major role on the average discharge regimes in two of the studied basins (Têt and Tech). A snow module was therefore added in the original version of the GR2M model to take into account these processes (Lespinas, 2008). Introduction of this snow module brought significant improvements in terms of model performance and gave different results in terms of changes in monthly discharge only for the Têt basin. This result led us to focus on the uncertainties which affect in whole the investigated basins and not on the processes regarding one specific basin. It can furthermore be noted that for the Têt basin, the relationship between X_2 and T found in the successive calibration periods still persist even by introducing the snow module. The lack of snow processes therefore does not significantly affect the results of the hydrological modeling uncertainties found in this study.

7. Conclusions

In this study the GR2M hydrological model was implemented on a sample of six coastal river basins in Southern France in order to (i) reproduce the observed flow regimes over the 1965–2004 period, (ii) produce estimates of the expected changes in water resources by the end of the 21st century (2071–2100) and (iii) evaluate the uncertainties in these estimates. Contrary to most of the previous modelling studies, the model was adjusted to discharge time-series that were not in a stationary-state. At least two of the investigated drainage basins (i.e. Aude and Hérault) showed a significant trend towards reduced water resources over the 1965–2004 period, but also in many of the other basins (at least at the sub-basin scale), clear signs of decreasing trends do exist (Lespinas et al., 2009).

Despite the good quality of the hydrological simulations in terms of NSE criteria, the GR2M model failed to reproduce the general decreasing trend of the mean annual discharge during recent decades. In all rivers except the Agly River, the model outputs deviated from the observed time series, leading to a systematic overestimation of the observed water volumes in the most recent years. This means that either the model parameterization is not well adapted to reproduce the hydrologic functioning of the studied river basins, or that the precipitation-runoff relationships in these basins have been changed over the study period.

Sensitivity tests on hydrologic modeling showed that different *PE* formulations perform similarly in the 1965–2004 period, but, however, lead to different estimates of projected changes in the hydrological scenarios produced for future climate. The choice of the parameterization period does not significantly affect the parameterization of GR2M and the corresponding hydrological scenarios are almost identical between them. These sources of uncertainty therefore have little impact on the model outputs.

In its standard calibration mode, the GR2M model leads to a reduction of the mean annual water discharge by the end of the 21st century of about 30% (20%) averaged over all basins under the A2 (B2) GHG concentration scenario. Discharge is projected to significantly decrease from late spring to the beginning of autumn while there are more uncertainties for the other seasons. These projections are rather optimistic if we consider the inability of the GR2M model to reliably reproduce the already observed trends. For the three river basins for which we could build a simple correction of the model drifts, the general decrease in water resources in the future climate scenarios is at least twice as great as in the standard calibration mode.

Direct application of this correction to future climate conditions is naturally to be done with caution since the underlying relationships in the $X2$–T correlations are unclear and were extrapolated to climate conditions far beyond the present conditions. Our approach should therefore be considered as sensitivity analysis, showing that fixed parameter models, although widely used in climate change impact studies, suffer from the limitation that they cannot reproduce changes in the hydrological functioning of the investigated river basins.

The model parameter values are calibrated for the present climate and often tend to compensate for shortcomings in the model structure and errors in data. A precise quantification of the available water resources in the study basins therefore remains highly speculative and is likely between the two extremes of our simulation results, which are defined by the GR2M model outputs in its standard calibration mode and the model outputs with the X_2 parameter varying with T.

The predicted decline of future water resources in this study, especially in summer and autumn, is in agreement with other climate change hydrological impact studies for the 21st century in the same area (Boé et al., 2009; Quintana Segui et al., 2010). Some differences in magnitude of projected changes exist and essentially come from the choices of the climate model, of the downscaling method and projected time horizon. However, it is very likely that the reduction of water resources already observed in this area will continue in future.

This study clearly demonstrates that uncertainties on the hydrologic scenarios are not only related to the uncertainties associated with the future climate scenarios, but also strongly to the choice and the structure of the hydrological model. Conceptual models like the GR2M model are often used for simulating future water resources since they are both easy to implement and require little input data (e.g. Arnell and Reynard, 1996; Kamga, 2001). However, these are mainly designed to reproduce water discharge under stationary conditions, so their ability to reproduce trends in water discharge should be examined as well. New criteria taking this into account are therefore necessary for better assessing the uncertainties in hydrological modeling in climate change impact studies, especially for Mediterranean river basins for which the predicted climate change might have severe impacts on the evolution of the surface water resources.

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