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Future low flows and hydrological drought: how certain are these for Europe?

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Abstract Climate data from a re-analysis dataset (WFD, 1971–2000) and three GCMs (1971–2100) for two emissions scenarios were used to: (i) explore future low flows and hydrological drought characteristics, and (ii) estimate how uncertainty in forcing propagates into these characteristics. Runoff was obtained through a multi-model mean from large-scale models forced with WFD and GCMs. Low flow and drought characteristics in two transects across Europe were intercompared for 1971–2000 to estimate forcing uncertainty, and for two future time frames to quantify climate change impact and to compare impact with forcing uncertainty (signal-noise ratios). Annual flow was projected to decrease (maximum 30%), but forcing uncertainty is larger (minimum 35%). Drought duration was predicted to increase (50–180%) with low forcing uncertainty (<10%). Similar observations were made for future deficit volumes. This study shows that future droughts can be predicted with higher certainty than low flows and that multi-forcing is required.

Key words hydrological drought; low flow; runoff; future; uncertainty; forcing; Europe

INTRODUCTION

Drought is likely to become more extreme in vast areas across the world, including regions in Europe. Droughts do not directly cause fatalities in Europe, but they have large socio-economic and environmental impacts affecting many sectors. Water-stressed areas of southern EU Member States are affected, but also countries where water availability has never been a major concern. Based upon data from the first part of the 21st century the European Commission reported in 2007 that each year, on average 15% of the EU total territory and 17% of the EU total population has suffered from the impact of droughts. The estimated total cost of droughts over the past 30 years was as high as 100 billion Euros.

Confidence in drought projections is still low according to a recent IPCC study on extremes (Field *et al*., 2012). Recent studies reveal that assessment of future drought depends on which drought type (meteorological, soil moisture, hydrological), or which drought characteristic is considered (e.g. Orlowski & Seneviratne, 2013). For water resources assessment, hydrological drought (e.g. Tallaksen & Van Lanen, 2004) is more relevant than the frequently used meteorological or soil water droughts (e.g. SPI, PDSI, SMA).

Feyen & Dankers (2009) examined the impact of global warming on hydrological drought in Europe. They conclude that streamflow droughts will become more severe and persistent in most parts of Europe, except in the most northern and northeastern regions. Their study is, as far as the authors know, the only investigation that addresses hydrological drought on a pan-European scale. They used a single Regional Climate Model, one emission scenario (A2) and a single hydrological model in their investigation. Hence, they hardly addressed uncertainty in the drought assessment.

This study aims to improve knowledge on future low flows and hydrological drought in Europe through a multi-model, multi-scenario setup, including uncertainty that is caused by climate forcing. The paper is organised as follows. The second section introduces the cross-sections, the following section describes past and future forcing data, large-scale models, and flow and drought characteristics followed by sections presenting the results, and discussion and conclusions.

PAN-EUROPEAN TRANSECTS

Low flows and hydrological drought were determined for two transects across Europe (Fig. 1). The north–south transect consists of the following study areas: the Netherlands, Rhine Valley, Switzerland and the Po River basin (Italy), and the west–east transect runs from Portugal, Júcar River basin (Spain), Po River basin to Syros (Greece). The transects are made of a total of 244 grid cells (0.5°).

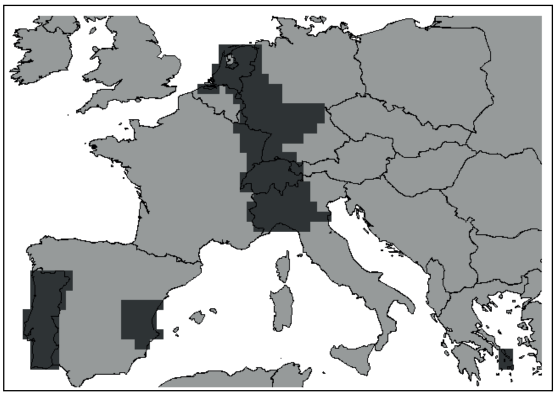

Fig. 1 Selected grid cells for the case study areas.

METHODS AND DATA

Climate forcing data

Daily meteorological data were used from a re-analysis dataset (1971–2000) and three General Circulation Models (GCMs, control period: 1971–2100, intermediate future: 2021–2050, far future: 2071–2100) for two emission scenario (A2 and B1). Data were made available through the EU WATCH (WATer and global CHange) project (Harding *et al.* 2011).

Re-analysis forcing data The WATCH Forcing Data (WFD) was chosen to retrieve historic meteorological data for the two transects. WFD is a gridded dataset (0.5°) covering the period 1901–2001. The data have been produced by combining the Climatic Research Unit's (CRU) monthly observations of temperature, wet days and cloud cover, plus the GPCCv4 monthly precipitation observations, and the ERA-40 re-analysis products (Weedon *et al.*, 2011). In this study, the WFD was used as a reference for the forcing over the period 1971–2000.

GCM forcing data Daily meteorological data were retrieved from three GCMs, i.e. CNRM (Centre National de Recherches Météorologiques, Météo-France), ECHAM5 (Max Planck Institute for Meteorology, Germany) and IPSL (Institute Pierre Simon Laplace, France). In the WATCH project the GCM data were downscaled and bias corrected (temperature, precipitation). GCM data were checked against WFD for the control period: 1971–2000, to quantify uncertainty in climate forcing (noise). Next the GCM data (three GCMs and two scenarios) were compared with the control period to assess the impact of climate change on future forcing (signal) for two time frames (2021–2050, 2071–2100), including examination of the signal–noise ratios.

Large-scale models

Gridded time series of total runoff (i.e. 244 cells) from six large scale hydrological models were retrieved from the WATCH project. The models included were: Htessel (University of Lisbon, Portugal), JULES (Centre for Ecology and Hydrology, UK), LPJ (Potsdam Institute for Climate Impact Research, Germany), MacPDM (University of Nottingham, UK), MPI-HM (Max Planck Institute for Meteorology, Germany) and WaterGAP (University of Kassel, Germany). These models were forced for: (i) the control period (1971–2000) with WFD and downscaled and bias-corrected output from three GCMs, and (ii) the 21st century with downscales and bias-corrected output from three GCMs. In this study, the effect of different structures of the hydrological models was reduced by computing the multi-model ensemble mean discharge (in most cases 6 ensemble members).

Low flow and drought characteristics were derived from the multi-model mean runoff for the control period. Drought characteristics obtained from GCM forced simulations were compared against those found with WFD forced simulations. The percent difference in low flow and drought characteristics for each of the GCMs was used as a metric for uncertainty due to climate forcing (noise in characteristics due to climate forcing). Differences between the GCMs provide additional information on forcing uncertainty.

In the second step, low flow and drought characteristics were computed both for the intermediate and far future for each of the GCMs and two emission scenarios (12 cases). Percent change in drought characteristics was used to explore the impact of climate change (signal in characteristics), which were intercompared with the noise. For more details, readers are referred to Alderlieste & Van Lanen (2013).

Flow and drought characteristics

Based on simulated total runoff time series, several for water resources assessment relevant flow and drought characteristics were calculated similar to Stahl *et al.* (2012) and Alderlieste & Van Lanen (2013).

Flow characteristics The following flow characteristics were determined: (i) mean annual flow, (ii) mean monthly flow, i.e. the monthly average runoff value (January, February, …, December), and (iii), May–November MAM7, i.e. the mean annual 7-day minimum runoff, over the period May to November..

Drought characteristics. The variable threshold method was applied to identify drought (e.g. Tallaksen & Van Lanen 2004) and to compute their characteristics (duration, deficit volume). Monthly thresholds were calculated for each cell and to avoid sudden jumps in the threshold, these monthly threshold values were smoothed using a 31-day sliding window (e.g. Van Huijgevoort *et al* 2012). The monthly thresholds were different per combination of GCM and large-scale model, and to assess future drought, the threshold of the control period was used.

RESULTS

Uncertainty in climate forcing and low flow and drought characteristics

For the control period (1971–2000) the downscaled and bias-corrected temperature and precipitation of the three GCMs and WFD were compared to assess noise in climate forcing. The median of the changes in temperature and precipitation is given in Fig. 2, which is a measure of climate forcing uncertainty. All three GCMs slightly overestimated the median of the annual temperature (0.2–0.5°C, Fig. 2, left, most left bar of each of the GCM clusters). The GCMs expected less precipitation than WFD (2–10%) (Fig. 2, right).

The median of the multi-model annual flow was clearly overestimated when using GCM forcing instead of WFD forcing. The overestimation varied between 37 and 55% (Fig. 3, left, most left bar of each of GCM clusters) (i.e. uncertainty in flow characteristic). The differences for the median July flow were even larger (57–161%, not shown). On the other hand, the differences in median MAM7 were substantially smaller for two GCMs (<25%), but substantial for CNRM (>100%, Fig. 3, right).

Average drought duration was derived from the multi-model runoff for each of the 244 grid cells. This was done for each of the three GCMs and WFD forcings for 1971–2000. The median of the average drought duration was slightly underestimated with the GCM forcing relative to the WFD forcing (10–16%) (Fig. 4, left, most left bar of each of GCM clusters) (i.e. uncertainty in drought characteristic). The difference in median drought deficit volume between the GCM and

WFD forcing was not mono-directional; the median was underestimated by 3% when the IPSL forcing was used, whereas the overestimation of the median varied between 22 and 32% in case of CNRM and ECHAM5 forcings (Fig. 4, right).

Change in future forcing

Projected change in in the median of the average annual temperature is provided in Fig. 2 (left). All three GCMs predicted a temperature increase, which agrees with common knowledge (e.g. Field *et al.*, 2012). Temperature increase in the far future was larger than in the intermediate future, and the increase for the milder B1 scenario was smaller than for the more extreme A2 scenario. The forcing uncertainty (noise, indicated with CTRL in Fig. 2) was clearly lower than the climate change signal.

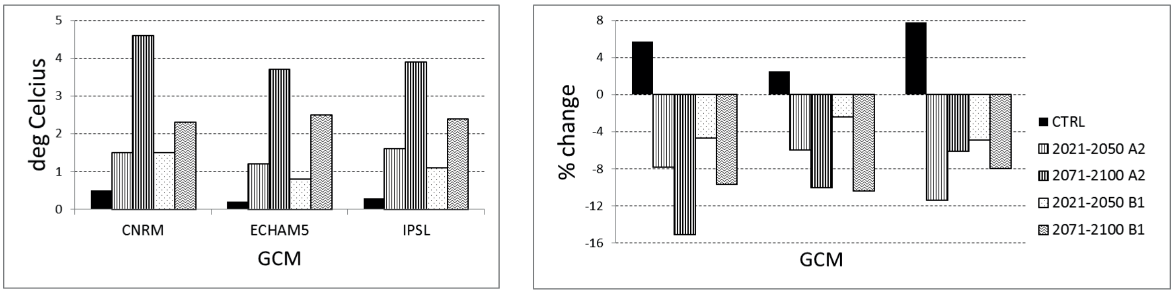

Fig. 2 Projected change in the median of the average annual temperature (left), and the median of the average annual precipitation (right) for three GCMs, two emission scenarios (A2 and B1) and the intermediate and far future. CTRL specifies the difference between the GCM and the re-analysis data (WFD), the forcing uncertainty. Results are shown for the average change of all 244 grid cells (Fig. 1).

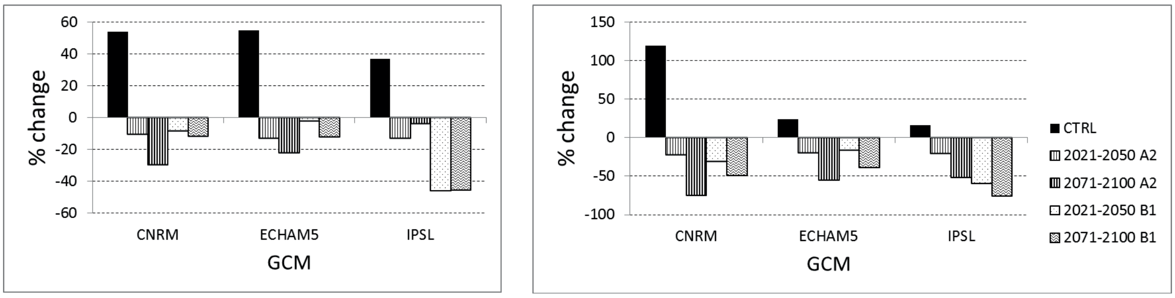

Fig. 3 Projected change in mean annual runoff (left), and mean annual 7-day minimum runoff, MAM7 (right) for three GCMs, two emission scenarios (A2 and B1) and the intermediate and far future. CTRL specifies the difference between runoff simulated with the GCM and the runoff simulated with re-analysis data (WFD). Results are shown for the average change of all 244 grid cells (Fig. 1).

According to the selected GCMs the median of the average annual precipitation will decrease in all cases (Fig. 2, right). In the far future, the projected precipitation decrease was 6–15% for the A2 scenario. The projected decreases with CNRM and ECHAM5 followed a regular pattern. In contrast, IPSL predicted for the intermediate future larger precipitation decrease than for the far future (A2 scenario). Forcing uncertainty was relatively large, in particular for CNRM and IPSL. The noise was similar to, or even larger than the climate change signal for the intermediate future under the B1 scenario, which indicates that predictions are uncertain.

Change in future flows

The median of the average annual runoff, as obtained from the multi-model ensemble, was projected to decrease in all cases (Fig. 3, left). CNRM and ECHAM5 gave a similar pattern, although the climate change signal with CNRM was somewhat stronger than with ECHAM5 (11–29% and 13–22%, respectively, A2), which corresponds with the higher temperature (likely higher evapotranspiration) and the lower precipitation predicted with CNRM (Fig. 2). According to the IPSL projections, the annual flow reduction was larger for the B1 scenario than for the A2 scenario, which contradicted the two other GCMs. Annual flow predictions, however, were in most cases smaller than the high uncertainty in annual flow because of climate forcing (exception IPSL, B1).

Models also projected a decrease of mean annual 7-day minimum runoff (MAM7) for all cases (Fig. 3, right). The decrease was larger than for the annual runoff. Patterns agreed with those obtained for the change in annual runoff; i.e. large similarity amongst CNRM and ECHAM5 with a slightly stronger climate signal for CNRM (22–75% and 19–55%, respectively, A2), and IPSL having stronger climate signal for the B1 than the A2 scenario. The change in MAM7, however, displayed one deviation from the annual runoff, namely the climate signal was larger for two GCMs (ECHAM5, IPSL) than the uncertainty in MAM7 caused by climate forcing.

Change in future hydrological drought

The change in the median of the average drought duration was derived from the multi-model runoff using GCM forcing for two future time frames and the control period. This was done for the A2 and B1 scenarios (Fig. 4, left). According to all GCM forcing, the median of the average drought duration will increase. For the A2 scenario, average drought duration was predicted to increase by at least 50%. The change was even over 150% when the CNRM or ECHAM5 forcing was used. IPSL predicted an increase of around 50%, irrespective of the time frame or emission scenario. Figure 4 (left) also shows that the climate change signal in drought duration was substantially larger than the difference due to forcing uncertainty (CTRL).

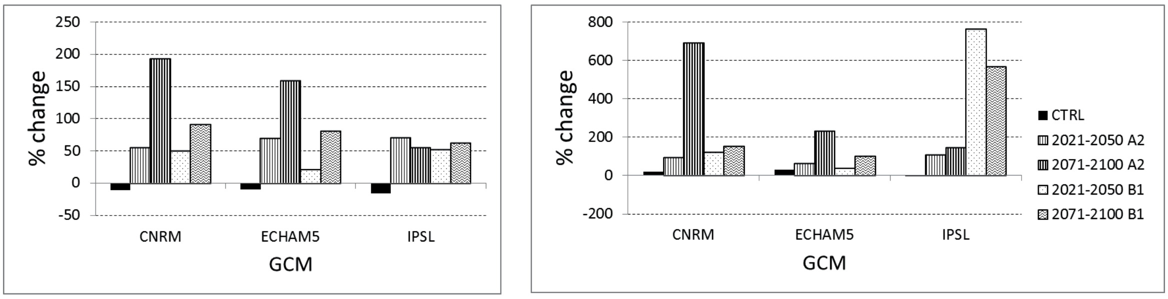

Fig. 4 Projected change in average drought duration in runoff (left), and deficit volume in runoff (right) for three GCMs, two emission scenarios (A2 and B1) and the intermediate and far future. CTRL specifies the difference between drought characteristics derived from runoff simulated with the GCM and the runoff simulated with re-analysis data (WFD). Results are shown for the average change of all 244 grid cells (Fig. 1).

An increase of the median of the future average drought deficit volume was found for all three GCM forcings (Fig, 4, right). Differences among the models were large because the magnitude of the average deficit volume was rather small. For the change in deficit volume, CNRM and ECHAM5 showed comparable patterns with a stronger climate signal when CNRM forcing was used (change is 690% and 230%, respectively, A2). IPSL showed a stronger climate signal for the B1 than for the A2 scenario, which agreed with the change in future annual flow (Fig. 3, left). Similar to drought duration, the climate change signal in drought deficit volume was considerably larger than the forcing uncertainty (CTRL, Fig. 4, right).

CONCLUSIONS AND DISCUSSION

This study using multi-models (GCMs and hydrological models) and multi-emission scenarios for two cross-sections across Europe (Fig. 1), shows that it is very likely that low flows will become more extreme and that more intense hydrological drought will develop in the future. This is a response to the higher expected temperatures and lower precipitation, although the latter has a rather high uncertainty because of differences among GCMs and how those agree with re-analysis data (Fig. 2). Annual runoff is predicted to decrease, but the climate signal in most projections is smaller than the noise caused by climate forcing uncertainty. The projected decrease in mean annual 7-day minimum flow (MAM7) is more robust, i.e. noise for most projections is clearly lower than climate signal for two GCMs. The predicted relative decrease in MAM7 is larger than in annual runoff (Fig. 3) and may exceed 50% in extreme cases. Future hydrological droughts are projected to become longer, i.e. increase may exceed 100% (Fig. 4). This is supported by Wanders & Van Lanen (2013), who reported that this was expected to occur in most climate regions across the world for the drought events that remain, which is associated with decreasing drought frequency. The predicted increase in average drought duration is reasonably robust, implying that the climate signal is smaller than the noise caused by climate forcing uncertainty. Orlowski & Seneviratne (2013) found less robust durations. However, we also observed that durations obtained from hydrological models forced with one particular GCM (IPSL) hardy differ, irrespective of the future time frame and emission, which contradicts the two other GCM forcings (CRNM and ECHAM5). Projected drought deficit volumes will also decrease. The predicted changes are fairly robust and even larger than for the drought duration (exceeds 100% by the end of the 21st century for the A2 scenario). The observed increase of deficit volumes in hydrological drought across Europe confirms results by Feyen & Dankers (2009), who used a single RCM-hydrological model-scenario setup.

This study provides average numbers for the change in low flows and hydrological drought characteristics in the two transects across Europe. Stahl *et al.* (2012) observed a clear dipole in Europe, where observed annual streamflow in northern Europe increased, whereas the opposite happened in southern and southeastern Europe. However, they also found that the summer low flow in most of Europe decreased, which is in line with our study. Alderlieste & Van Lanen (2013) provide lookup tables with change in low flows and hydrological drought characteristics for each case study area in the transects, which has the potential for further investigation of spatial differences across Europe, including uncertainty.

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