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Escalating impacts of climate extremes on critical infrastructures in Europe

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A R T I C L E I N F O

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A B S T R A C T

Extreme climatic events are likely to become more frequent owing to global warming. This may put additional stress on critical infrastructures with typically long life spans. However, little is known about the risks of multiple climate extremes on critical infrastructures at regional to continental scales. Here we show how single- and multi-hazard damage to energy, transport, industrial, and social critical infrastructures in Europe are likely to develop until the year 2100 under the influence of climate change. We combine a set of high-resolution climate hazard projections, a detailed representation of physical assets in various sectors and their sensitivity to the hazards, and more than 1100 records of losses from climate extremes in a prognostic modelling framework. We find that damages could triple by the 2020s, multiply six-fold by mid-century, and amount to more than 10 times present damage of €3.4 billion per year by the end of the century due only to climate change. Damage from heatwaves, droughts in southern Europe, and coastal floods shows the most dramatic rise, but the risks of inland flooding, windstorms, and forest fires will also increase in Europe, with varying degrees of change across regions. Economic losses are highest for the industry, transport, and energy sectors. Future losses will not be incurred equally across Europe. Southern and south-eastern European countries will be most affected and, as a result, will probably require higher costs of adaptation. The findings of this study could aid in prioritizing regional investments to address the unequal burden of impacts and differences in adaptation capacities across Europe.

1. Introduction

'Critical infrastructures' refers to the array of physical assets, functions, and systems that are vital to ensuring the European Union's (EU's) health, wealth, and security (European Council, 2008). According to this definition, they include existing transport systems, renewable and non-renewable energy generation plants, industry, water supply networks, and education and health infrastructures. The main threats presented by climate to infrastructure assets include damage or destruction from extreme events (Handmer et al., 2012), which climate change is expected to exacerbate (Fischer and Knutti, 2015; Pall et al., 2011; Rahmstorf and Coumou, 2011; Stott et al., 2004). Different types of infrastructures have different levels of vulnerability to climate change. Moreover, as climate change impacts are manifested locally, individual assets have different hazard exposures depending on their geographical location. Understanding and quantifying these risks is crucial for planning suitable adaptation measures to safeguard and secure the functioning of society.

Previous studies on sectorial impacts of climate change have focused mostly on single hazards or a limited set of hazards, so their estimates can only partially represent the potential consequences of future climate extremes (Arnell et al., 2013; Ciscar et al., 2011; Hsiang et al., 2017; Lung et al., 2013; Piontek et al., 2014; van Vliet et al., 2012). Furthermore, they usually refer to broad sectorial categories (e.g. water, agriculture), without providing information on the climate effects at infrastructure level, quantifying which is essential to develop climate-proofing measures for key societal services. Various impacts of climate extremes on infrastructures are acknowledged in the literature, but they are primarily presented in qualitative, descriptive terms (Cruz and Krausmann, 2013; Michaelides et al., 2014; Schaeffer et al., 2012).

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Quantifying the effects of climate hazards on infrastructures is a complex task because of incomplete scientific methodologies and limited understanding of vulnerabilities of infrastructures (Mechler et al., 2014; Neumann et al., 2014). Existing methods of assessing direct costs generally focus on specific hazards or sectors by the use of susceptibility curves derived analytically under specific conditions (Carleton and Hsiang, 2016; Ciscar et al., 2011; Meyer et al., 2013). However, such approaches showed large uncertainties due to the poor calibration on observed damage (Jongman et al., 2012). Difficulties in establishing comparisons across hazards and sectors remain particularly relevant (Kappes et al., 2012). Moreover, datasets of existing infrastructures are collected and maintained by various institutions (e.g. public or private) for different purposes and thus lack homogeneity in terms of spatial and thematic coverage and detail, semantics, format, and units of measurement. Harmonizing geo-data is essential to develop spatially coherent assessments of the potential impacts of natural hazards (Fekete et al., 2016); however, it remains challenging for continental-scale approaches given the relevant variety across and within datasets.

In this study we seek to fill the above-mentioned gaps by providing a comprehensive multi-hazard risk assessment of critical infrastructures in Europe under climate change and identifying the most affected regions throughout the 21st century. For this purpose, we developed a novel method that combines climate-related disaster records with a set of high-resolution projections of climate hazard, a detailed representation of sectorial physical assets, and their vulnerability to the hazards. We believe that our data-model integration approach adds significant value in the following ways:

1 We consistently assess how the seven most harmful climate-related extremes (heat- and cold waves, droughts, wildfires, river and coastal floods and windstorms) evolve in Europe in view of global warming. Previous assessments of the sectorial impacts of climate extremes focused mostly on single or a limited set of climate hazards.
2 We develop a detailed and spatially coherent representation of current sectorial physical assets and productive systems. This analysis enables us to investigate impacts at infrastructure level never reached in previous studies on sectorial impacts.
3 We derive a qualitative appraisal of the vulnerability of critical infrastructures to each hazard based on the combination of an extensive literature review and a survey run amongst ~2000 experts. This represents the first attempt to fill a gap in the scientific knowledge and provides a tractable database for appraising and comparing sensitiveness of different types of infrastructures to climate hazards, a prerequisite for assessing multi-hazard/multi-sector climate change impacts.
4 We calibrate risk scenarios based on more than 1100 climate-related losses recorded in the most comprehensive public disaster database so that projections of expected annual damages (EADs) are strongly rooted on the observational records.
5 We provide an exploration of the potential costs of adaptation required to increase resilience against future climate hazards based on reported benefit-to-cost ratios reported in literature.

The integration of these elements provides a range of plausible estimates of future extreme climate-related risks for the current stock of European infrastructures.

The paper is structured as follows. Section 2 (Methods) presents the overall framework and describes each specific component, including climate hazards, exposure data collection and harmonization, climate sensitivity of critical infrastructures, risk integration and adaptation scenarios. Section 3 (Results) reports and discusses the overall multi-hazard multi-sector risks, the impacts at sector- and infrastructure level, including the spatial and temporal variability therein, and the costs of adaptation. This section further describes the main limitations of our study and knowledge gaps. Section 4 (Conclusions) synthesizes the key findings of this study and highlights challenges for future research.

2. Methods

2.1. Methodological framework

We employed the risk framework proposed by the IPCC (2014) to estimate the climate impacts as a combination of climate hazards (*H*), exposed infrastructures (*E*) and their sensitivity (*S*) to the hazards. The data-driven prognostic approach employed by Forzieri et al. (2017) to estimate human mortality due to multiple climate extremes has been further developed here to derive the susceptibility to climate hazards of critical infrastructures and to monetize consequent impacts. The methodology integrates a set of high-resolution climate hazard projections generated under a “business-as-usual” greenhouse gas emissions trajectory, a detailed representation of sectorial physical assets and productive systems, and a qualitative appraisal of their sensitivity to the hazards based on the combination of expert view and literature review. The three above-mentioned components are linked with more than 1100 records of climate disaster damage in order to derive a comprehensive and comparable set of climate hazard damage functions strongly based on observational records. Fig. 1 shows the methodological approach used in this work. Each of the risk components is visually represented in the figure by a different color and described in the following sections.

We present the multi-hazard impacts of future climate to the present stock of infrastructures in order to avoid hypotheses on changes in society up to the end of the century. Damage estimates cover the EU28 plus Switzerland, Norway, and Iceland (referred to herein as EU+) undiscounted and expressed in 2010 euros. Finally, based on literature-derived average benefit-to-cost ratios (BCRs), we provide an exploration of the possible costs of adaptation required to increase resilience against future climate hazards.

2.2. Climate hazards (H)

The analysis focuses on seven climate hazards, namely heat and cold waves, river and coastal floods, droughts, wildfires, and windstorms, derived for 1981–2010 (baseline), 2011–2040 (referred to as the 2020s for short), 2041–2070 (2050s) and 2071–2100 (2080s), for an ensemble of bias-corrected climate projections under the A1B emissions scenario (Table S1). The quantification of the hazard component is based on the analysis of the changes in frequency of extreme climate events proposed by Forzieri et al. (2016). Baseline return levels of the climate hazard indicators with return periods from 2 to 100 years were obtained at each 1-km grid cell by extreme value analysis, and corresponding future variations in frequency were calculated by inversion of the fitted probability functions. Hazard magnitude levels (H_L) were classified based on the probability of occurrence of events in current climatology; given T_R as return period corresponding to H_L in today's climate, we assigned the intensity class to the H_L event as very high ($T_R \geq$ 100yr), high (100yr > $T_R \geq$ 50yr), moderate (50yr > $T_R \geq$ 20yr), low (20yr > $T_R \geq$ 10yr), very low (10yr > $T_R \geq$ 2yr) or no hazard (2yr > T_R). The fraction of a given area that is expected in the future to be annually exposed to a hazard of H_L magnitude − hereafter labelled as *H* to simplify the notation − was derived for each intensity class by integrating the potential exposure to hazard events over the probability of occurrence. Thus, *H* inherently accounts for the future changes in frequency of the hazardous event. The significance of the changes in climate hazard was evaluated separately for each climate model by the Kolmogorov–Smirnov test applied on the annual values of future time windows versus baseline. For pixels with non-significant changes, we kept baseline *H* values for future time periods. This implies that the projections of impacts reported herein reflect only significant changes (p-value < 0.05) in hazards due to climate change. More details are available from Forzieri et al. (2016).