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Impact of climate changes on the water resources in the river Meuse basin

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Abstract
The SCHEME hydrological model has been developed to study the impacts of climate changes on the hydrological cycle in large river basins. A conceptual approach has been applied to grid cells of ~50 km^2. Model parameters are optimised on a selection of gauged subcatchments and are regionalised using Artificial Neural Network algorithms. The routing module is based on the width function of the river network. This model has been applied on the river Meuse basin in Belgium and France (~20,000 km^2). Observed series of meteorological data have been perturbed using climate changes simulated by General Circulation Models. These climate changes are distributed by the IPCC Data Distribution Center. Results obtained using perturbed and unperturbed series are compared to assess climate change impacts. For the 2100 climate, almost all the simulations show an increase in precipitation during winter; floods might occur more often. The summer decrease of precipitation would result in more frequent drought and low flow periods.

INTRODUCTION

Previous studies were performed using the IRMB (Integrated Runoff Model – F. Bultot) conceptual hydrological model applied on catchments ranging from 100 to 1000 km^2. Using a 2×CO_2 climate scenario derived from different experiments to perturb a long observed time serie, Bultot *et al*. (1988) demonstrated that impacts could appear very different between three catchments in Belgium characterised by contrasted infiltration rates and storage capacities. Using a set of climate scenarios provided by the IPCC (Cubash, 1994) on 8 catchments spread over Belgium, Gellens and Roulin (1999) could settle the same conclusion but emphasised the uncertainty raised by climate scenario variability. The purpose of this study is to enlarge the scale of the impact study to the scale of 10^4 km^2 like the river Meuse and Scheldt basins. Modelling the hydrological cycle at this scale requires that spatial variability be taken into account and that the routing to the outlet be described explicitly. For this purpose, the IRMB model has been adapted into a coarse gridded version, the SCHEME model. In this study, a set of more recent climate change scenarios, also provided by the IPCC, have been used. The regional scale hydrological model and the climate scenarios are described in the next section followed by the results of the impact study.

The Meuse is a 935 km long river flowing from France through Belgium and the Netherlands. Its area is about 36,000 km^2 and is draining also small parts of Germany and Luxembourg (Figure 1). In Belgium, the river Meuse basin covers 13,500 km^2, that is 44% of the country's area. This study is focused on the river Meuse basin upstream Visé near the Belgian-Dutch border (20,600 km^2). Two main parts may be described. The first is the

“Meuse Lorraine” in France from the spring to the confluence with the river Chiers. This part of the basin is lengthy and narrow and gently undulated. The second part is the Belgian Meuse draining the Ardennes that is characterised by a steeper relief and by higher rainfall. In this study, three other sub-basins have been selected: the sub-basins of the Meuse at Chooz at the Belgian-French border (10,120 km^2) that includes the Meuse Lorraine, the Ourthe Orientale at Mabompre (317 km^2) in the Ardennes and, downstream, the Ourthe at Tabreux (1,620 km^2) (Figure 1). In Belgium, the baseline climatological conditions is a humid and mild climate. Annual precipitation ranges from some 700 to some 1,200 mm. It rains throughout the year with a frequency close to two days out of three. In winter, rainfall in the Ardennes is twice the rainfall in the other parts of the river Meuse basin. The evapotranspiration reaches 500 mm per year.

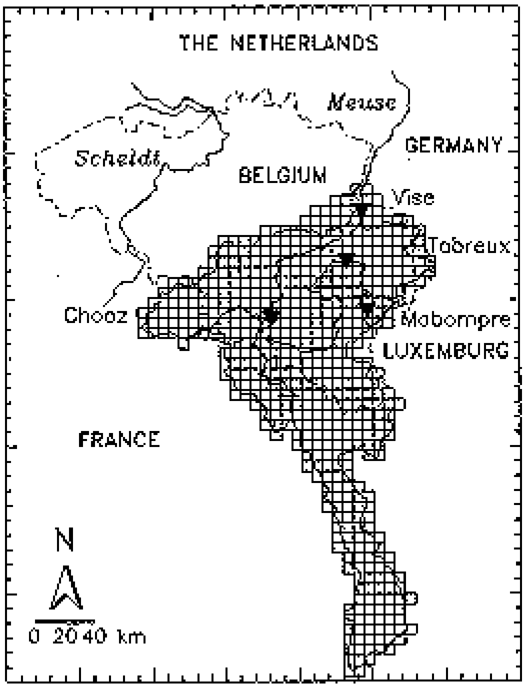

Figure 1. Location map of the SCHEME model grid on the Meuse river basin and the studied sub-basins.

METHODOLOGY

The SCHEME model has been developed to study impacts of climate changes on the river Scheldt and Meuse basins that cover most area of Belgium. Its name reminds also that within the 50 km^2 grid cells, the hydrological cycle is simulated with a conceptual approach derived from the lumped IRMB model (Bultot and Dupriez, 1976, 1985). The SCHEME model runs at daily time step.

The surface sub-model (Figure 2) includes the snow accumulation and melting and for each of 9 land-covers, the interception by vegetation and the accounting of two soils layers. The other components of the initial IRMB model have been simplified in view to the model parameters optimisation and regionalisation. The groundwater storage is represented by two reservoirs. Surface water flow is convolved with a unit hydrograph within the grid cells.

The routing method is based on the width function (Naden, 1992, Naden *et al*., 1999). The network width function is the number of channels at increasing distances from the outlet as measured along the network. The total flow produced within each grid cell is distributed among the different links situated in the cell. The flows of the links situated at equal distance from the outlet are summed up. The resulting distribution is then convolved with a routing function depending upon the time and the distance from the outlet. This routing function is calculated with a finite-difference approximation of an analytical solution to the diffusive wave equation.

Twelve model parameters have to be optimised (in grey in Figure 2). Within the grid cells, the depth of the upper soil layer, wdsx, the four seasonal runoff coefficients, scr, and the three parameters describing the unit hydrograph, a, b and c, have been optimised using a method based on observed streamflow separation (Bultot and Dupriez, 1976). For this purpose, streamflow time series from 22 sub-catchments of area lower than 500 km^2 have been used. The recession coefficients of the two underground reservoirs, α_1 and α_2, as well as the coefficient μ controlling the flow to the alluvial reservoir have been optimised using the SCE-UA method (Duan *et al*., 1992). The values of the two parameters of the routing module, v, the wave velocity and D, the diffusion coefficient, have been tuned on streamflow data of sub-basins of area ranging from 700 to 16,500 km^2.

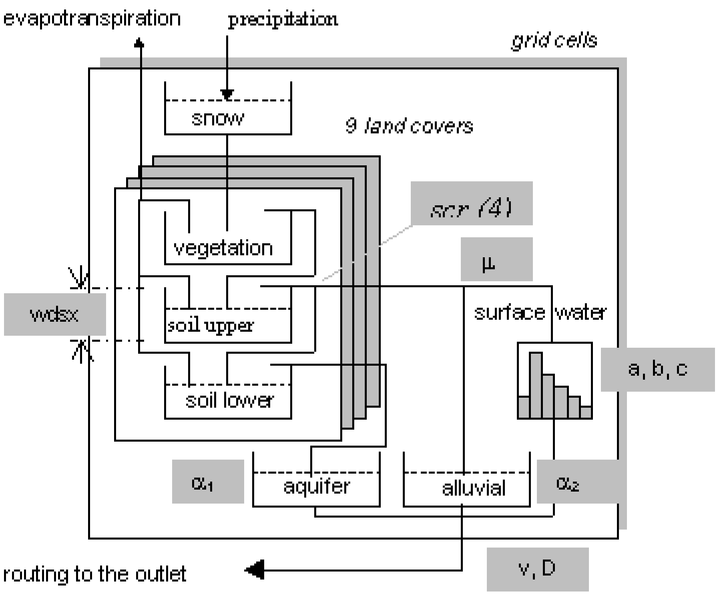

Figure 2. Flow chart of the SCHEME model.

The values of the ten parameters related to the within grid cell processes have to be estimated over the all grid. In order to regionalise parameter values optimised on gauged sub-catchments, a set of indices have been estimated for the sub-catchments as well as for the all grid. These indices are based on the CORINE Land-Cover 250m raster database and on the CORINE Soil Map of the European Countries at 1:1,000,000. The indices are fraction area covered with covers or with soils that have a specific property. Relationships between parameter values and indices have been searched using an artificial neural network, NevProp3® (Goodman, 1996). The best neural network models, i.e. the set of indices resulting in the best correlation with optimised parameter values, were selected for each parameter. The models were then applied to the all grid. Finally, the model has been validated on data corresponding to a period independent from the calibration period, for the small sub-catchments and for the larger sub-basins.

In this study, the last set of climate change scenarios distributed by IPCC have been used. They have been selected by the IPCC Task Group on Scenarios for Climate Impact Assessment (IPCC-TGSCIA) following several criteria: they are the results of transient experiments using the greenhouse gas scenario IS92a (Legget et al., 1998), i.e. a 1% increase, with or without aerosols, they are in the public domain, the ocean-atmosphere general circulation model (AOGCM) are well documented and have taken part to intercomparison experiment. At the beginning of 2000, 7 AOGCM were available on the IPCC Data Distribution Centre (IPCC-DDC) web-site. Among these, three have been used in this study for two main reasons: they have the best resolution and they provide changes not only for temperature and precipitation but also for other meteorological variables necessary to estimate potential evapotranspiration i.e. radiation or cloudiness, water vapour pressure and wind speed. Some information on these models are on Table 1. The integrations with HadCM2 have been repeated four times, resulting in an ensemble prevision that reflects the variability of the scenarios. Monthly changes provided for the AOGCM grid have been interpolated on a central point in Belgium (50°5'N, 5°E). Changes in temperature and precipitation are plotted in Figure 3 for three 30-year periods.

Table 1. AOGCMs selected by the IPCC/TGCIA and used in this paper.

Model	Institution and reference	Resolution	
ECHAM4	German Climate Research Centre (Roeckner et al., 1996)	T42	~2.81×2.81 °
HadCM2	UK Hadley Centre for Climate Prediction and Research (Johns et al., 1997)	Grid 96×73	3.75×2.75 °
CGCM1	Canadian Centre for Climate Modelling and Analysis (Reader and Boer, 1998)	T32	~3.75×3.75 °

The most striking changes are the increase in temperature simulated in all the scenarios. This increase is more pronounced around August and the higher levels would be reached in the latest period, at the end of the century. Another feature common to all the scenarios is the decrease in summer rainfall. The decrease is getting worst for the latest period. The increase in rainfall in winter, even if simulated by most of the scenarios is more uncertain due to the low level of changes and the high variability among scenarios. It can be noticed that the ECHAM4 model simulates the highest increase in temperature and the highest decrease in summer rainfall.

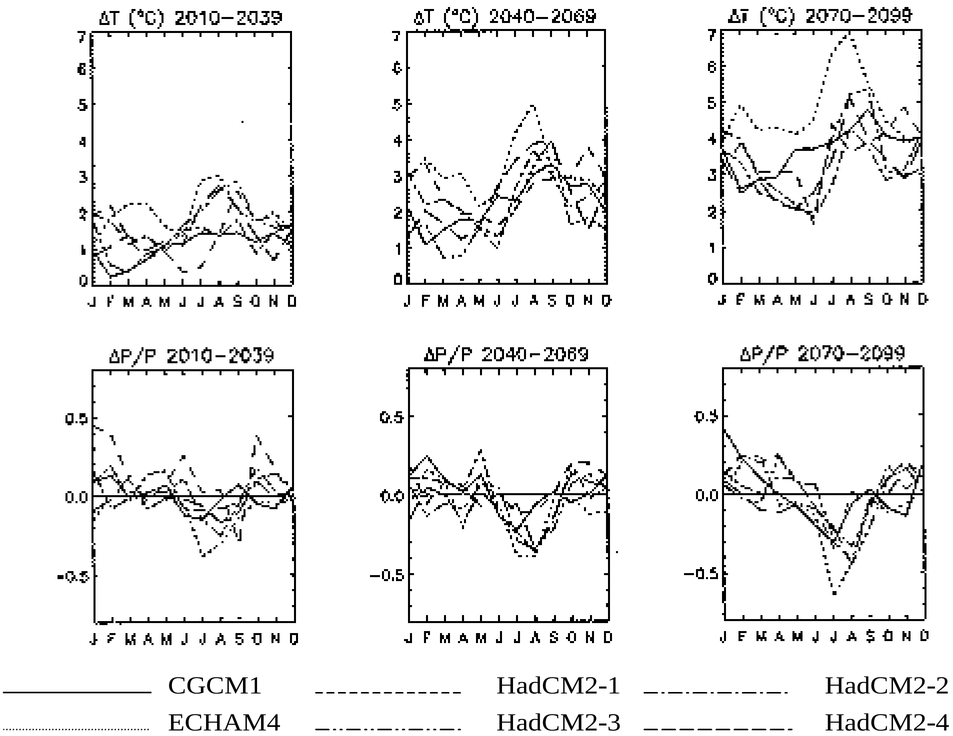

Figure 3. Changes in temperature and precipitation in Belgium from IPCC scenarios.

RESULTS

The results are presented in Figure 4, 5 and 6 for basins of area ranging from ~300 to ~20,000 km2 and for the three 30-year periods. They have been obtained by running the model first with the meteorological data of the period 1971-1995 – the baseline climate – then running the model with the same meteorological time-series perturbed by the average changes provided by the AOGCM's scenarios and finally comparing the simulated streamflow under climatic change conditions and under the baseline climate.

The changes in monthly values of the streamflow are shown as percentage of the baseline streamflow in Figure 4. The variability of impacts between the different scenarios from different AOGCMs or even between different ensemble members in the case of HadCM2 prevent from an unique and misleading picture of what might happen in the future. The uncertainty given by the spread of monthly changes is confusing for the period 2010-2039. For the next period, 2040-2069 and even more for the last period, 2070-2099, a decrease of the streamflow during summer is simulated with all the scenarios. The streamflow simulated for the sub-basins of the Ourthe are more affected than the Meuse basins at Chooz and at Visé. This is more an effect due to the quickest response of these catchments characterised by shallow soils on impervious bedrock than an effect of scale.

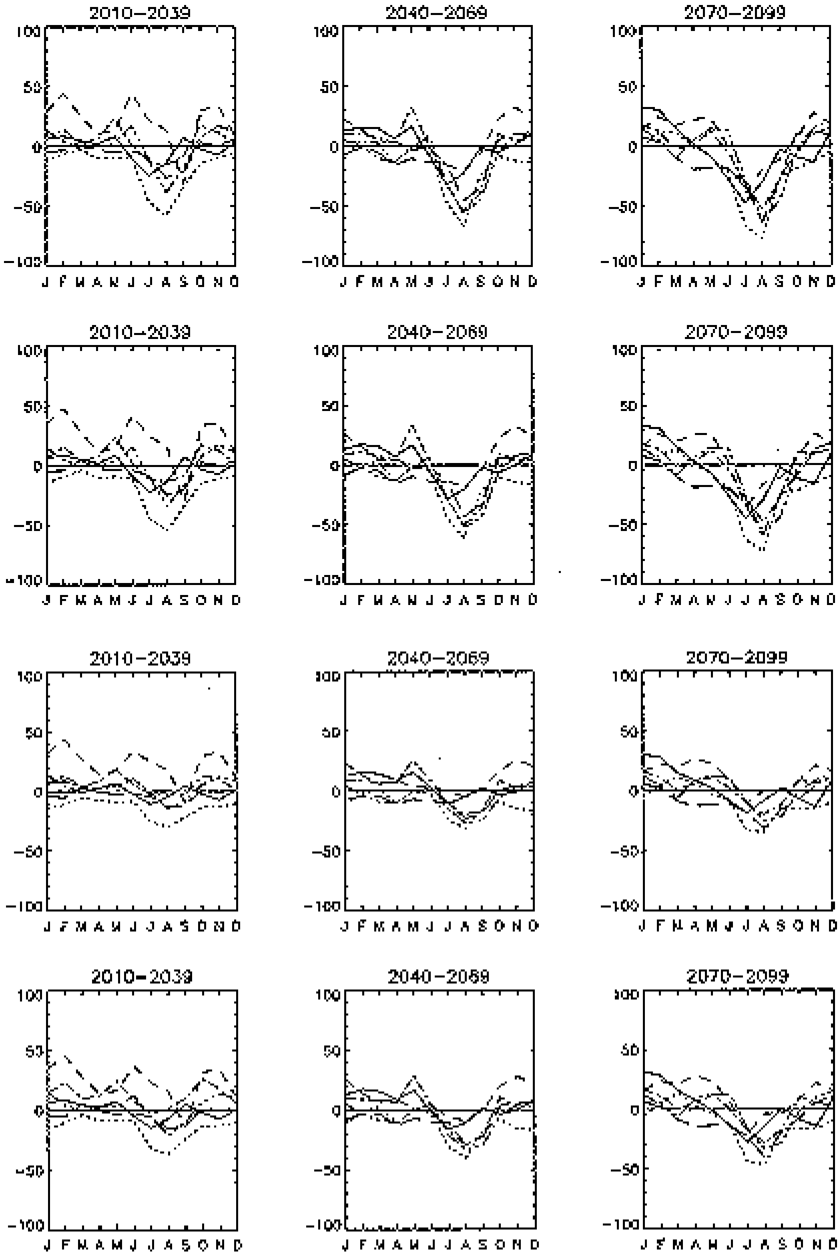

Figure 4. Change in monthly values of streamflow under climatic change conditions (see Figure 3 for legend) as percentage of the baseline streamflow; from top to bottom: Ourthe Orientale at Mabompré, Ourthe at Tabreux, Meuse at Chooz and at Visé.

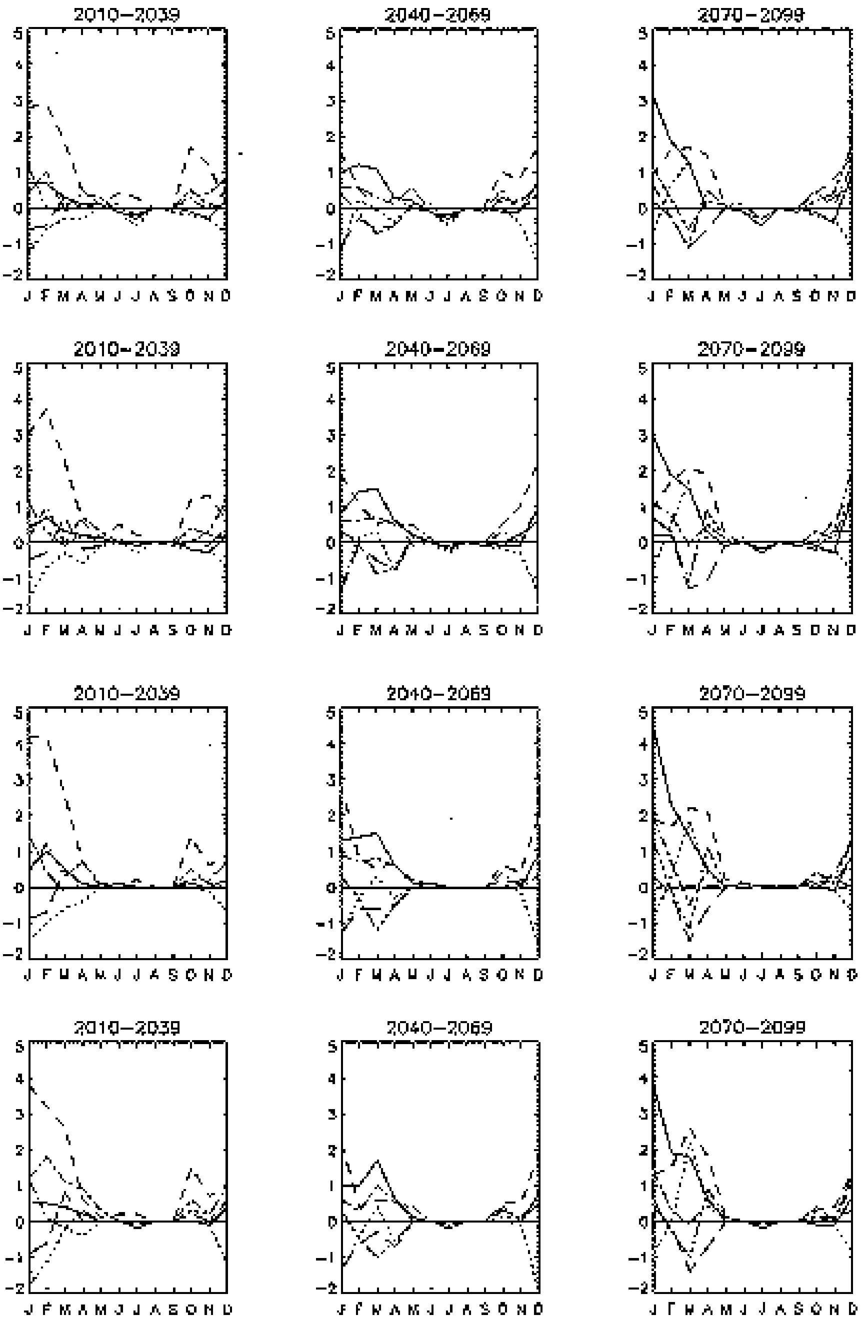

Figure 5. Difference in the number of flood days under climatic change conditions (see Figure 3 for legend) and under the baseline climate; from top to bottom: Ourthe Orientale at Mabompré, Ourthe at Tabreux, Meuse at Chooz and at Visé.

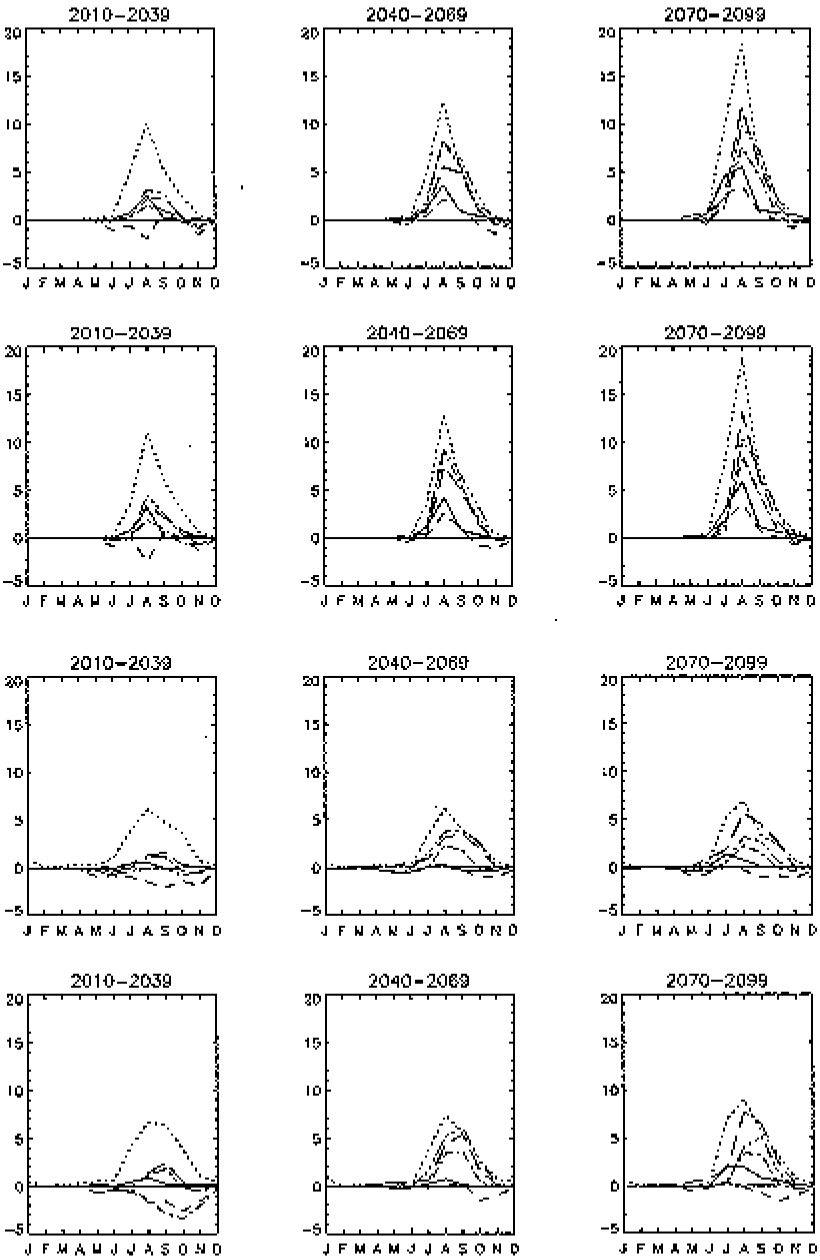

Figure 6. Difference in the number of low flow days under climatic change conditions (see Figure 3 for legend) and under the base-line climate; from top to bottom: Ourthe Orientale at Mabompré, Ourthe at Tabreux, Meuse at Chooz and at Visé.

The number of flood days has been set to the number of days with a simulated streamflow higher than the 95-percentile of the streamflow corresponding to the 1971-1995 baseline period. The impact of climate change on the flood frequency is given by the difference between the number of flood days simulated with a scenario and the corresponding number simulated with the unperturbed baseline time-series (Figure 5). Since floods occur mostly during winter, with nearly no effect of evapotranspiration, the changes in various senses of winter rainfall result in changes in the same various senses in the flood frequency. No conclusion can be drawn for the first two periods except about the high variability in responses. For the last period, an increase of the flood frequency is simulated with all the scenarios except the ECHAM4.

In the same way as for the flood days, the 5-percentile of the daily total streamflow is used as a threshold to define low flow days. Under the present day conditions, the 18 low flow days per year are distributed with a maximum at the end of the summer season and early fall. The monthly changes in the number of low flow days is presented in Figure 6. These results may be related to the summer decrease in streamflow. But in the case of low flow days, the contrast between the increase in their frequency in the Ourthe and in the Meuse is more pronounced. The Ourthe sub-basins with their quicker response are not able to sustain the streamflow during summer. Other parts of the Meuse basin are characterised by larger aquifers and their baseflow contribute to feed the Meuse streamflow during summer.

CONCLUSIONS

Previous sensitivity to climate change studies focused on small sub-catchments representative of the various hydrologic conditions in Belgium (Bultot et al., 1988, Gellens and Roulin, 1998). It had been shown that in catchments with high infiltration rates, impacts are damped by the large groundwater capacities and that the catchments with prevailing surface runoff are more sensitive to climate changes. The use of a macroscale hydrological model learns about how the responses of such distinct sub-basins are integrated on a larger basin.

In this study, more recent scenarios have been used. It is supposed that the changes gain in reliability due to modelling improvements and better resolution. They provide a consistent set of changes of the meteorological variables relevant to the water cycle. Furthermore they provide perspectives throughout the century given a rate of increase in greenhouse gas content. Using this common set of scenarios, the impacts of climate change on the hydrological cycle in different regions can be compared. A typical West European rainfed river basin like the river Meuse basin could experience a decrease in water resources during summer. This has been shown by the impacts on the streamflow and on the low flow frequency. Further analysis of the outputs of the SCHEME model will tell more about other related risks like soil droughts and groundwater shortage. As far as an increased risk of flooding events during winter is concerned, due to the high variability in the responses to the different scenarios, the most convergent response has been found in a higher risk for the end of the century. But looking towards the security, the increase simulated with a large fraction of the scenarios should warn us for an appropriate management.

Acknowledgments

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