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Predictive uncertainty in climate change impacts on floods

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Abstract It is crucial for flood management that information about the impacts of climate change on floods and the predictive uncertainties therein becomes available. This has been achieved by using information from different Regional Climate Models for different emission scenarios to assess the uncertainty in climate change for the Meuse River in northwestern Europe. A hydrological model has been used to simulate flows for current and changed climate conditions. The uncertainty in the hydrological model is assumed to be represented by the difference between observed and simulated discharge and incorporated in the uncertainty analysis through the model parameters. Climate change results in an increase of the 100-year flood of about 30%. This increase is primarily caused by an increase of precipitation in winter. The predictive uncertainty in this impact is about 20% resulting from uncertainties in climate change (about 50%) and uncertainties in hydrological model parameters (about 50%).

Key words climate change; floods; fuzzy objective function; HBV model; Meuse basin; Monte Carlo analysis; Regional Climate Model; uncertainty

INTRODUCTION

Higher and more frequent river floods in western Europe are expected as a result of climate change. These flooding events may cause enormous economic, social and environmental damage and even loss of human life. Facing these problems, it is crucial for flood management that information about the impacts of climate change on floods and in particular the uncertainties therein becomes available.

Recent studies generally show increases in peak discharges with climate change in western Europe using (downscaled) results from Global Climate Models (GCMs) and conceptual hydrological models. Gellens & Roulin (1998) found, for eight small basins in Belgium, a rise in the frequency of floods in winter for the basins where surface flow prevails for six out of seven GCM climate scenarios using the hydrological model IRMB. Middelkoop *et al*. (2001) expect for the middle and lower Rhine basin an increase in peak flows of 5–10% by 2050 using results from two GCMs and a monthly water balance model. This is the result of increases in winter of both rainfall and the melt water runoff contribution from the Alps. Andréasson *et al.* (2004) calculated for six Swedish basins an increasing frequency for autumn floods and a decreasing frequency of spring floods with downscaled GCM results and the hydrological model HBV. Booij (2005) found for the Meuse basin in France and Belgium an increase of peak discharges of about 10% using results from GCMs and Regional Climate Models (RCMs), and the HBV model.

A cascade of uncertainty sources is present in this climate impact assessment ranging from uncertainties about future greenhouse gas emissions and responses of the GCMs to uncertainties in regional climatic effects, physical basin characteristics and hydrological models. The uncertainty sources in emissions and climate models can be aggregated and represented by scenarios for future radiative forcing for different global climate models (Carter *et al*., 1999). The uncertainty sources in the hydrological model can be grouped into model input uncertainty (including uncertainties from emissions and climate models), model parameter uncertainty and model structure uncertainty. Numerous studies have assessed these different uncertainties, for emissions and climate models (e.g. Visser *et al*., 2000), as well as for hydrological models (e.g. Uhlenbrook *et al*., 1999). However, only a few attempts have been made to evaluate the whole uncertainty cascade associated with the impact of climate change on river flows, a notable one being Wilby (2005) for the River Thames in the UK.

Therefore, the objective of this study is to assess the uncertainty in impacts of climate change on floods in the Meuse River (surface area about 21 000 km^2) in north-western Europe. This objective is achieved by first assessing climate change and its uncertainty for the study area. Next, an existing hydrological model is calibrated and validated and uncertainty sources in the hydrological model are quantified. The different uncertainty sources are propagated through the hydrological model using Monte Carlo simulation. Finally, results are discussed and conclusions are drawn.

METHODOLOGY AND DATA

Climate change and uncertainty

Changes in climate variables relevant for hydrology, in particular precipitation and temperature, are assessed using observed station data and results from RCMs for different greenhouse gas emission scenarios. The RCM results have been obtained from the EU-project PRUDENCE (Christensen *et al*., 2002) in which ten different RCMs for two different IPCC emission scenarios, A2 (Medium-High emissions) and B2 (Medium-Low emissions), different driving GCMs and different samples have been compared. The uncertainty in the future projections of climate variables (input uncertainty of hydrological model) is therefore assumed to be mainly the result of different emission scenarios, sampling errors, different boundary forcing by GCMs and different RCMs. The uncertainty in future emissions is underestimated by using results of only the two scenarios A2 and B2, i.e. the uncertainty in the global mean temperature in 2100 as a result of scenarios A2 and B2 is about half of the uncertainty as a result of all scenarios (Houghton *et al*., 2001). The underestimation of this uncertainty source has been accounted for by using a scaling factor. The uncertainty in changed climate variables (temperature and precipitation) is captured in Gaussian probability distributions for relevant statistics of these variables based on Déqué (2004) and Christensen (2004). In the uncertainty analysis, statistics are randomly drawn from these probability distributions and used to transform current and changed climate series using the change factor (CF) method. The CF method calculates climate series by adding (temperature) or multiplying (precipitation) climate information from the RCMs to observed time series (see e.g. Middelkoop *et al*., 2001).

Hydrological modelling and uncertainty

The conceptual hydrological model HBV (Bergström, 1995) lumped for each of the 15 sub-basins in the Meuse basin upstream of Borgharen, and with a daily time step, is used to simulate hydrological behaviour in general and floods in particular for current and changed climate conditions. This model (HBV-15) was originally calibrated and validated by Booij (2005). To improve its performance, HBV-15 has been re-calibrated for current climate conditions using a fuzzy measure as the objective function (as in e.g. Seibert, 1997). This fuzzy measure combines several objective functions for high and low flow simulation (e.g. modelling error in peak discharges) and simulation of the discharge regime (e.g. Nash-Sutcliffe coefficient). Fuzzy logic allows the handling of the concept of a partial truth value between completely true and completely false. Validation of the model is done for a different period (1985–1996) to the calibration period (1970–1984).

The uncertainty in the hydrological model is assumed to be represented by the difference between observed and simulated discharge and expressed by the Nash-Sutcliffe coefficient. This model uncertainty is incorporated in the uncertainty analysis through the model parameters. Through consideration of this parametric uncertainty, model structure related uncertainties are not explicitly taken into account. However, these are assumed to be at least partly covered by the parametric uncertainty. Similarly as for the climate variables, in the uncertainty analysis values for HBV parameters are randomly drawn from uniform probability distributions of the parameters. The ranges of these probability distributions are determined by forcing the average of Nash-Sutcliffe coefficients for pairs of simulated discharge series ("simulated" NS) to be equal to Nash-Sutcliffe coefficients for pairs of observed and simulated discharge series from the calibration ("observed" NS). The HBV parameters are assumed to have the same relative uncertainty range (expressed relative to their means). The average Nash-Sutcliffe coefficient for the simulated discharge series is determined from all combinations of simulated discharge series in a Monte Carlo analysis. The number of runs in this Monte Carlo analysis is 1000 resulting in $(1000^2 - 1000)/2$ different combinations (or Nash-Sutcliffe coefficients).

Uncertainty analysis

The different uncertainty sources (input uncertainties, HBV parameters) are propagated through the HBV model using Monte Carlo analysis. This finally results in a probability distribution of floods for current and changed climate conditions. This enables an assessment of the significance of changes in flooding conditions with climate change by comparing changes and uncertainties. Floods are described by the annual maximum daily discharge with a return period of 100 years estimated using the Gumbel extreme value distribution. Although return periods of 250 and 1250 years are used for design purposes in the Meuse basin, a return period of 100 years is considered to be the upper limit in this study in view of the limited length of the data series considered and all other uncertainties.

RESULTS AND DISCUSSION

Climate change and uncertainty

Figure 1 shows the probability density functions of basin-averaged temperature and precipitation as a result of different uncertainty sources for the current (1970–1996) and changed (2071–2100) climate for DJF (December–January–February), MAM (March–April–May), JJA (June–July–August) and SON (September–October–November). The results show an average increase in annual temperature of 4.0°C for climate change conditions varying between 3.3°C in DJF and 5.1°C in JJA. Precipitation decreases slightly by 2.5% on an annual basis, varying between +24% in DJF and –35% in JJA. Uncertainties with climate change (expressed as standard deviation) vary between 1.3°C in DJF and 2.1°C in JJA for temperature and 11% in MAM and 16% in JJA for precipitation. Uncertainties in these climate variables for current conditions (1971–2000) are 30–50% smaller, because emission scenario uncertainties do not apply. In general, changes in temperature seem to be significant for all seasons and changes in precipitation seem to be only significant for winter (DJF) and summer (JJA) taking into account the uncertainty in these variables as a result of different emission scenarios, different RCMs, different boundary forcing by GCMs and sampling.

Hydrological modelling and uncertainty

Results of the HBV model calibration show good performance for high flows as well as for average and low flow simulation using the fuzzy measure. Nash-Sutcliffe coefficients for different sub-basins of the Meuse are between 0.80 and 0.90, and over 0.90 for the complete basin showing a slight improvement with respect to Booij (2005). Figure 2 gives an illustration of the calibration results using a fuzzy objective function. It shows dotty plots of values of HBV parameters *FC* (affecting both low and high flow conditions), *ALFA* (primarily affecting high flow conditions) and *PERC* (affecting low flow conditions) against the Nash-Sutcliffe coefficient and the fuzzy measure when varying all other relevant HBV parameters randomly at the same time. For all parameters together, the identifiability has increased using this fuzzy measure with considerable improvements for parameters affecting low flows (e.g. *PERC*, see Fig. 2) and slight deteriorations for parameters primarily affecting high flows (e.g. *ALFA*). Validation results are slightly better than calibration results due to the better data quality for the validation period as also observed by Booij (2005). The parametric uncertainty for different sub-basins is found to be between 22% and 31% (expressed relative to their means) forcing the simulated NS to be equal to the observed NS for these different sub-basins. An illustration of the determination of the parametric uncertainty for the Amblève sub-basin is given in Fig. 3, which shows that a parametric uncertainty of about 27% results in a simulated NS equal to the observed NS for the Amblève.

Impacts of climate change on floods and uncertainty

Combining RCM and HBV results enables an assessment of climate change impacts on floods and related predictive uncertainties. Figure 4 shows probability density
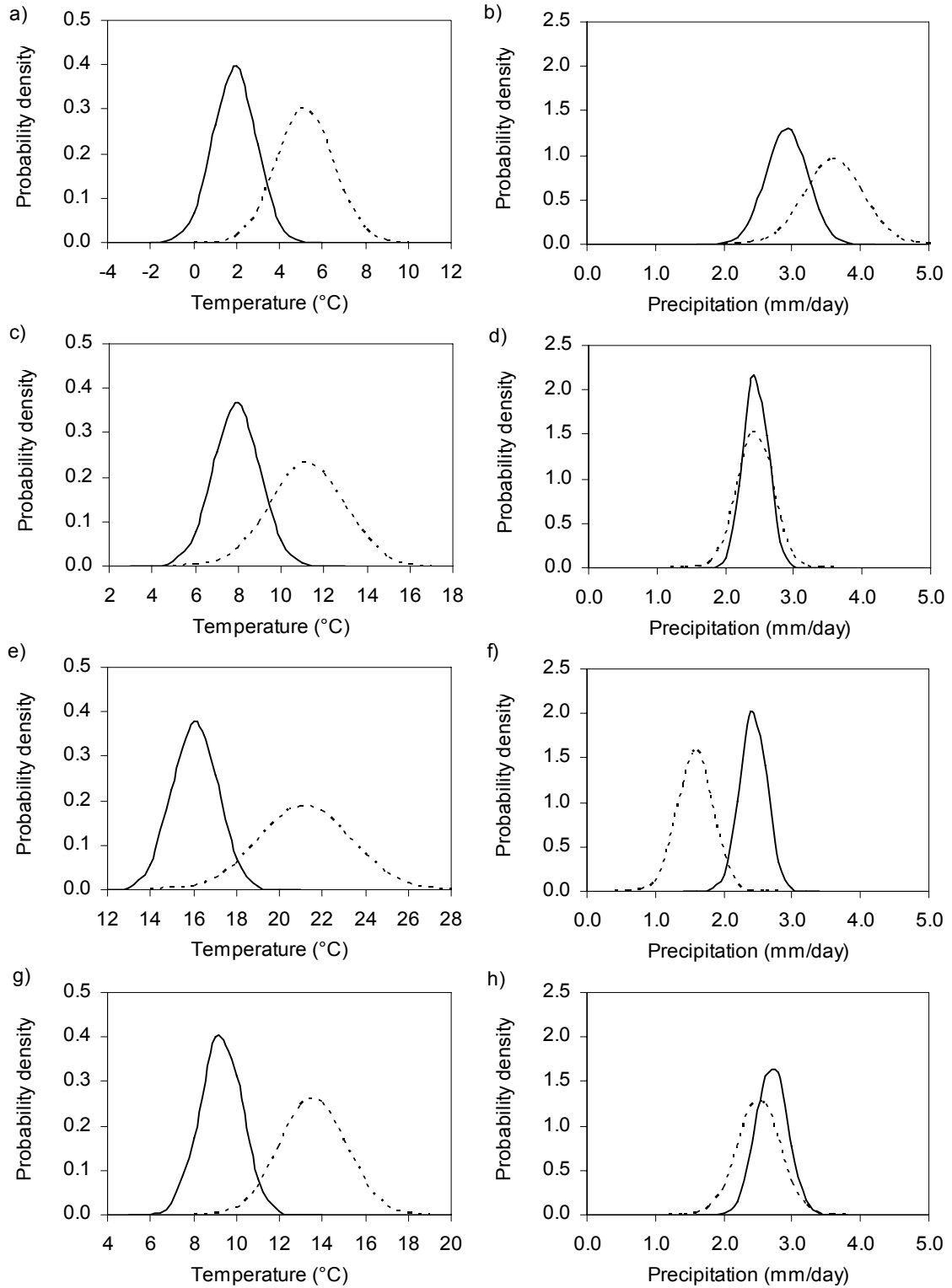
Fig. 1 Probability density functions as a result of different uncertainty sources for current climate (solid) and changed climate (dotted) for DJF (a), MAM (c), JJA (e) and SON (g) temperature (°C) and DJF (b), MAM (d), JJA (f) and SON (h) precipitation (mm day^{-1}).
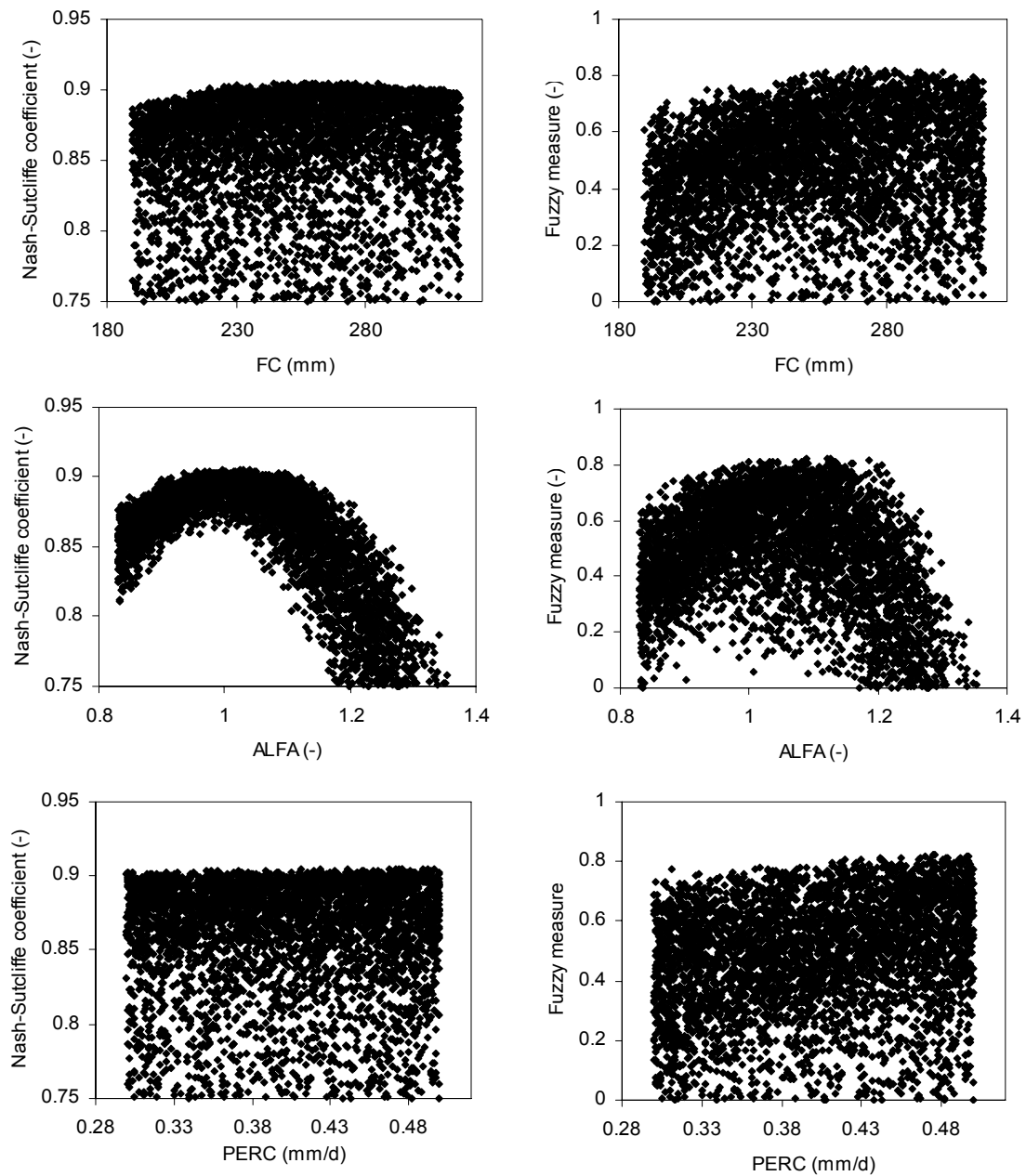
Fig. 2 Dotty plots of the Nash-Sutcliffe coefficient (left) and fuzzy measure (right) for HBV parameters *FC* (mm), *ALFA* (-) and *PERC* (mm).

functions of the annual maximum daily discharge with a return period of 100 years for the current and changed climate. Climate change results in an increase of the 100-year flood of about 1100 m^3 s^{-1} or 30%. This increase is primarily caused by an increase of precipitation in DJF. The total uncertainty in this impact (expressed as standard deviation) is about 950 m^3 s^{-1} or 20% resulting from uncertainties in climate change (about 50% of total) and uncertainties in hydrological parameters (about 50% of total). The most important uncertainty sources related to climate change are those resulting from different emission scenarios and different GCMs. For the hydrological model, the dominant uncertainty source is in the parameters of the quick runoff routine of HBV.
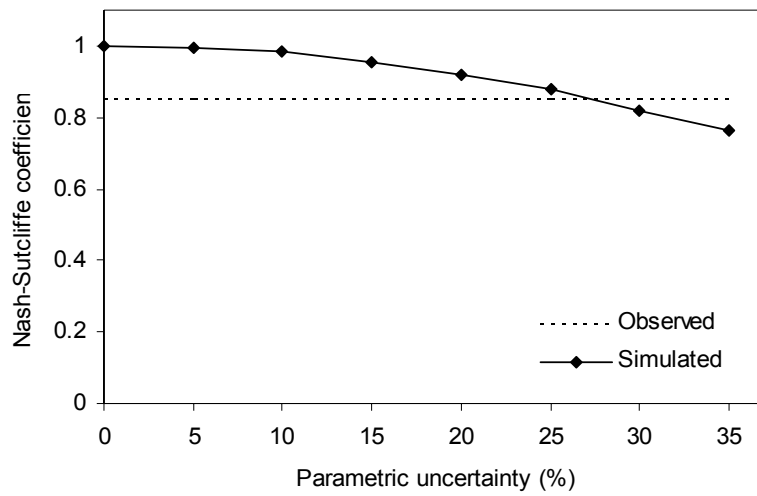
Fig. 3 Nash-Sutcliffe coefficient for observed and simulated discharge series from the calibration (observed) and average of Nash-Sutcliffe coefficients for pairs of simulated discharge series (simulated) as a function of parametric uncertainty for the Amblève.
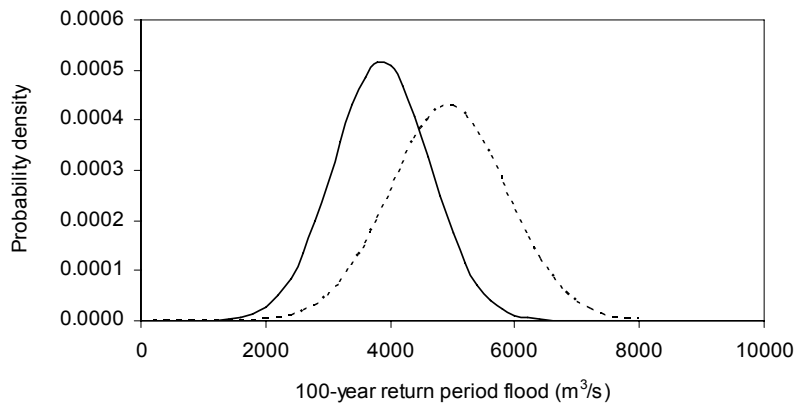

Fig. 4 Probability density functions of the annual maximum daily discharge with a return period of 100 years ($m^3 s^{-1}$) as a result of different uncertainty sources for current climate (solid) and changed climate (dotted).

The total uncertainty under current climate conditions is about 25% less than under changed conditions, because emission scenario uncertainties do not apply.

CONCLUSIONS

It thus can be concluded that the impacts of climate change on floods are considerable, resulting in an increased occurrence of floods in the Meuse River. Uncertainties in these impacts are large, although only partly disguising the climate change signal. These uncertainties are both the result of uncertainties in climate variables and uncertainties related to the hydrological model. Most important uncertainty sources are those resulting from different emission scenarios, different global climate models and the quick runoff routine of the hydrological model.

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