Environmental Science

AIMS Environmental Science, 10(5): 593–608.
DOI: 10.3934/environsci.2023033
Received: 10 July 2023
Revised: 12 September 2023
Accepted: 25 September 2023
Published: 20 October 2023

http://www.aimspress.com/journal/environmental

Research article

Long-term economic impacts of coastal floods in Europe: a probabilistic analysis

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Abstract: In this article we quantify the long-term economic impacts of coastal flooding in Europe. In particular, how the direct coastal damages generate long-term economic losses that propagate and compound throughout the century. A set of probabilistic projections of inundation-related direct damages (to residential buildings, firms' physical assets and agriculture production) is used as an exogenous shock to a dynamic stochastic economic model. The article considers explicitly the uncertainty related to the economic agents' behaviour and other relevant macroeconomic assumptions, i.e., how would consumers finance the repairing of their homes, how long does it take for a firm to reconstruct, whether firms decide to build-back-better after the inundation and possibly compensate the losses with a productivity gain. Our findings indicate that the long-term impacts of coastal floods could be larger than the direct damages. Under a high emission scenario (RCP8.5) the EU27 plus UK could lose every year between 0.25% and 0.91% of output by 2100, twice as much as the direct damages. The welfare losses present a strong regional variation, with the South (Bulgaria, Greece, Italy, Malta, Portugal and Spain), and United Kingdom (UK) plus Ireland regions showing the highest damages and a significant part of the population that could suffer significant welfare losses by the end of the century.

Keywords: climate change; coastal impacts; uncertainty; economic analysis

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1. Introduction

More frequent and intense coastal inundations due to climate change combined with the fast growth of population and economic assets along the European coastline are expected to significantly raise the risk of large economic losses [1]. The recent case of the 2019 flood of Venice, a 1-in-50 years event that caused damages of around a billion euro in a few days, might become recurrent in the next decades [2].

Understanding and assessing economic risks associated with coastal inundations, and more in general with all different kinds of natural disasters, has been the subject of a growing number of studies. The general approach integrates the three main components of the economic risk assessment, i.e., hazard, exposure and vulnerability, in a framework that combines a biophysical model for the assessment of the natural hazards, a land use and economic module to quantify the exposure and vulnerability (computing the direct economic damages) and a macroeconomic model that quantifies the additional indirect economic costs to the economy [3].

For the particular case of sea level rise and coastal inundations, there are several studies that apply an integrated assessment framework to quantify the economic impacts in Europe in a no-adaptation case [4–6] Inasmuch as the cited studies use different metrics (i.e., either percentage of GDP or of household consumption) and in some cases refer to different climate scenarios, different socio economic assumptions, different reference year or different regional aggregation, the comparison is not straightforward. However, a tentative range goes from the positive impacts on GDP for big EU countries like Germany (0.0028 %), France (0.0045 %), Italy (0.0026 %) [4] in a high SLR scenario by 2085 to the mild negative impacts on household consumption (around -0.25 %) [5] for the whole European Union (EU28) in 2100 in an RCP 8.5 scenario, to the significant impacts on GDP in 2100 (-6%) [6] again in an RCP 8.5.

Climate change impacts other than coastal inundations have also been the subject of similar analyses applying a multi-model dynamic framework. With a particular focus on direct vs. indirect economic consequences, Dottori F et al. [7] and Tanoue M et al. [8] analyse impacts of river floods at different warming levels, different geographical scope and under different socio-economic scenarios, finding that the ratio of indirect vs. direct effect could go from a minimum of 1.5 to a maximum of 2.5 the direct impacts.

While most of the literature focuses primarily on trade, sectoral impacts and factor substitution effects, they often neglect or offer a simplified view on long-term growth dynamics. In the present study, we therefore complement the scope of the existing literature and explore more in detail how different growth dynamics assumptions and scenarios might either amplify or mitigate the consequences on GDP and welfare of those initial climate impacts. Mochizuki J et al. [9] offer a thorough discussion of the relationships between climate, disasters and economic development.

In addition to analysing the impacts of coastal floods from a growth-dynamic angle, the scope of the present study also covers the uncertainty associated to the economic decisions of both firms and consumers in the aftermath of the climate event. Severe and more frequent inundations will most likely generate large losses of physical assets for firms and households that in turn will cause both a temporary fall in the productive capacity and changes in private expenditure behaviour, which will trigger a series of cascade effects on investment, income, consumption and productivity [10]. The magnitude and direction of these effects will largely depend on: i) how fast firms reconstruct and return to the pre-disaster level of productive capacity, ii) how households finance the repairing of the residential properties, iii) the existence or not of spillovers from investments to productivity and iv) the technology embodied in the assets replaced after the disaster. In particular, households can repair the residential damages either via a reduction in consumption or in savings, a choice that can have different macroeconomic implications as the reduction in savings will reduce investment, and therefore future growth, while a reduction of consumption will affect their overall welfare level. Similarly, firms can reconstruct the damaged physical assets in various ways, which will also affect the long-term growth prospects as the capital stock of the economy will be adjusted in different manners. Those features relate to the duration of the reconstruction process, whether there are spillovers from investments to productivity, and the technology embodied in the assets replaced after the disaster. All those possible responses by households and firms are uncertain and cannot be easily characterized. Therefore, we have proposed a probabilistic scheme to consider a wide spectrum of possible alternatives.

A similar approach has been applied in those works [11,12] in order to analyse the energy transition process of the Chinese economy in a risk management perspective. However, to our knowledge, the same approach has not yet been implemented for climate impact analysis.

In the present analysis [13], direct coastal damages projections are taken from and are derived with a risk analysis based on the model LISCOAST (Large-scale Integrated Sea-level and Coastal Assessment Tool) that assesses coastal flood impacts under present and future climates for a high emissions scenario (RCP8.5). In LISCOAST, state-of-the-art large-scale modelling tools and datasets are used to quantify hazard, exposure and vulnerability and quantify consequent risks in monetary terms. The extent, depth and frequency of coastal flooding during the century is the result of the evolution of the climate and the extreme sea levels, with the latter driven by extreme wind, atmospheric pressure and tidal levels [14]. The framework combines all the above factors as well as the major sources of uncertainty in a Monte Carlo approach, considering also the spatial dependence of extreme weather events utilizing Copulas (see [13] and SI for further information). In a second step, the direct impacts are used as an input to an economic growth stochastic model that allows to consider different responses by households and firms to the climate shocks in a probabilistic way. A similar model has been used in climate impacts analyse [15,16]. Moreover, the papers by Fankhauser S et al. [17–19] and more recently Piontek F et al. [20] provide with interesting overviews of both methodological and numerical issues related to the use of long-term growth models for climate impacts analysis. Our growth model is aligned to the official demographic and economic projections for the EU Member States until 2100 [21].

This paper is organized as follows. Section 2 describes the modelling framework used to evaluate the long-term economic impacts of coastal inundations. Section 3 presents and discusses the results of the analysis. Finally, Section 4 presents our conclusions.

2. Economic model and analysis

In our analysis, coastal flooding generates three different types of direct physical impacts, which are: damages to residential buildings, damages to firms' physical assets (the capital stock) and foregone agricultural output. These direct damages are derived from LISCOAST (further details are provided in the SI) and used as an exogenous shock of a Solow type of economic model [22]. We calculate economic losses from coastal flooding and their propagation in time. In this context, the saving rates are very relevant, because they determine, ceteris paribus, how fast the economy recovers after a disaster. Moreover, as pointed out in those works [23–25], losses of welfare provide a broader view of the impacts that better reflects how physical impacts affect people and households. Therefore, in addition to the usual measure expressed as a percentage of GDP, we provide also estimates of welfare losses measured in terms of consumption per capita above the autonomous level.

In order to have a representation of the uncertain economic agents' reaction and behaviour with respect to the coastal impacts, we implement a stochastic version of the Solow-Swan model where some of the crucial parameters of the analysis are assumed to be uniformly distributed within plausible ranges. The assumption of uniform distributions is somewhat arbitrary, but justified by the absence of better information. Previous examples of this type of modelling framework can be found [26–28].

The uncertainty in the response of firms and households to the coastal shocks is structured in five mechanisms. The first mechanism relates to the repairing of residential buildings by the consumer. In particular, the repairing of the damages to private properties is considered as part of the autonomous consumption, which is the subsistence or minimum expenditure that must be made, even without any income. Households are assumed to finance the repairing by either dissaving (or asking a bank loan), and increase their overall expenditure level, or by reallocating their consumption and giving up spending on more welfare-enhancing consumption categories. In the first case, households preserve their living standard but make less financial resources available for investments in the future at country level, which in turn slows down both the renovation and reconstruction of the firms' productive capital stock. In the second case, their overall welfare level is negatively affected in the short-term, but the economy does not suffer any drop in total investments. The choice between dissaving or consumption reallocation might depend on several factors, for instance a more or less precautionary behaviour, the level of income or of indebtedness as well as the functioning of the credit system, among others. The full spectrum of reaction possibilities is captured in this analysis by specifying this choice as a uniform distribution between a minimum of zero, i.e., dissaving by the entire amount of the damage and no change in welfare, and a maximum of 1, i.e., complete reallocation of consumption with the entire damage affecting the households' welfare level.

The second mechanism concerns the available resources for the reconstruction of the capital stock. Damages to the firms' physical assets are modelled as a loss of the productive capital stock, as a lower/damaged capital stock produces a lower output. As suggested by Hallegatte S et al. [29], the model also takes into account the frictions and inefficiency inherent to the process of rebuilding that follows the destruction of physical assets after a coastal flood event. We assume, in fact, that the amount of resources that can be used for the rebuilding activities are not unlimited. Instead, due to institutional rigidities and/or logistic difficulties, only a small fraction of the overall national investments can be diverted from the renovation and growth of the existing capital stock to the reconstruction activities. This parameter is assumed to be uniformly distributed between 0.01% of total investments, a very pessimistic scenario that generates accumulation of the damages in time, and 1%, which is a very optimistic value that allow asset damages to be repaired almost entirely in one time period, which in our model corresponds to one year.

Destructive events like coastal flooding might be in theory beneficial for the economic system if the destroyed productive assets are replaced with more efficient, modern productive technologies. This aspect of post-disaster economic implications has been analysed and discussed theoretically and empirically in various works [29–32,34–39], but to our knowledge remains unexplored for EU countries in relation to specific coastal flooding scenarios. The third mechanism, therefore, relates to the degree of capital upgrade, as explained in what follows. In order to account for the potential positive effects of coastal flooding on growth, we partially reformulate the equation for the growth of technology/productivity levels, to take into account the fact that the money spent on reconstruction upgrades the technological level of the economy and increases its productivity. We use an approach similar to the one explained by Hallegatte S et al. [29] and assume that after a disaster, firms have the possibility of replacing the damaged assets with newer ones that embody the technological level of the European frontier (state-of-the-art, potentially transferable technology [40]), which in this case we assume to be the one of Denmark. Assuming that firms will replace all damaged assets with frontier technology is an optimistic hypothesis and there are several reasons that this may not be the case. It is likely that firms might not have access to the frontier technology, or may lack the financial resources, so they may decide to repair at lower costs the physical assets partially damaged by the inundation. Another reason is time constraints, as firms may need to restart their activities as soon as possible, in order to limit the losses or in order to ensure basic services [29]. To model this uncertainty, we assume that the share of damaged assets replaced with frontier technology is a random parameter uniformly distributed between 0 and 1.

A fourth mechanism affects the trade-off between quality and duration of the reconstruction process. As suggested by Hallegatte S [29], there might be a trade-off between the *quality* of the reconstruction and its duration, i.e., with large embodiment of new technologies in reconstructed assets the reconstruction process takes longer. Hallegatte S [29] suggest that the quality-duration trade off occur for a variety of reasons, i.e., the new technology is not immediately available or its functioning depends on workers training that takes time. The authors propose a simple relationship where the larger the embodiment of new technologies the longer the duration of the reconstruction. We assume that this trade-off between quality and duration is a random parameter uniformly distributed between 1, i.e., no trade off, and 10, a very pessimistic assumption where the installation of frontier technology takes 10 times longer.

The fifth mechanism is related to the source of productivity growth. With the exception of the part of the overall productivity that depends on the amount of assets replaced after the disaster, the overall level of the economy's productivity can be assumed to be either exogenous, i.e., manna from heaven, or endogenous, i.e., growing in part as a function of the level of the investments per worker [18,41–43]. We assume that both exogenous and endogenous productivity have equal chances.

Impacts from agricultural output losses are subtracted from the overall output of the economy. A lower output of the economy translates into lower resources for investments and a slower accumulation of physical assets compared to the baseline, no-climate impacts scenario.

2.1. Model details

The model considers three main categories or channels of SLR damages, similar to the damage mechanisms considered in the work of Fankhauser S et al. [17]: agriculture output losses (Agr), damage to capital stock (Cap) and damage to residential buildings (Res). Those direct damage estimates are provided by the sectoral, bottom-up biophysical models.

The dynamic adjustment of the economic system is assumed to be the following: the agriculture damages are fully absorbed during the year of the climate shock, the damages to residential buildings are all repaired by the household in the year of the climate shock either by reallocating consumption expenditures or by reducing savings and, finally, the damages to capital stock are repaired in the year of the shock up to a certain threshold, which makes these damages to accumulate and generate compounding negative effects over time.

In our modelling framework, EU countries plus the UK are represented as a collection of closed economies where firms have access to the same constant returns to scale production technology, which is based on the combination of two inputs, i.e., capital and labour, and a technology/productivity multiplier. The economy produces one single good, which is used for both consumption and investments; the latter contribute to the accumulation of the firms' stock of physical assets, while the former contributes to the households' welfare.

The production technology uses capital and labour to produce a homogenous final good.

$$Y(t) = \left(A(t) \cdot L(t)\right)^{1-\alpha} \cdot \left(K(t) - Dam(t)\right)^{\alpha} - Agr(t) \tag{1}$$

Equation 1 is a standard Cobb-Douglas production function where Y is the output of the economy, A is a scalar for the productivity of labour input, L is labour, K is the capital stock, Dam is the stock of physical assets destroyed by the inundations and Agr is the agricultural loss. L is assumed to grow according to $L(t) = L0 * \ e^{kt}$, where $L0$ is labour at time 0 and k is the constant exogenous rate from the Ageing Report [21].

Equation 2 is the equation for consumption C, where s is the exogenous saving rate.

$$C(t) = (1 - s) * Y(t) \tag{2}$$

In Equation 3, Res stands for the overall damaged residential property and overall saving S of the economy (country) is calculated as the difference between total output (GDP) and consumption minus the part of the residential damages repaired via dissaving, as shown in Eq 3.

$$S(t) = Y(t) - C(t) - Res(t) * \ \varphi \tag{3}$$

We assume that $\varphi \sim \mathrm{U}(0, 1)$. Therefore, when $\varphi = 0$, the households are assumed to reshuffle consumption and repair the damages to their property (i.e., no dissaving) and by doing so they reduce their welfare by a proportional amount, while when $\varphi = 1$ households dissave and increase their expenditure level to cover the repairing cost. Being a model for closed economies, the usual assumption that domestic investment equals domestic savings ($S = I$) applies.

Welfare W is calculated as: $W(t) = \frac{C(t) - (1-\varphi)*Res(t)}{L(t)}$

Following Hallegatte S et al. [33] , the overall investment of the economy I in Eq 4 is composed of two different types of investments, i.e., investments that increase the productive capital and compensate for the natural depreciation of the assets (In), and those that are used to reconstruct the capital assets of the firms after a climatic event has occurred, (Ir).

$$I(t) = In(t) + Ir(t) \tag{4}$$

As the study of Hallegatte S et al. [33], we assume that there are short-term constraints: (i) insurance companies or public institutions need time to redirect high amounts of money to reconstruction activities or (ii) limited skills or organization capacity of the reconstruction/building sector of the economy, which make impossible the immediate mobilization of all the financial resources needed for the reconstruction process, even if those investments have higher returns compared to normal investments.

Equation 5 refers to the investment used for reconstruction of the capital assets of the firms, the variable Ir. The short-term constraints are reflected in the parameter $fmax$, which is the fraction of I that can be immediately redirected or mobilized for reconstruction investments.

$$Ir(t) = \min\left(Dam(t), \quad I(t) * fmax\right) \tag{5}$$

According to Eq 5, the investment for reconstruction Ir are equal to $Dam(t)$ if the fraction of destroyed capital stock is lower than the fraction of investments available for reconstruction. However, when the variable $Dam(t)$ is larger than the threshold, the reconstruction process takes longer as the constraints to the reconstruction activity becomes binding in the model. In fact, if the damaged capital is lower than the fraction of the total investments I that can be readily mobilized and redirected, the damaged capital is repaired in one-period time. However, the reconstruction process might take longer than one period, and this depends on whether the stock of damaged capital is larger than the amount of financial resources that can be redirected from business as usual investment activities.

Equation 6 represents the rule for the accumulation of potential. The parameter δ is the depreciation rate. We use the country specific depreciation rates as reported in the Penn World Table 10 [44], which reflects that different countries may have a different composition of their capital stock.

$$\dot{K}(t) = -\delta \cdot K(t) + In(t) \tag{6}$$

Equation 7 refers to the growth of the fraction of the destroyed capital Dam, which is equal to the difference between the capital lost at time t, i.e., Cap, and the investment for reconstruction Ir.

$$\dot{Dam}(t) = Cap(t) - Ir(t) \tag{7}$$

The productivity growth equation (Eq 8) has three components. Productivity grows in time in part exogenously, i.e., the part of the equation $A \cdot \mathrm{g}$, in part endogenously as an implication of the investments in physical assets $b \cdot \left(\frac{In}{L}\right)^{c}$ and also as a result of the upgrade of the capital stock in the aftermath of a disaster, i.e., $\frac{Ir*\theta}{K_0} \cdot (Afront - A)$. In particular, we consider that the physical assets installed with the reconstruction, i.e., the term $Ir * \theta$, embodies a level of technology that corresponds to the European technological frontier and therefore increases the level of overall productivity of the economy. We assume that the parameter $\theta \sim \mathrm{U}(0, 1)$.

$$\dot{A} = A \cdot \mathrm{g} + \mathrm{b} \cdot \left(\frac{In}{L}\right)^{c} + \frac{Ir * \theta}{K_0} \cdot (Afront - A) \tag{8}$$

In Eq 8 the variable $Afront$ is used as a proxy for the European technological frontier and corresponds to the productivity growth of Denmark.

In order to capture the trade-off between quality and duration of reconstruction, we make the parameter $fmax$ dependant on the size of θ. In particular we assume that: $fmax = fmax_0 * \frac{1}{1-(\gamma-1)*\theta}$, where $fmax_0 \sim \mathrm{U}(0.001, 0.01)$ and $\gamma \sim \mathrm{U}(1, 10)$.

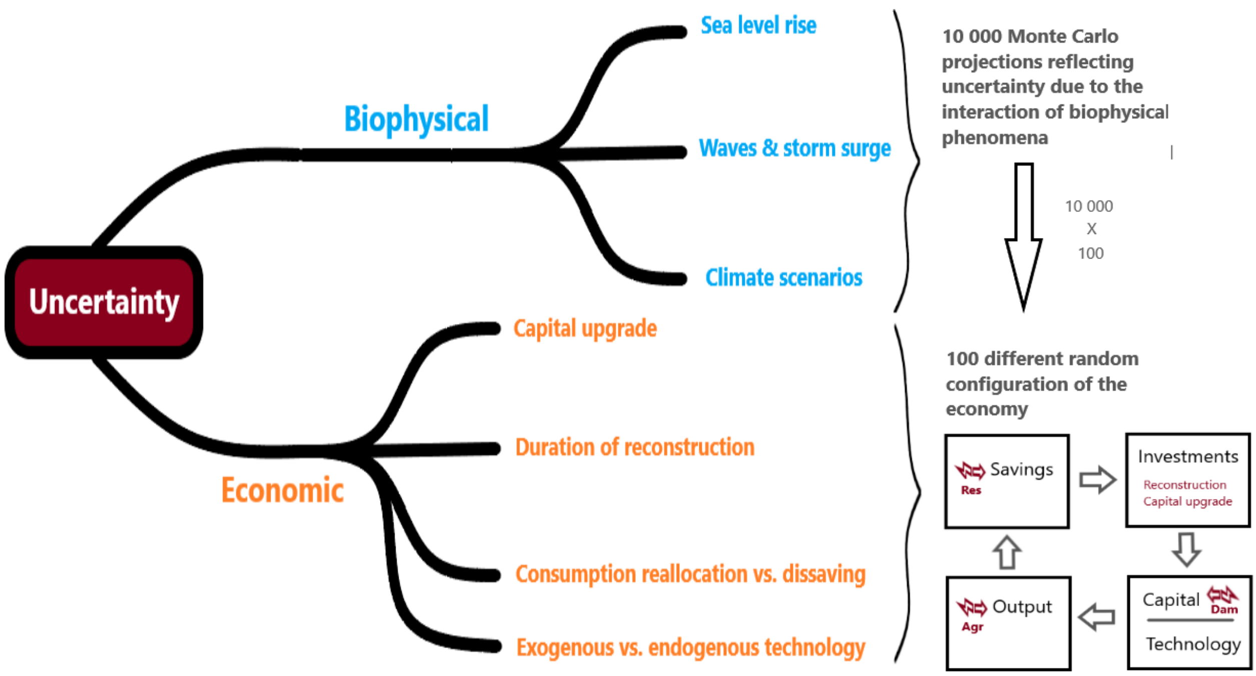

Figure 1. Uncertainty dimensions analysed. Each of the 10000 inundation projections is analysed under different economy configurations (100). The resulting ensemble comprises both physical and economic uncertainty.

The present analysis has two uncertainty dimensions, as represented in Figure 1. The first dimension is the uncertainty of the biophysical phenomena that is represented with the 10000 realisations of coastal flooding resulting from the Monte Carlo simulation. The second dimension is the economic uncertainty that depends on the different model specifications, i.e., exogenous technology vs. productivity spillovers from investments, and on the firms, and households, behavioural choices reflected in the parameter uncertainty. Each of the 10000 coastal flooding realisation are analysed with 100 different models and agents' choice specification randomly sampled from the specified distributions. The 100 different specifications give enough representation of the parameter space while keeping the computing time within reasonable limits. Figure 1 also provides with a schematic description of the economic model and how the exogenous climate shocks affect the specific economic variables.

The model is calibrated using publicly available data. Projections for population, GDP and productivity are taken from the Ageing Report 2021 [21], while additional data are taken from the Penn World Table 10, i.e., initial stock of capital and cross country depreciation rates, and World Development Indicator of the World Bank, i.e., country specific saving rates [44–46].

3. Results

The economic consequences for Europe (EU countries plus the UK) of future coastal flooding under a high emissions scenario (RCP8.5) are presented in Figure 2 in terms of GDP and welfare percentage losses w.r.t. to the counterfactual economic scenario that does not include any coastal flooding shocks into the model. For both GDP and welfare we are comparing direct impacts, which are mainly represented by asset losses either in the form of productive capital for firms or of residential property for consumers, with the associated income or welfare losses. We distinguish between direct impacts on production or firms and direct impact on welfare or households. The first corresponds to the combined value of the lost agricultural production, the value of productive assets damaged, plus the part of the residential damages repaired via dissaving. The second, only the residential damages. Being a comparison between a stock variable and the associated flow variable of the model, the comparison is not entirely meaningful in economic terms and must be taken only for the sake of comparing direct vs. indirect losses to the economy and answering the question of how large the income are losses for similar levels of direct losses, which provides with an indication of economic resilience.

In particular, panel A in Figure 2 compares the distribution of indirect GDP losses, represented by the shaded areas and the purple line in the middle, with the distribution of the direct impacts on production represented by the red lines in the graph. For both direct and indirect impacts, the range of the results corresponds to the 95% of the overall distribution, i.e., the *very likely range* in IPCC terms [47]. The thick purple line in the middle corresponds to the mean value. The indirect losses in 2100 for EU27 plus the UK vary within a wide range comprised between 0.25% and 0.91% of GDP relative to the baseline. The majority of projections, i.e., our most likely scenario that corresponds to the dark grey part in the figure (Figure 2, panel A), cumulate around a value of 0.57% of GDP by 2100 and are approximately twice as much the direct impacts that affect the production side of the economies.

In panel B of Figure 2 the results for both GDP and welfare are shown for five macro-regions and taken as the average of the last thirty years of the projection period 2071-2100. The most affected region for GDP is *South* (Bulgaria, Greece, Italy, Malta, Portugal and Spain), with losses varying within the very likely range of 0.18% to 0.78% (mean 0.46%). *UK and Ireland* is the second most affected region for GDP with losses comprised in the very likely range of 0.19%-0.72% (mean 0.44%). *Center-South* (France, Romania and Slovenia) and *North* (Denmark, Estonia, Finland, Latvia, Lithuania and Sweden) have comparable GDP losses at the end of the century in the very likely range of 0.16%–0.74% (mean value of 0.43%) and 0.16%–0.75% (mean value of 0.43%), respectively. The *Center-north* region (Belgium, Germany, Nederland and Poland) GDP impacts are projected to be the lowest in Europe and comprised in a range of 0.03%–0.30% (median 0.13%). The large range of variation for the GDP impacts depends on the range of the direct damages and on the stochastic assumptions underlying the economic analysis. Clearly, a longer reconstruction process, a reconstruction without any capital upgrading, large share of residential damages repaired via dissaving (and not consumption reallocation) and large spillovers from capital loss to productivity will generate larger GDP losses, while the contrary is true for a variation of those parameters in the opposite direction.

The impacts on welfare are transmitted via two main channels: directly by the amount of repairing that is financed via an increase of the non-welfare enhancing minimum consumption and indirectly by a gradual reduction of the income due to a general impoverishment of the economy, i.e., lower level of GDP, when the residential damages are repaired via dissaving. In both cases, the households have to bear the entire impacts with limited possibilities of reducing it and, in fact, the range of welfare impacts corresponds to the range of the residential damages. Most affected regions in terms of welfare are *North* and *Centre-South*, with impacts in the range of 0.61%-1.04% (mean 0.81%) and 0.57%-0.86% (mean 0.71%). Slightly smaller losses are projected for *South* and *UK & Ireland*, where welfare is affected in a range of 0.52%-0.85% (0.67% mean) and 0.45%-0.78% (0.60% mean), respectively.

Also, for welfare the region with the lowest impact is *Centre-North*, with impacts comprised in the range of 0.078%-0.53% (0.24% mean).

For both GDP and welfare, the long-term losses are larger than the direct physical impacts hitting the economy's production or the households' welfare. The ratio between direct and indirect losses is indicative of different degrees of resilience. Our projections show that *UK and Ireland, South* and to some extent *Centre-South* are the regions with low levels of long-term resilience with a unit of direct loss hitting the production side of the economy generating 2.58, 1.91 and 1.59 unit of indirect losses. Low levels of resilience are also reflected in an increase of the uncertainty range between direct and indirect losses.

For welfare losses, indirect impacts are generated as a second order effect of the model. Households can only temporarily avoid impacts on their welfare; should they decide to dissave for the entire amount of the damages and preserve their welfare, those impacts would anyway affect their income in subsequent periods. Larger ratios of indirect losses over direct losses are, also for welfare, recorded for those regions with lower level of resilience. *UK & Ireland*, *South* and *Centre-South* are the regions with the largest ratios between direct and indirect losses also for welfare: 2, 1.76 and 1.37, respectively.

The most affected countries are Cyprus, Greece, Croatia and Denmark with relative GDP losses comprised in a very likely range of 2.99%–7.5% (mean 5.12%), 1%–4.68% (mean 2.69%), 0.55%–2.48% (mean 1.5%), 0.29%–1.84% (mean 0.98%) and welfare losses equal to 5.86%–7.9% (mean 6.76%), 2.6%–4.9% (mean 3.57%), 1.42%–2.77% (mean 2.20%), 1.38%–2.75% (mean 2%), respectively. The full list of results for countries is included in the SI.

In none of the countries where impacts for both GDP and welfare are large, the upgrading of the capital stock generates gains or has a significant mitigation effect. With few exceptions, the technological level for European economies is not low and the marginal improvement from a build-back-better policy is therefore limited. There are nonetheless countries where according to these projections there might be some GDP and welfare gains, and these are: Bulgaria with 30% chances of GDP gains larger than 0.05% and 20% chances of welfare gain larger than 0.03%; Estonia with 5% chances of GDP gains larger than 0.007%; Slovenia with 5% chances of GDP gains larger than 0.01%.

The welfare impacts at a country level, expressed in euro per worker (real terms in 2015 prices), are plotted in panel C of Figure 2 for the values at the end of the century. The error bars report again the 5% and 95% quintiles. Around 5% of the European workforce will be hit by an average income loss larger than 3000 euros (the bars located on the right-hand side of the plot). Around 30% of the overall workforce will be exposed by the end of the century to an average income loss above 1000 euro per year. In relative terms, if we take a 2% annual income loss as the threshold that defines exceptional losses (approximately the per-capita income losses generated in 2020 by the COVID-19 pandemic in EU27), we estimate that there is a probability of 20% that more than 5 million workers (around 2.5% of the overall workforce) will incur annual losses larger than that threshold of exceptional impacts.

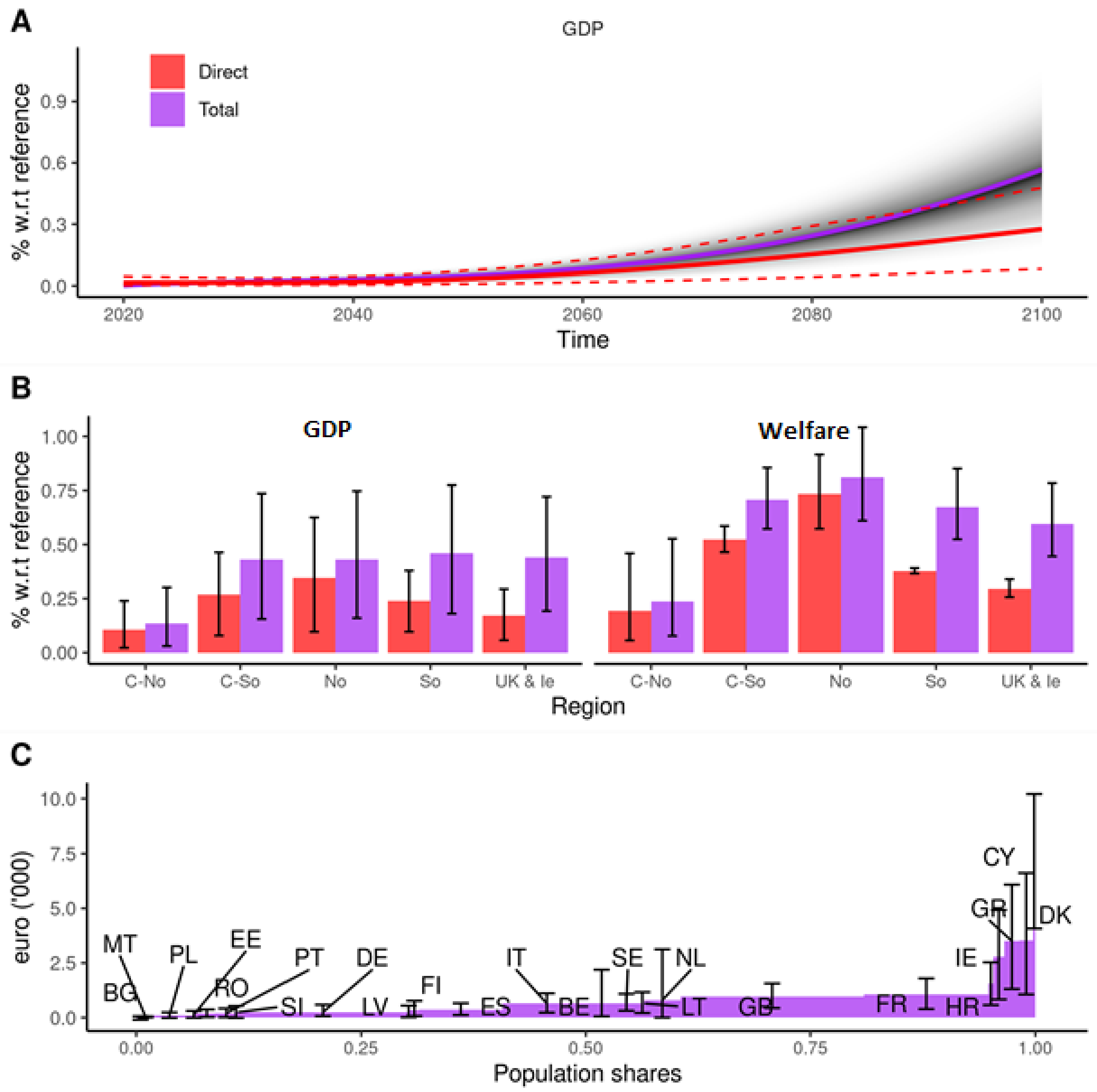

Figure 2. Panel A) distribution of impacts for EU+UK on GDP, the grey to black colour scale represents the concentration of the GDP impacts around the most likely scenarios. The red lines show the mean (continuous) and the very likely range of the direct impacts (dashed); panel B) shows both the GDP and welfare impacts for the five considered macro regions and by the end of the century (average of the last 30 years from 2071 to 2100) expressed as relative change w.r.t the reference scenario (% of GDP and % of Per capita consumption; annuitized); the abbreviation for the regions are: C-No (Center North), C-So (Center South), No (North), So (South), Uk & Ie (UK and Ireland). Panel C) indicates the welfare losses per country and measured in thousands euros; the plot compares the impacts with the population shares of each country over the overall population. The error bars reflect the very likely range for the impacts, while the different colours refer either to direct (red) or total (purple) impacts; BG (Bulgaria), Mt (Malta), PL (Poland), EE (Estonia), RO (Romania), PT (Portugal), SI (Slovenia), DE (Germany), LV (Latvia), FI (Finland), ES (Spain), IT (Italy), BE (Belgium), SE (Sweden), NL (Nederlands), LT (Lithuania), GB

(Great Britain), FR (France), HR (Croatia), IE (Ireland), GR (Greece), CY (Cyprus), DK (Denmark).

4. Summary and conclusions

This work integrates a large ensemble of probabilistic direct coastal damage projections in a stochastic macroeconomic framework in order to comprehend how and to what extent physical impacts would interfere with the process of economic growth and generate long-term economic losses. Direct physical impacts of coastal flooding projected up to 2100 under a high emissions scenario (RCP8.5) have been used in combination with an extended/stochastic Solow model to assess the macroeconomic implications in terms of annuitized relative GDP and welfare losses. In our analysis, we complement the uncertainty range assessed for the biophysical phenomena with the uncertainty related to the behaviour of the households in a post inundation scenario, to the firms' response with respect to the duration and quality of the reconstruction process and to the existence or not of productivity spillovers from investments in physical assets. The majority of the direct coastal flood impacts come from damages to residential properties, whose repairing is expected to affect the consumption vs. saving decision. Households will dissave, increase their overall expenditure and repair the damages without any immediate welfare loss, or alternatively reshuffle their consumption, give up some other expenditure along with part of their welfare and repair. Large coastal flood impacts are also associated with the loss of productive physical assets and we model the reconstruction process with different duration and different levels of upgrades of the replaced assets. Instead of analysing extreme cases we model these scenarios in terms of parameters distribution and analyse a larger spectrum of plausible scenarios.

The results show that the EU economy might lose between 0.25% and 0.91% (median 0.57%) of annual GDP by the end of the century. Considering that the EU budget corresponds to around 2% of the yearly EU27 GDP (2021 data), one can better comprehend the relevance of these GDP losses, with a high chance (more than 50% probability) of being larger than a quarter of the EU annual budget.

The most affected region for GDP is the South where losses might be in the range of 0.18% to 0.78% (mean 0.46%). The most affected regions regarding welfare are North and Centre-South, with losses in the range of 0.61%-1.04% (mean 0.81%) and 0.57%-0.86% (mean 0.71%), respectively.

Looking at the welfare impacts, our estimates indicate that there are high chances (around 20%) that for approximately 5 million workers welfare impacts could reach levels that one could consider today exceptional (comparable to those occurred during the COVID-19 pandemic), and that might represent a serious threat of poverty for a large part of the population.

We also analysed the economic effect of replacing damaged assets with new ones that have a higher productivity. The results indicate a mitigation of the impacts only for economies with large technology gaps, where the upgrade of the capital stock might generate significant productivity gains. However, on an EU basis we can conclude that it is very unlikely that the benefits of a build-back-better policy could be sufficient to compensate of even having a significant mitigation of the direct physical losses for the case of coastal floods.

Our estimates of indirect economic losses both on production and welfare are substantially larger than the direct impacts, which underlines the importance of considering the two measures for a complete assessment of the economic risks of climate impacts.

Despite the implementation of a stochastic framework for the economic analysis, our results are expressed at the country level, which might hide sub-country-level disparities, potentially exacerbating the overall impact profile. A possible extension of the present work could therefore be the application of the same framework at a more refined geographical scale, which would allow within-country heterogeneity to be reflected more accurately.

In our analysis, the savings rates determines the level of resilience of the economy: a low saving rate makes the transition back to pre-inundation levels slower and therefore amplifies the indirect impacts on GDP and welfare. Our results underline the relevance of saving rates and of promoting risk management policies as mitigation measures of long-term economic impacts of coastal flooding.

This study has a number of caveats and limitations. First, the results of the assessment should not be interpreted as projections or forecasts of the likely impact of SLR. This study is an illustration of the application of one methodology integrating direct cost estimates from a specific coastal impact model (LISCOAST) into a specific economic model (a dynamic growth model). Even if some key uncertainties in the modelling exercise have been considered, there remain other sources of uncertainties not considered. For instance, a limitation of the present analysis is the assumption of uniform distribution for the agents' reaction to the disaster. In that respect, a major extension of the present study would be to provide an empirical foundation to the choice of different distributions for different agents in different countries or regions, which would allow cross-country heterogeneity to be reflected in the analysis more accurately. A further limitation, and at the same time a future extension of the present study, is the treatment of spatial and cross regional spillover effects originating from the climate impacts. They have not been considered and appear in the research agenda for further developments.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare no conflict of interest.

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