Global Environmental Change 23 (2013) 1737–1751

Contents lists available at ScienceDirect

Global Environmental Change

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

Climate change and river floods in the European Union: Socio-economic consequences and the costs and benefits of adaptation

Rodrigo Rojas [a,*], Luc Feyen [a], Paul Watkiss [b,c]

[a] Climate Risk Management Unit, Institute for Environment and Sustainability, Joint Research Centre, European Commission, Via E. Fermi 2749, TP261, 21027 Ispra, VA, Italy
[b] Paul Watkiss Associates, Oxford, UK
[c] School of Geography and the Environment, University of Oxford, Oxford, UK

ARTICLE INFO

Article history:
Received 31 January 2013
Received in revised form 5 August 2013
Accepted 14 August 2013

Keywords:
Flood damage assessment
Avoided damages
EU Flood Directive
Flood risk
Flood mitigation
Climate change

ABSTRACT

This study presents the first appraisal of the socio-economic impacts of river floods in the European Union in view of climate and socio-economic changes. The assessment is based on two trajectories: (a) *no adaptation*, where the current levels of protection are kept constant, and (b) *adaptation*, where the level of protection is increased to defend against future flooding events. As a basis for our analysis we use an ensemble-based pan-European flood hazard assessment for present and future conditions. Socio-economic impacts are estimated by combining flood inundation maps with information on assets exposure and vulnerability. Ensemble-based results indicate that current expected annual population affected of ca. 200,000 is projected to increase up to 360,000 due to the effects of socio-economic development and climate change. Under the *no adaptation* trajectory current expected annual damages of €5.5 billion/year are projected to reach €98 billion/year by the 2080s due to the combined effects of socio-economic and climate change. Under the adaptation trajectory the avoided damages (benefits) amount to €53 billion/year by the 2080s. An analysis of the potential costs of adaptation associated with the increase in protection suggests that adaptation could be highly cost-effective. There is, however, a wide range around these central numbers reflecting the variability in projected climate. Analysis at the country level shows high damages, and by association high costs of adaptation, in the United Kingdom, France, Italy, Romania, Hungary and Czech Republic. At the country level, there is an even wider range around these central values, thus, pointing to a need to consider climate uncertainty in formulating practical adaptation strategies.

1. Introduction and scope

In the last decade, major flooding events have occurred in Europe including, for example, the catastrophic floods along the Elbe and Danube (August 2002, March/April 2006); flooding in Romania and the Alpine countries (August 2005); the severe summertime flooding in Britain in 2007; several events in Czech Republic, Italy, and Poland in 2009; and very recently the devastating floods that hit central and Eastern Europe in June 2013. Between 1998 and 2009 alone, the European Environment Agency estimated that 213 flood events in Europe caused about 1126 fatalities, affected more than 3 million people and caused at least €52 billion in losses out of which €12 billion were insured economic losses (EEA, 2010).

Albeit some recent studies suggest that there may be an increase in the number of extreme floods in Europe in the last decades (see, e.g., Kundzewicz et al., 2013) there is still no conclusive evidence of a climate signal in the occurrence and severity of floods. Detecting a possible trend is hampered by the interaction between the climate-driven physical causes and socio-economic factors such as urban development in flood-prone areas (Barredo, 2009; Feyen et al., 2009; Elmer et al., 2012). Moreover, the statistical analysis of extreme river discharges, which serve as the basis to assess trends in floods, is an inherently difficult process plagued with uncertainties given the natural variability of extreme events (see, e.g., Mudelsee et al., 2003; Kundzewicz et al., 2005; Wilby et al., 2008).

The current knowledge on climate modelling suggests that climate change will be a determining factor in intensifying the hydrological cycle (Christensen and Christensen, 2007; van der Linden and Mitchell, 2009). This will most likely lead to an increase

* Corresponding author. Tel.: +39 0332785528.
E-mail addresses: Rodrigo.Rojas@jrc.ec.europa.eu, rodrigo.rojasmujica@gmail.com (R. Rojas), Luc.Feyen@jrc.ec.europa.eu (L. Feyen), paul_watkiss@btinternet.com (P. Watkiss).

0959-3780/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.gloenvcha.2013.08.006

in the magnitude and frequency of intense precipitation events in many parts of Europe (see, e.g., Frei et al., 2006; Christensen and Christensen, 2007; Fowler and Ekström, 2009; van der Linden and Mitchell, 2009; Nikulin et al., 2011), which may lead to an increase in future flood hazard in those regions (e.g., Dankers and Feyen, 2009; Whitfield, 2012). Non-linear relationships between temperature and snow/rainfall and changes therein might also trigger alterations in flood hazard, especially in northern Europe. Due to increased temperatures, early spring snowmelt floods are likely to reduce (Kundzewicz et al., 2006) but compensation effects between rainfall- and snow-driven river floods in currently snow-dominated areas make projections of future flood hazard in these regions highly uncertain (Dankers and Feyen, 2009; Rojas et al., 2012). Using a 12-member ensemble of bias-corrected climate simulations based on the SRES-A1B emission scenario (Nakicenovic and Swart, 2000) to drive a pan-European hydrological model, Rojas et al. (2012) further observed a strong increase (>40%) in future flood hazard for the United Kingdom, northwest and southeast of France, and northern Italy, whereas less pronounced increases (10–30%) were projected for central Europe and the upper reaches of the River Danube and its main tributaries. A significant variability in future flood hazard was reported by Rojas et al. (2012), which was explained by the diverse signals in the magnitude of climate changes simulated by the climate models used in the analysis.

Traditionally, flood damage assessments have been limited to basin (e.g., de Kok and Grossmann, 2010; te Linde et al., 2011) or national (e.g., Hall et al., 2005; EA, 2009) scales and, up to date, only few studies have assessed current and/or future damages at global or continental scales. Lugeri et al. (2010) assessed the current damages at pan-European scale on the basis of a topography-based flood hazard map where no hydrological modelling was involved. Feyen et al. (2012) performed current and future damage assessment at pan-European scale for a small multi-scenario (A2 and B2) ensemble of four (non-corrected for bias) climate simulations. Recently, Jongman et al. (2012) presented global yearly damage estimates until 2050 due to river and coastal flooding using a purely data-driven approach. From these studies, only the work by Feyen et al. (2012) considered large-scale hydrological modelling driven by future climate simulations forced by IPCC-based emission scenarios (Nakicenovic and Swart, 2000). At the same time, none of the aforementioned studies considered adaptation scenarios, the quantification of avoided damages and/or costs of adaptation measures, or the uncertainty in damage estimates arising from different climate projections for the 21st century.

Besides changes in climate also dynamics in the socio-economic system may alter the consequences of floods in the future. In practice, the accumulation of wealth and urban development in flood-prone areas as well as the expansion of residential areas may significantly contribute to rise the damages from flooding events (see, e.g., Mitchell, 2003; Barredo, 2009; Feyen et al., 2009; Elmer et al., 2012). In this work the socio-economic dimension is accounted for by using high-resolution land use and population density maps as well as socio-economic developments projected for the future which are in line with the SRES-A1B scenario defined by Nakicenovic and Swart (2000). This scenario projects a fast economic growth, global population peaking in mid-century, rapid introduction of new and more efficient technologies, and a balance across all energy sources. The objective of our assessment is to evaluate how future climate and socio-economic developments will affect future flood risk in Europe, and at what cost the negative impacts could potentially be abated through adaptation.

This article builds upon the works of Rojas et al. (2012) and Feyen et al. (2012). First, we use flood hazard estimates under the SRES-A1B emission scenario (Nakicenovic and Swart, 2000) obtained from Rojas et al. (2012) to calculate the expected damages and population affected at pan-European scale following the methodological framework presented in Feyen et al. (2012). This work provides the first pan-European assessment of flood risks and potential costs and benefits of adaptation explicitly accounting for uncertainty arising from the definition of an ensemble of climate simulations. In particular, our work shows several innovative aspects which overcome some of the limitations identified in previous works (e.g., Feyen et al., 2012): (a) a very large ensemble of high-resolution (25 km) climate simulations considering 12 members is used, (b) biases in the precipitation and (min, avg, and max) temperature fields are corrected using a Quantile Mapping technique (see Rojas et al., 2011; Dosio et al., 2012, (c) more than twice the number of gauging stations (554 stations across Europe) are used for the validation of extreme discharges, (d) impacts are estimated throughout the 21st century and compared with current conditions, (e) socio-economic dynamics are taken into account through the use of GDP and population projections in line with the SRES-A1B scenario, and (f) an exploration of the possible costs and benefits of adaptation to increase protection against future flood hazard is provided.

We note that a flood is defined here as the temporary covering of land by water outside its normal confines. There exist different types of floods, such as large-scale river floods, flash floods, ice-jam or snowmelt induced floods, and coastal floods due to sea level rise/storm surges. This work focuses on river flooding, which is mainly linked with prolonged or heavy precipitation events as well as with snowmelt. Furthermore, we limit the analysis to estimating the direct tangible damages derived from the physical contact of flooding waters with the exposed assets and population. Theoretically, indirect damages can be estimated and there exist several methods to achieve this (see, e.g., Jonkman et al., 2008; Merz et al., 2010). In practice, however, they are hardly ever estimated given the current data and model limitations, and the dependence of the magnitude of the indirect damages on the boundaries in space and time of the damage assessment. Moreover, in a national or international setting, indirect economic damages at the regional scale tend to disappear as they are often compensated by production gains in regions outside the flooded area (Merz et al., 2010). Some methods include a fixed share of the total costs to account for indirect damages in a flood risk assessment: for example, the Damage Scanner used in the Netherlands adds about 5% of indirect damages (mainly reflecting business interruption) to the total damage, hence suggesting that direct damages dominate the total damage figures (e.g., Ward et al., 2011; te Linde et al., 2011).

In Section 2, we describe the methodological framework, including the details of the climate simulations, hydrological modelling, the depth-damage functions used to estimate damages as well as the assessment of cost/benefits of adaptation. Results are reported in Section 3, whereas a comprehensive discussion and main conclusion of this work can be found in Section 4.

2. Methodology

Fig. 1 shows the methodological approach used in this work. In a first step, a series of bias-corrected climate simulations (Dosio et al., 2012) were used to force the hydrological model LISFLOOD (van der Knijff et al., 2010). Subsequently, by using extreme value analysis techniques we obtained river discharge and water levels for return periods ranging between 2 and 500 years (see Rojas et al., 2012). A planar approximation approach following Bates and de Roo (2000) was then employed in which the flood wave is considered as a plane that is intersected with a high resolution digital elevation model to estimate flood inundation extent and water depth, resulting in inundation maps at a 100 m $\times$ 100 m