Global Environmental Change 23 (2013) 450–464

Contents lists available at SciVerse ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

Global river discharge and water temperature under climate change

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ARTICLE INFO

Article history:
Received 15 June 2012
Received in revised form 23 October 2012
Accepted 2 November 2012

Keywords:
Climate change
Water temperature
River discharge
Global water resources

ABSTRACT

Climate change will affect hydrologic and thermal regimes of rivers, having a direct impact on freshwater ecosystems and human water use. Here we assess the impact of climate change on global river flows and river water temperatures, and identify regions that might become more critical for freshwater ecosystems and water use sectors. We used a global physically based hydrological-water temperature modelling framework forced with an ensemble of bias-corrected general circulation model (GCM) output for both the SRES A2 and B1 emissions scenario. This resulted in global projections of daily river discharge and water temperature under future climate. Our results show an increase in the seasonality of river discharge (both increase in high flow and decrease in low flow) for about one-third of the global land surface area for 2071–2100 relative to 1971–2000. Global mean and high (95th percentile) river water temperatures are projected to increase on average by 0.8–1.6 (1.0–2.2) °C for the SRES B1–A2 scenario for 2071–2100 relative to 1971–2000. The largest water temperature increases are projected for the United States, Europe, eastern China, and parts of southern Africa and Australia. In these regions, the sensitivities are exacerbated by projected decreases in low flows (resulting in a reduced thermal capacity). For strongly seasonal rivers with highest water temperatures during the low flow period, up to 26% of the increases in high (95th percentile) water temperature can be attributed indirectly to low flow changes, and the largest fraction is attributable directly to increased atmospheric energy input. A combination of large increases in river temperature and decreases in low flows are projected for the southeastern United States, Europe, eastern China, southern Africa and southern Australia. These regions could potentially be affected by increased deterioration of water quality and freshwater habitats, and reduced water available for human uses such as thermoelectric power and drinking water production.

1. Introduction

Hydrologic and thermal regimes of rivers are of major importance for freshwater ecosystems and human water use. Both river discharge and water temperature directly affect water quality (Ducharne, 2008; Haag and Westrich, 2002; Ozaki et al., 2003), and the growth rate and distribution of freshwater organisms (Eaton and Scheller, 1996; Ebersole et al., 2001; Mohseni et al., 2003). In addition, water temperature and availability are economically important, for example for thermoelectric power production (Forster and Lilliestam, 2011; Koch and Vögele, 2009; Manoha et al., 2008), drinking water production (Ramaker et al., 2005; Senhorst and Zwolsman, 2005), fisheries (Bartholow, 1991; FAO, 2008; Ficke et al., 2007) and recreation (EEA, 2008b; Webb et al., 2008).

Due to climate change, hydrological and thermal regimes of rivers are expected to change. This will have direct consequences for freshwater ecosystems, water quality and human water use. Many previous macro-scale hydrological modelling studies have been carried out to assess the impact of climate change on water availability at continental (Arnell, 1999b; Lehner et al., 2006) and global scales (Arnell, 1999a; Döll and Zhang, 2010; Sperna Weiland et al., 2012; Vörösmarty et al., 2000). However, most of these studies ignore changes in water temperature (or water quality in general) and focus on monthly or annual mean estimates of river discharge, while higher temporal resolution (e.g. daily) estimates are commonly required to address impacts for freshwater ecosystems and water use sectors.

For water temperature, both statistical (e.g. Mantua et al., 2010; Pilgrim et al., 1998) and process-based modelling approaches (e.g. Gooseff et al., 2005; Sinokrot et al., 1995; Stefan and Sinokrot,

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http://dx.doi.org/10.1016/j.gloenvcha.2012.11.002

1993) have been applied to project the effects of future climate on catchment scale river temperatures. Less work has been done on modelling climate change impact on river temperatures at larger scales, although some regression studies have addressed the sensitivity of water temperatures to air temperature increases in the United States (Mohseni et al., 1999) and the combined impacts of river flow changes on river temperatures at the global scale (van Vliet et al., 2011).

Although river temperatures are generally most sensitive to atmospheric conditions, changes in streamflow also significantly affect water temperatures, especially during warm, dry periods with low river flows (Sinokrot and Gulliver, 2000; van Vliet et al., 2011). Combined effects of atmospheric warming and changes in river flow should therefore be considered in modelling future climate change impacts on river water temperature.

Here we assess the impact of climate change on daily river discharge and water temperature on a global scale, by using a physically based hydrological and water temperature modelling framework forced with an ensemble of daily bias-corrected general circulation model (GCM) output. The daily projections were used to assess the magnitude and significance of changes in mean and extremes in river flows and water temperature on both global and river basin scales. We then used the global river discharge and water temperature projections to identify regions characterized by substantial decreases in low flow in combination with large increases in water temperature, because these regions could potentially experience increased deterioration of freshwater habitats and reduced potential for human water use.

The global hydrological-water temperature modelling framework consists of the Variable Infiltration Capacity (VIC) macro-scale hydrological model (Liang et al., 1994) and stream temperature model (RBM) (Yearsley, 2009). The modelling framework includes anthropogenic impacts of thermal discharges from thermoelectric power plants on water temperatures, and the modelling performance has been evaluated for 14 large river basins globally, situated in different hydro-climatic zones and with different anthropogenic impacts (van Vliet et al., 2012a). Overall, a realistic representation of daily river discharge and water temperature was found for the historical period 1971–2000, with a similar performance during warm, dry summer periods.

In this study, future projections of daily river discharge and water temperature under climate change were produced on a global scale by forcing the global hydrological-water temperature modelling framework (Section 2.1) with statistically bias-corrected GCM output for both the SRES A2 and B1 scenario for 2071–2100 and for 1971–2000 (Section 2.2). These global projections were used to quantify changes in river discharge (Section 3.2) and water temperature (Section 3.3) and to identify regions characterized by a strong increase in river water temperature and decreases in river discharge (water availability) (Section 3.4).

2. Materials and methods

The methodological framework for this study is shown in Fig. 1. Bias-corrected output from three GCMs for both the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) (Nakicenovic et al., 2000) A2 (red) and B1 (orange) emissions scenarios for 2071–2100 and for 1971–2000 (control; blue) were used to force the hydrological-water temperature (VIC-RBM) modelling framework. The resulting daily simulations of global river flow and water temperature were used in three control experiments and six future GCM experiments. The background of the hydrological-water temperature modelling framework, climate scenarios and bias-correction are described in Sections 2.1 and 2.2.

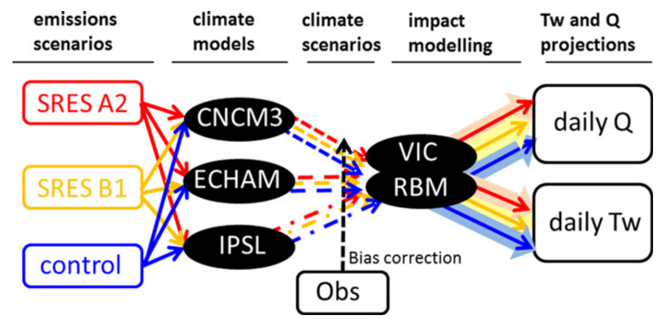

Fig. 1. Schematic representation of the modelling framework with selected emission scenarios and GCMs, and bias-correction of GCM output with observed meteorological dataset (Obs). These data were used to force the physically based hydrological-water temperature (VIC-RBM) modelling framework, resulting in daily simulations of river flow (Q) and water temperature (Tw) under control and future climate.

2.1. Hydrological-water temperature modelling framework

The hydrological-water temperature modelling framework consists of the physically based Variable Infiltration Capacity (VIC) model (Liang et al., 1994) and the one-dimensional stream temperature model RBM (Yearsley, 2009, 2012). VIC is a grid-based water-energy balance model and is used with an offline routing model (Lohmann et al., 1996) to simulate daily streamflow. The VIC hydrological model was applied using the elevation and land cover classification as described in Nijssen et al. (2001b) and using the DDM30 routing network (Döll and Lehner, 2002) for lateral routing of streamflow.

RBM is a process-based computationally efficient water temperature model that solves the 1D-heat advection equation using the semi-Lagrangian approach (Yearsley, 2009). Daily river water temperature is simulated using climate forcings (air temperature, shortwave and long wave radiation, vapor pressure, density, pressure and wind speed) disaggregated to a 3-h time step and daily channel flows, width, depth and flow velocity from VIC and the routing model (see Yearsley (2012) for a description of the linkages between the components in the modelling framework).

The VIC-RBM modelling framework has been implemented on a global scale on a $0.5^\circ \times 0.5^\circ$ spatial resolution (van Vliet et al., 2012a). The model system runs on a daily time step. Impacts of anthropogenic heat effluents from thermoelectric power plants on water temperature were incorporated by using global gridded thermoelectric water use datasets (Flörke et al., 2011; Vassolo and Döll, 2005; Voß and Flörke, 2010) and representing thermal discharges as point sources in the heat-advection equation (see supplementary information van Vliet et al. (2012b) for details). The headwater temperatures were estimated using the nonlinear water temperature regression model of Mohseni et al. (1998) for 333 GEMS/Water stations for 1980–2000. The estimated parameters were then interpolated to $0.5^\circ \times 0.5^\circ$ global grids using ordinary kriging. For the headwater grid cells in RBM, water temperatures were estimated based on daily air temperature and the parameter values for these headwater grid cells (van Vliet et al., 2012b).

2.2. Climate change scenarios

Daily output of the three coupled atmosphere/ocean GCMs ECHAM5/MPIOM (Jungclaus et al., 2006; Roeckner et al., 2003), CNRM-CM3 (Déqué et al., 1994; Madec et al., 1998; Salas-Mélia, 2002) and IPSL-CM4 (Fichefet and Morales Maqueda, 1997; Goosse and Fichefet, 1999; Hourdin et al., 2006) for both the SRES A2 and B1 emissions scenario (Nakicenovic et al., 2000) from the CMIP3