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European scale climate information services for water use sectors

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SUMMARY

This study demonstrates a climate information service for pan-European water use sectors that are vulnerable to climate change induced hydrological changes, including risk and safety (disaster preparedness), agriculture, energy (hydropower and cooling water use for thermoelectric power) and environment (water quality). To study the climate change impacts we used two different hydrological models forced with an ensemble of bias-corrected general circulation model (GCM) output for both the lowest (2.6) and highest (8.5) representative concentration pathways (RCP). Selected indicators of water related vulnerability for each sector were then calculated from the hydrological model results. Our results show a distinct north–south divide in terms of climate change impacts; in the south the water availability will reduce while in the north water availability will increase. Across different climate models precipitation and streamflow increase in northern Europe and decrease in southern Europe, but the latitude at which this change occurs varies depending on the GCM. Hydrological extremes are increasing over large parts of Europe. The agricultural sector will be affected by reduced water availability (in the south) and increased drought. Both streamflow and soil moistures droughts are projected to increase in most parts of Europe except in northern Scandinavia and the Alps. The energy sector will be affected by lower hydropower potential in most European countries and reduced cooling water availability due to higher water temperatures and reduced summer river flows. Our results show that in particular in the Mediterranean the pressures are high because of increasing drought which will have large impacts on both the agriculture and energy sectors. In France and Italy this is combined with increased flood hazards. Our results show important impacts of climate change on European water use sectors indicating a clear need for adaptation.

1. Introduction

Global warming is likely to change the global and regional water cycles (Harding et al., 2011). These changes can potentially have a large impact on different water use sectors (Bates et al., 2008; Ludwig et al., 2009; Jiménez Cisneros et al., 2014). Changes in surface water availability and soil moisture affect agricultural production (Supit et al., 2012; Haddeland et al., 2014); changed river discharge and water temperature affect the energy sector (Van Vliet et al., 2013a) and changes in extreme flows affect flood risk and the need for protection. Also water quality can be affected by climate change (Van Vliet et al., 2013b; Arheimer et al., 2012). However, the hydrological impacts of climate change are also very uncertain and many studies show large spreads in projected changes (Hagemann et al., 2013; Haddeland et al., 2014). Studies using large datasets and several climate and hydrological models are often difficult to interpret and use for policy makers.

Several previous studies have addressed impacts of climate change on European water resources (Arnell, 1999; Schroter et al., 2005), floods (Dankers and Feyen, 2008, 2009), droughts (Feyen and Dankers, 2009), and water temperatures for the energy sector (van Vliet et al., 2012b). Most of these studies only focus on a specific aspect of hydrological change or a specific sector, leaving the interpretation of the change to the decision maker.

Therefore, a clear need exists to develop climate information services for multiple sectors affected by changes in the water resources with tailored indices for different sectors. This information is needed for adaptation not only at local or country scale but also at regional (river basin) and continental-scale. We define a climate information service as a service providing tailored information on the impacts of climate change for one or more specific sectors. These services could be of interest for a variety of institutions. For example, for the insurance industry, continental scale flood risks are important. For the European Commission future

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changes in drought risk and soil moisture deficits are important because they effect agricultural production and regional food security. These climate information services could also assist in the development and implementation of different European directives (*e.g.* European Flood Directive, European Water Framework Directive). Other potential users of a Europe wide climate information service include European authorities such as the European Monitoring and Information Centre (MIC) (for risk and safety aspects), European Environment Agency (EEA) (environmental impacts); and the European Commission for Agriculture and Rural Development and the European Drought Observatory (agricultural impacts). Furthermore, European climate information services can also be of importance for electricity providers and energy trading companies and thus cover a broad range of potential uses.

Covering the interest for multi-sectoral impacts for decision making, we demonstrate here a preliminary example of a pan-European climate information service with tailored information available for European sectors affected by changes in the water cycle. We focused on the research question: what is the impact of climate change on European water resources and how will this affect four main sectors: (1) risk and safety; (2) agriculture; (3) energy; and (4) environment?

To address this question, we used two different hydrological models forced with an ensemble of bias-corrected climate model output from the newest generation of climate scenarios developed under CMIP5/IPCC AR5. We combined the projected changes in average and extreme conditions of streamflow, soil moisture and water quality under climate change with hydrological indices tailored to different sectors. Maps with projected changes in these indices have been presented to show the impacts of climate change on each of the sectors separately. In addition, we studied where cross-sectoral impacts coincide for better planning and adaption and discuss the potential for further development of European-scale climate information services.

2. Methods

2.1. Modelling framework

Climate information service for pan-European water use sectors that are vulnerable to climate change induced hydrological changes were assessed by developing a modelling framework which links climate and hydrological models. We used two different hydrological models (HMs) which were forced with an ensemble of bias-corrected general circulation model (GCM) output for both the lowest (2.6) and highest (8.5) representative concentration pathways (RCP) (Moss et al., 2010) (Fig. 1). The two different hydrological models vary in levels of complexity in different process descriptions and can therefore be used to capture some uncertainties related to the structure and parameterization of hydrological processes. The two models selected were the Hydrological Predictions for the Environment (HYPE, Lindstrom et al., 2010) hydrological model set up for Europe (E-HYPE) (Donnelly et al., in press) and Variable Infiltration Capacity (VIC) (Liang et al., 1994) land surface scheme linked to the physically-based stream temperature model RBM (Yearsley, 2009) which was previously set up globally (van Vliet et al., 2012b). Both large-scale hydrological models were selected because they have previously shown realistic estimates of streamflow for Europe on a daily time step (Donnelly et al., in press; van Vliet et al., 2012a,b). In addition, both of these models simulate hydrology and some aspects of water quality variables on daily time steps. Output from the hydrological model projections were used to calculate impact indices that are relevant for different sectors.

2.2. Hydrological Predictions for the Environment (HYPE) model

Hydrological Predictions for the Environment (HYPE (Lindstrom et al., 2010; Strömqvist et al., 2012)) is a semi-distributed rainfall–runoff and nutrient model, which for the rainfall–runoff component calculates the processes of snow melt, evapotranspiration, surface runoff, infiltration, percolation, macro-pore flow through soil, tile drainage, and groundwater outflow to the stream. HYPE divides the soil column into three layers and uses the variability in vegetation, soils and elevation within and between subbasins to represent variability in hydrological processes across the model domain. Snow melt is calculated using a degree day method. Potential evapotranspiration is calculated using a modified Hargreaves-Semani routine (where daily minimum and maximum air temperature is used as a proxy for incoming solar radiation). Surface runoff may occur due to either insufficient infiltration capacity or saturation excess and groundwater flow to the stream occurs from each of the soil layers with water content above field capacity, tile drains or via regional groundwater. Streamflow is routed with both delay and dampening in local rivers and main rivers and via local (within the subbasin) and main lakes (along the main river). Lake rating curves determine outflow from lakes and a simplified reservoir scheme describes production outflow from regulated reservoirs. The model also describes major sources and sinks and turnover processes of nutrients in the soil and surface water. The pan-European application of the HYPE model used in this study (E-HYPE) including the input data used, calibration strategy and an evaluation of model results is described in Donnelly et al. (2013) with a focus on nutrients, and Donnelly et al. (in press) with a focus on the hydrological variables. The domain is divided into subbasins with a median size of 215 km^2, which are approximately comparable to a grid of 15×15 km. Model evaluation showed that E-HYPE can reproduce the spatial variation in mean discharge, runoff and runoff generation across the continent for catchments of varying size, physiography and climate as well as the magnitude and variability at many individual sites (Donnelly et al., in press). For water quality, E-HYPE can reproduce the main processes driving the variation in nutrient concentrations at different locations as well as magnitude and variability at individual sites (Donnelly et al., 2013).

2.3. Variable Infiltration Capacity (VIC) model

The Variable Infiltration Capacity (VIC) model (Cherkauer et al., 2003; Liang et al., 1994) is a grid-based macro-scale hydrological model that solves both the surface energy and water balance equations. VIC was originally developed as a land surface scheme providing the boundary conditions for GCMs, but it has now been widely used as a hydrological model. Sub-grid variability is included in vegetation, elevation, and soils by partitioning each grid cell into multiple land cover (vegetation) and elevation classes. The soil column is commonly divided into three soil layers. Evapotranspiration is calculated based on the Penman–Monteith equation and snow accumulation and ablation processes are solved on sub-daily time step via an energy balance approach (Wigmosta et al., 1994). Surface runoff in the upper soil layer is calculated based on the variable infiltration curve (Zhao et al., 1980), and release of baseflow from the lowest soil layer is simulated according to the non-linear Arno recession curve (Todini, 1996). Surface runoff and baseflow are routed along the stream network to the basin outlet with an offline routing model that uses the unit hydrograph principle within the grid cells and linearized St. Venant's equations to simulate river flow through the stream channel (Lohmann et al., 1998). Water temperature is simulated using the physically-based stream temperature river basin model (RBM) (Yearsley, 2009, 2012), which is linked to VIC. RBM was recently