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Economy-wide effects of coastal flooding due to sea level rise: A multi-model simultaneous treatment of mitigation, adaptation, and residual impacts

Thomas Schinko[1,*], Laurent Drouet[2], Zoi Vrontisi[3], Andries Hof[4,5], Jochen Hinkel[6], Junko Mochizuki[1], Valentina Bosetti[2], Kostas Fragkiadakis[3], Detlef van Vuuren[4,5], Daniel Lincke[6]

Abstract

This article presents a multi-model assessment of the macroeconomic impacts of coastal flooding due to sea level rise and the respective economy-wide implications of adaptation measures for two greenhouse gas (GHG) concentration targets, namely the Representative Concentration Pathways (RCP)2.6 and RCP4.5, and subsequent temperature increases. We combine our analysis, focusing on the global level, as well as on individual G20 countries, with the corresponding stylized RCP mitigation efforts in order to understand the implications of interactions across mitigation, adaptation and sea level rise on a macroeconomic level. Our global results indicate that until the middle of this century, differences in macroeconomic impacts between the two climatic scenarios are small, but increase substantially towards the end of the century. Moreover, direct economic impacts can be partially absorbed by substitution effects in production processes and via international trade effects until 2050. By 2100 however, we find that this dynamic no longer holds and economy-wide effects become even larger than direct impacts. The disturbances of mitigation efforts to the overall economy may in some regions and for some scenarios lead to a counterintuitive result, namely to GDP losses that are higher in RCP26 than in RCP45, despite that the direct coastal damages are higher in the latter scenario. Within the G20, our results indicate that China, India and Canada will experience the highest macroeconomic impacts, in line with the respective direct climatic impacts, with the two first large economies undertaking the highest mitigation efforts in a cost-efficient global climate action. A sensitivity analysis of varying socioeconomic assumptions highlights the role of climate-proof development as a crucial complement to mitigation and adaptation efforts.

Keywords coastal flooding due to sea level rise; macroeconomic assessment; economy-wide effects; multi-model assessment; mitigation-adaptation interaction; well below 2°C

[1] International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria. ORCID: 0000-0003-1156-7574
[2] RFF–CMCC European Institute for the Economy and the Environment (EIEE), Milan, Italy.
[3] School of Electrical and Computer Engineering, E3MLab, National Technical University of Athens, Athens, Greece.
[4] PBL Netherlands Environmental Assessment Agency, the Hague, the Netherlands.
[5] Utrecht University (UU), Utrecht, the Netherlands.
[6] Global Climate Forum (GCF), Berlin, Germany.
* Corresponding author: Schlossplatz 1, A-2361 Laxenburg, Austria. E-mail: schinko@iiasa.ac.at; Tel: +43 2236 807467

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1. Introduction

The Paris Conference, officially known as the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC), set out a long-term goal to limit "the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C" (UNFCCC 2015). This ambitious global agreement is based on the notion that a 2°C target may not adequately safeguard the planet from the dangerous effects of climate change, while keeping temperature increase well below 2°C could substantially reduce the impact of climate change on the frequency and intensity of extreme events (IPCC 2018; Knutti et al. 2016; Mitchell et al. 2016). However, what may be considered as acceptable and unacceptable warming thresholds is open to societal value judgment. This requires an open and transparent debate about possible impacts as function of alternative temperature targets as well as the costs associated with reaching these targets (IPCC 2018).

Previous research has identified coastal impacts due to SLR as one of the key economic damages associated with climate change (e.g., Watkiss 2011), second after health impacts (i.e. premature mortality) and before agricultural impacts, energy sector impacts and riverine flooding (e.g., Ciscar et al. 2014). A growing body of literature assesses the direct economic costs due to coastal flooding due to SLR, as well as the costs and benefits of adapting to these risks (e.g., Hinkel et al. 2014; Diaz 2016). Many studies conclude that estimates of future damages are more sensitive to assumptions made on adaptation and risk reduction measures than to variations in climate- and socioeconomic scenarios (Hinkel et al. 2014; Abadie 2018). Without adaptation, expected direct annual losses due to coastal floods could amount to 0.3-9.3% of global GDP by 2100 (Hinkel et al. 2014). The global costs for protection measures are estimated to be significant but much lower than the associated benefits through avoided damages (Hinkel et al. 2014). Adaptation could potentially reduce sea level induced flood costs by a factor of 10, while failing to achieve global mean temperature targets of 1.5°C or 2°C will lead to higher levels of coastal flood risk worldwide (Jevrejeva et al. 2018). In the long term, even under strong 1.5°C and 2°C scenarios, potential impacts due to SLR continue to grow for centuries (Nicholls et al. 2018). These results indicate that strengthening adaptation and proactive disaster risk management efforts remains essential, and that in the long-run, soft and hard limits to adaptation may cause residual losses and damages even under stabilization of global temperature increase at 1.5°C or 2.0°C.

The above-mentioned studies do, however, not take the economy-wide effects into account. These indirect economic effects, which may arise due to feedback effects throughout the value chain and via

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international trade channels, are of crucial importance in climate change impact assessments since they can either add to or counterbalance the negative direct impacts.

CGE models have been heavily applied in the literature for the economy-wide assessment of climate-related impacts in several economic sectors (Bigano et al. 2008; Ciscar et al. 2011, 2012, 2014; Aaheim et al. 2012; OECD 2015; Steininger et al. 2016). The PESETA and PESETA II projects, for example, applied a comparative-static CGE analysis by introducing biophysical impacts as inputs to the General Equilibrium Model for Economy - Energy - Environment (GEM-E3) for Europe (Ciscar et al. 2011, 2012, 2014). Other CGE studies have focused on SLR impacts explicitly (Bosello et al. 2007, 2012; Carrera et al. 2015; Pycroft et al. 2016). Bosello and De Cian (2014) present a thorough literature review covering the different applications and methodologies followed by CGE models for the assessment of SLR impacts, indicating the strengths and caveats of the approaches.

CGE model-based impact assessments have the advantage that they provide large sectoral detail and regional detail as well as endogenous trade and substitution dynamics and hence are well suited to depict an estimate of the related cross-sectoral and cross-regional and macroeconomic feedback effects (OECD 2015). This large detail also has a drawback: many assumptions have to be made, for instance regarding price elasticities, most of which can be uncertain, especially in the far future. CGE models are calibrated against current structures of the economy, and only some take into consideration the changing structure of the economy in time. More simple economic growth models feature substantially less assumptions and are thus more flexible and easy to reproduce. However, as these models feature only an aggregate economy-wide representation with no sectoral detail, they utilize the "damage function" approach translating temperature change to GDP loss at the aggregate level only and can thus these benefit-cost models are not able to provide insights on a sectoral level (Fisher-Vanden et al. 2013).

A further limitation of the abovementioned impact and adaptation studies is that they ignore the changes in economic structure induced through mitigation efforts. Studies generally only evaluate the benefits of mitigation in terms of reducing impacts (e.g., Hinkel et al. 2013 for the case of coastal floods), or the net benefits of adaptation in terms of reduced impacts (Ciscar et al. 2011, 2012; OECD 2015; Diaz 2016) but without explicitly modeling underlying mitigation scenarios that entail a complete transformation of production processes and consumption patterns.

In this study we address the above mentioned limitations in assessing the macroeconomic impacts of coastal flooding due to SLR and related adaptation ambitions. The direct impacts are based on DIVA

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(Hinkel et al. 2014), a coastal climate change impact model that assesses coastal flood risk based on local distributions of coastal extreme water levels (due to surges and tides), sea-level rise scenarios, socio-economic scenarios and adaptation strategies. The macroeconomic impacts are assessed by comparing between growth and CGE models, applying the relatively simple macroeconomic growth models FAIR (Den Elzen et al. 2014) and WITCH (Emmerling et al. 2016), and the more complex CGE model GEM-E3 (Capros et al. 2014; E3MLAB 2017). In addition, our assessment of impacts is conducted in a framework that takes into consideration the evolution of economic structure induced through the transitions required to get to well-below 2°C. We evaluate the direct and indirect economic effects ~~costs and benefits~~ of climate impacts and adaptation and assess how these effects would evolve under different adaptation and mitigation assumptions, thus providing insights on the mitigation-adaptation synergies and trade-offs. We also identify regional and sectoral hotspots due to SLR and coastal flooding. A sensitivity analysis further clarifies the effects of alternative socioeconomic development assumptions.

Taken together, this study moves beyond the current state of the literature in three ways: by applying different types of macroeconomic models for increased robustness of the results; evaluating climate impacts and adaptation on top of mitigation for acknowledging the feedback effects between climate change mitigation, remaining climate damages and adaptation policies; and conducting a dynamic analysis instead of a comparative static one for the investigation of different pathways related to different future climate and socioeconomic scenarios. It is important to note that for this study, we focus only on coastal flooding due to SLR and not on other climate-related impacts. Moreover, we concentrate on the assessment of indirect economic impacts from physical damages and associated direct impacts as provided by DIVA, but do not take into account further non-economic impacts, such as people at risk.

2. Methods

In the following section, we describe in detail the methodological approach as well as the climate and policy scenarios employed in this paper.

2.1. Research approach, methods and data

We perform a multi-model macroeconomic assessment (Fig. 1) employing two different kinds of global macroeconomic assessment models: the inter-temporal optimal economic growth models FAIR and WITCH (Den Elzen et al. 2014; Emmerling et al. 2016), and the CGE model GEM-E3 (E3MLAB 2017). These state-of-the-art modeling tools are extensively used to evaluate the consequences of climate-related impacts and the effects of climate change adaptation in the medium-to-long term (Hof et al. 2008, 2010,

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Ciscar et al. 2012, 2014; Clark et al. 2014; De Cian et al. 2016; Admiraal et al. 2016). The DIVA model provides estimates of the direct impacts of coastal SLR in terms of expected annual damages by sea floods (the costs of migration or people actually flooded are not taken into account in our analysis), as well as annual costs for adaptation in terms of dike construction and dike maintenance. This exogenous input is introduced to the global macroeconomic models of WITCH, FAIR and GEM-E3 to quantify both the direct and indirect economic impacts of coastal flooding due to SLR. Further to the overall global picture of longer-term ripple effects on average, the GEM-E3 model provides a regional and sectoral disaggregation of costs.

While each of the models employed here has – to varying degrees – different theoretical backgrounds, structures and solution algorithms, the socioeconomic development and policy assumptions are harmonized in this study. To this end, we employ the widely used Shared Socioeconomic Pathways (SSPs) (Riahi et al. 2017) with updated GDP projections from Labat et al. (2015), which together reflect plausible global socioeconomic developments that together would lead to different challenges for climate change mitigation and adaptation. Each SSP can be projected under different radiative forcing pathways (RCPs), of which we include RCP2.6 and RCP4.5 (van Vuuren et al. 2011). For our central scenarios, the socioeconomic and population assumptions are calibrated to the 'middle of the road' storyline of SSP2. This means that the three economic models are calibrated in a baseline run, which is not accounting for climate impacts, mitigation and adaptation measures, to match regional SSP2-based GDP projections.

In the following we present the main characteristics of each model employed in this study as well as a description of how the linkage between the coastal impact model DIVA and the macroeconomic models is established (see also Table S1 in the Supplementary Material for a detailed summary of the macroeconomic models' characteristics and assumptions).

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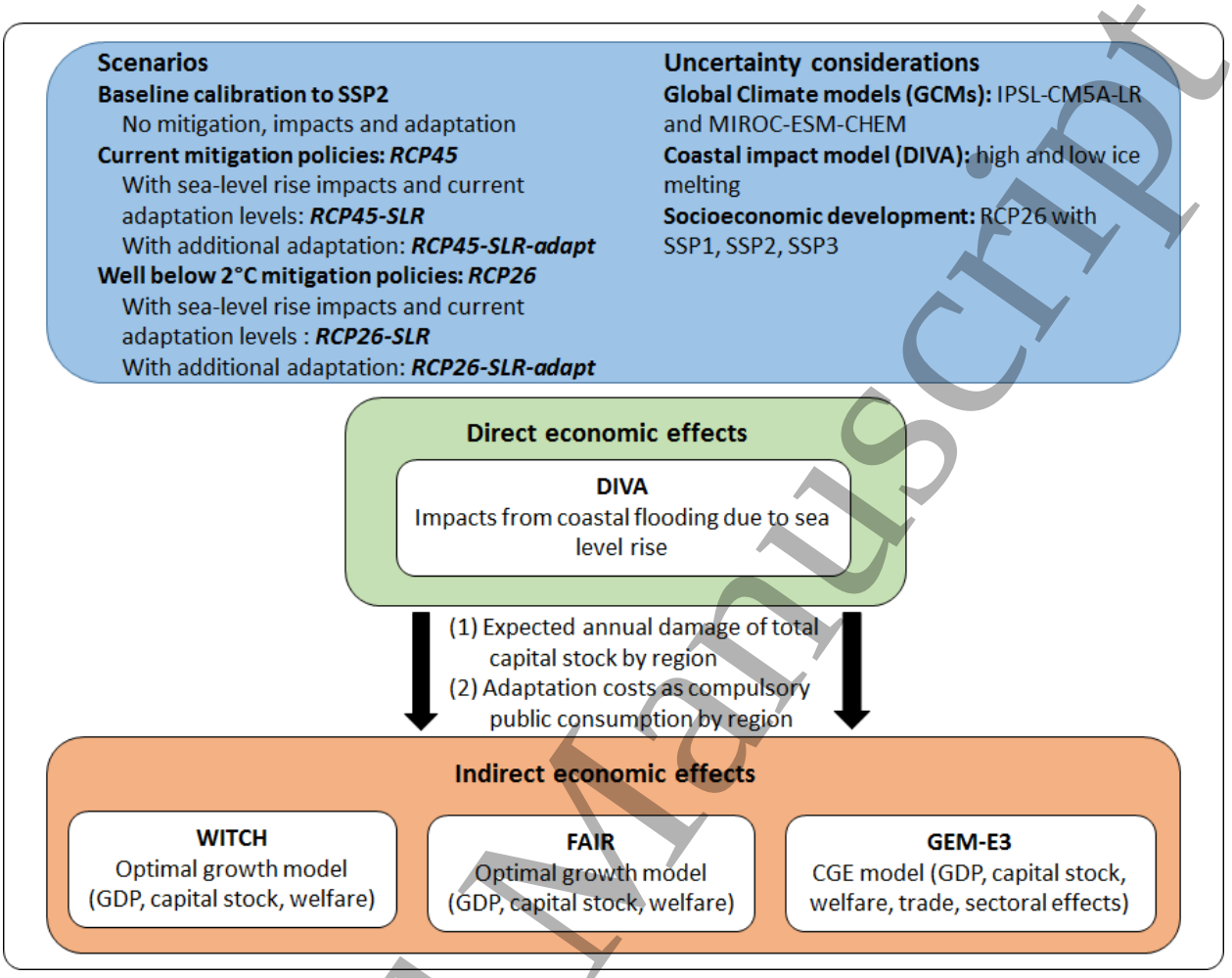


Fig. 1 Multi-model framework adopted in this study

FAIR includes a simple economic growth model based on a Cobb-Douglas production function. This approach has been commonly used for similar purposes in cost-benefit integrated assessment modeling (see e.g. Nordhaus 2007). We assumed that the regional trends in labor follow from those in the regional population, as given by the respective SSP. Historical capital stocks and capital formation rates were based on the IMF Investment and Capital Stock Dataset, 2015 (Gaspar et al. 2015). Regional savings rates are assumed to converge linearly from 2013 historical levels to the same global level by 2100. In the baseline scenario, total factor productivity is calibrated so that GDP corresponds to the exogenous GDP path of the SSP2 scenario. In FAIR, the direct damages from SLR are deducted from productive investment to calculate the GDP effects. Hence, the direct damages have a long-term effect on GDP by lowering the productive capital stock. Technological progress is not assumed to be affected by direct damages. Adaptation costs are included by assuming that they replace productive investments, similarly as damages do.

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WITCH is a global integrated assessment model, including a top-down inter-temporal Ramsey-type optimal growth model (i.e. intertemporal optimization of a regional welfare function, employing a Cobb-Douglas production function) linked with a bottom-up representation of the energy sector (Emmerling et al. 2016). The non-cooperative nature of international relationships is explicitly accounted for, so that the simultaneous policy responses of a set of representative regions satisfy an open-loop Nash equilibrium (i.e. regions decide about own action without knowing what other regions are doing). For this study, similarly to FAIR, the DIVA SLR direct damages destroy regional capital stocks (excluding the energy-related assets) and the building and operating costs of dikes are withdrawn from regional consumption. This means that adaptation costs are implemented via increasing savings requirements and thus a reduction in regional final consumption.

GEM-E3 is a hybrid general equilibrium model with a detailed regional and sectoral representation (E3MLAB 2017). The model assesses the macroeconomic and sectoral impacts of the interactions of the environment, the economy and the energy system. The GEM-E3 model has been calibrated to the latest statistics (GTAP 9, IEA, UN, ILO) while for the EU Member States, Eurostat statistics have been included. CGE models like GEM-E3 simultaneously calculate the equilibrium in goods and service markets, as well as in the labor and capital markets, based on an optimization of welfare for households and cost for firms (Capros et al. 2014). Production functions assume a constant elasticity of substitution across labor, capital, energy and intermediate goods, while consumer behavior is optimized and distinguishes between durable and disposable goods and services. A distinctive feature of the GEM-E3 model is the representation of an imperfect labor market through involuntary unemployment, both for skilled and unskilled labor supply. The model is dynamic, recursive over time, and driven by accumulation of capital and equipment. The GEM-E3 regions are linked through endogenous bilateral trade in accordance with the Armington assumption, meaning that products traded internationally are differentiated by country of origin via an elasticity of substitution parameter. This version of the GEM-E3 model includes 19 regions, explicitly representing the G-20 members except those that are Members of the European Union, and 39 categories of economic activities. In addition, the GEM-E3 environmental module covers all GHG emissions and a wide range of abatement options, as well as a thoroughly designed carbon market structure (e.g., grandfathering, auctioning, alternative recycling mechanisms). The integration of climate impacts in the GEM-E3 model follows the most up-to-date approach, in line with the applications of GEM-E3 in the PESETA and PESETA II projects (Ciscar et al. 2012, 2014). SLR is assumed to directly affect the available capital stock of the economy, thus we deduct the monetary estimations of these damages, as provided by the DIVA model, from the total capital stock. Capital is mobile across all sectors, so this destruction of

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capital affects capital supply and demand in all economic activities. The effects of SLR are considered in this analysis as slow onset climate change events that lead to a resource limitation similar to what can be observed in overall economic activity once part of available capital is considered obsolete. In GEM-E3, the expenditure for the construction of dikes (i.e. the defensive capital) and the maintenance of dikes (defensive capital O&M) are introduced as additional expenditures by the government that do not add to the productive capacity of the entire economy, i.e. are not added to the capital stock of the economy that is available for the production of goods and services. We thus assume that this is a type of compulsory consumption and in particular assume that it is publicly funded through the increase of government demand of construction services. These increased public expenditures for adaptation to SLR in turn increase the public deficit (or reduce public surplus).

We rely on previously published (Hinkel et al. 2014) DIVA model (Dynamic Interactive Vulnerability Assessment modeling framework, DIVA model 2.0.1, database 32) estimates of coastal impacts from sea-level rise and socio-economic change as exogenous input for the comprehensive macroeconomic assessment. DIVA's underlying DINAS-COAST database (Vafeidis et al. 2008) represents the world's coast (excluding Antarctica) as 12,148 coastal segments with homogenous bio-physical and socio-ecological characteristics. For each segment area exposure is derived from the Shuttle Radar Topographic Mission (SRTM) high resolution digital elevation model (Jarvis et al. 2008) and the GTOPO30 dataset (USGS 2015) for areas above 60° N and 60° S. SRTM has a vertical resolution of 1 m (which is the highest resolution available today on global scale) and spatial resolution of approximately 90 m at the equator (30 arc sec). For the calculation of population exposed to flooding the Global Rural Urban Mapping Project (GRUMPv1) elevation dataset with a spatial resolution of 30 arc sec was employed (CIESIN et al. 2011). Exposed population is translated into exposed assets by applying sub-national GDP per capita rates (Vafeidis et al. 2008) to the population data, followed by applying an assets-to-GDP ratio of 2.8 (Hallegatte et al. 2013). Future exposure follows the population and GDP change projections from the SSP scenarios. Extreme water levels are also taken from the DINAS-COAST database (Vafeidis et al. 2008) and are assumed to uniformly increase with SLR, following 20th century observations, which implies no change in storm characteristics (Menéndez and Woodworth 2010). Flood damages are calculated by combining elevation-based population and asset exposure with flood depths caused by extreme events. Following (Messner et al. 2007) we assume a logistic depth-damage function (giving the fraction of assets damaged for a given flood depth) with a 1-m flood destroying 50% of the assets. Expected annual flood damages are computed as the mathematical expectation of damages based on extreme event distributions (Hinkel et al. 2014). In this paper we consider only the damages to capital due to extreme sea-level events as the damages from

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land loss due to the gradual rise of sea-level are much smaller. It is a widely made assumption that submergence by gradual sea-level rise does not lead to damages to capital because this is a slow process and by the time gradual SLR arrives the capital stock will have fully depreciated (Tol et al., 2016). Protection is modeled by the means of dikes, following a demand function for safety based on local population density and GDP per capita, with a population density threshold of 30 people per km² for protected land (Hinkel et al. 2014). Adaptation cost are based on dike unit cost (1 km length, 1 m height) for protection infrastructure. Unit costs in earlier studies such as Hinkel et al. (2014) are based on older studies (Dronkers et al. 1990; Hoozemans et al. 1993). For this study, these numbers have been updated with the newer estimates given by Jonkman et al. (2013). Adaptation capacities are modelled by the demand-for-safety (Hinkel et al. 2014) and depend mainly on local GDP per capita and local coastal population density and thus vary between SSP scenarios. It is a widely accepted assumption that these two parameters are the main determinants of adaptation (Sadoff et al, 2015; Hallegate et. al 2013). Without further adaptation, dike heights are maintained, but not raised, so flood risk increases with time as relative sea level rises. With further adaptation, dikes are raised following the demand function for safety.

2.2. Scenarios

For socioeconomic development assumptions, we assume the SSP2 pathway in all scenarios. To assess the effects of different levels of mitigation ambition, we compare impacts from coastal flooding due to SLR in a 'current policies' climate change mitigation scenario ('RCP45-SLR') with a 'well below 2°C' mitigation scenario ('RCP26-SLR') (see Tables S8 and S9 for the two policy scenarios' sectorally resolved emission reduction pathways). These economic impact projections are compared with respective "no climate impacts" reference scenarios, either with RCP4.5 ('RCP45') for the former 'current policies' scenario, or with RCP2.6 ('RCP26') for the latter 'well below 2°C' scenario. The costs of mitigation are accounted for in each model leading, all else being equal, to lower levels of GDP for the most ambitious mitigation scenarios. In terms of energy and climate policy assumptions, the `current policies` scenario does not feature a specific carbon budget but is constructed in a bottom up manner by introducing current climate and energy policies and then allowing for a continuation of this climate policy ambition after 2020 (see section 5.2 of the SM for further information on how the 'current policies' mitigation scenario is linked to the RCP4.5 SLR impact scenario). The 'well below 2°C' scenario is a cost-efficient global mitigation scenario that aims to limit the increase in global average temperatures below 2°C above the pre-industrial level by 2100 with a > 66% likelihood (Luderer et al., 2018). A global carbon price on all greenhouse gases

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is introduced after 2020 so as to limit global carbon dioxide (CO_2) emissions to a carbon budget of approximately 1,000 $GtCO_2$ over the 2011-2100 timeframe and limit other GHGs as well. No burden sharing regimes or carbon trading schemes are introduced, so emission reductions occur where and when it is most cost-effective. The FAIR and WITCH models optimize, while for these runs GEM-E3 has used the 2011-2050 budget as derived by IAMS (e.g. IMAGE) and has then optimized the pathway. See Luderer et al. (2018) for a more detailed description of the 'current policies' and 'well below 2°C' mitigation scenarios. When extending the analysis to the economic effects of adaptation to coastal flooding due to SLR, we consider two different adaptation ambition levels of each scenario. The first one ('RCP45-SLR' and 'RCP26-SLR') assumes that no additional adaptation measures are taken on top of current adaptation levels (i.e. dyke levels are maintained but not heightened above 2015 levels). The second one ('RCP45-SLR-adapt' and 'RCP26-SLR-adapt') assumes that adaptation ambitions follow an increasing demand for safety as described in Hinkel et al. (2014).

To take into account biophysical modeling uncertainties, we employ both low and high ice melting scenario results from DIVA. Moreover, each of the scenarios is run for two different global climate models (GCMs) from the ISI-MIP archive (IPSL-CM5A-LR and MIROC-ESM-CHEM, which are spanning the whole SLR-range within the ISI-MIP data) to account for climate model uncertainties. With these models global mean sea-level rise values (in cm) range under RCP26 from 15-25 in 2050 and 25-56 in 2100, and under RCP45 from 18-29 in 2050 and 40-81 in 2100 (the exact values and their composition are given in Tables S2 and S3 in the Supplementary Material). In a sensitivity analysis employing the optimal growth models FAIR and WITCH, we set out to asses yet another source of uncertainty by identifying the influence of changes in socioeconomic and population assumptions (the exposure component of climate risk) on the economy wide effects of coastal flooding due to SLR in a below 2°C world. We contrast the 'current policies' scenarios with three different versions of the 'well below 2°C' scenario that account for differences in socioeconomic development assumptions (i.e. reflecting population and economic growth assumptions for SSP1, SSP2 and SSP3, respectively)[1]. See Fig. 1 for a summary of all scenarios and variations thereof considered in this analysis.

[1] Even though the existing IAM modeling literature (Riahi et al. 2017) finds that, when starting from an SSP3 baseline, achieving a 2.6W/m^2 forcing level is unlikely, we run the three different SSPs with RCP2.6 as an important exercise to identify the role of exposure as driver of climate-related impacts. Moreover, there is still a chance that climate sensitivity is on the lower end of the uncertainty range (Cox et al. 2018), which means that the socio-economic developments of SSP3 could still be consistent with achieving 2°C.

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3. Results

The results section is split into two subsections. The first subsection presents the macroeconomic model aggregate results on economic impacts from coastal flooding due to SLR with and without adaptation, and discusses them in relation to existing direct coastal flood impact assessments available in the literature (Hinkel et al. 2014). The second subsection presents a regional and sectoral break-down of economy-wide effects. It is important to note that while FAIR and WITCH models calculate until 2100, the more complex GEM-E3 model is only used for the assessment of the time horizon until 2050. Detailed numbers on sea regional flood cost and regional protection levels and cost can be found in the SM (Table S4 - Table S7).

3.1. Global macroeconomic impacts

Fig. 2 presents global economic impacts (measured in terms of global GDP losses) of coastal flooding due to SLR across climate scenarios (RCP45-SLR and RCP26-SLR) until 2050 and 2100. In addition, two different adaptation levels are compared: no further adaptation and full adaptation to SLR. The macroeconomic effects of impacts in each climate scenario are shown relative to global GDP levels of the respective mitigation scenario (i.e., RCP45-SLR is compared to RCP45, and RCP26-SLR is compared to RCP26). The portrayed uncertainty ranges account for three different dimensions of uncertainty, namely model ranges from FAIR, GEM-E3 and WITCH results, climate uncertainty due to high and low ice-melting and climate model uncertainty from two different GCM (IPSL and MIROC) projections. The differences between the three macroeconomic models' results are driven by the models' respective structures and their approaches to model climate change impacts as well as mitigation and adaptation policies (see Fig. S1 in the Supplementary Material for an annotated version of Fig. 2 with additional labels for the macroeconomic models). For example, endogenous mitigation costs are highest for the WITCH model, which in turn also lead to higher overall macroeconomic impacts when adding impacts from coastal flooding due to SLR (see Luderer et al. (2018) for a detailed assessment of mitigation costs).

Global GDP losses in all scenarios strongly depend on the level of adaptation and the assumed degree of ice melting. Without further adaptation measures, global GDP loss is about twice as high by 2050 with high ice melting (about 0.4%), than with low ice melting (about 0.2%). Full adaptation lowers the impact to less than 0.1% of global GDP in all cases, with much smaller differences between low and high ice melting. Hence, adaptation is found to be highly economically efficient, with adaptation costs being much lower than the corresponding benefits from avoided damages.

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We find that up to 2050 the low- and high-end values of global GDP losses in the case of no further adaptation (RCP45-SLR and RCP26-SLR) are similar across the two policy scenarios. However, in the longer term, global GDP effects increase strongly by an order of magnitude, with higher impacts projected in the RCP45-SLR scenario compared to RCP26-SLR. Without further adaptation and assuming high ice melting, projected global economic losses can amount to more than 4% in RCP45-SLR and more than 3% in RCP26-SLR. With low ice melting, these numbers are more than halved. Again, further adaptation reduces the impacts significantly to less than 0.15% in all scenarios over the whole century. These effects include both the residual coastal flooding impacts and the costs of adaptation measures. This again confirms the importance and economic efficiency of adaptation in reducing global GDP loss from SLR, as costs of adaptation infrastructure affect the global economy much less than unabated climate impacts.

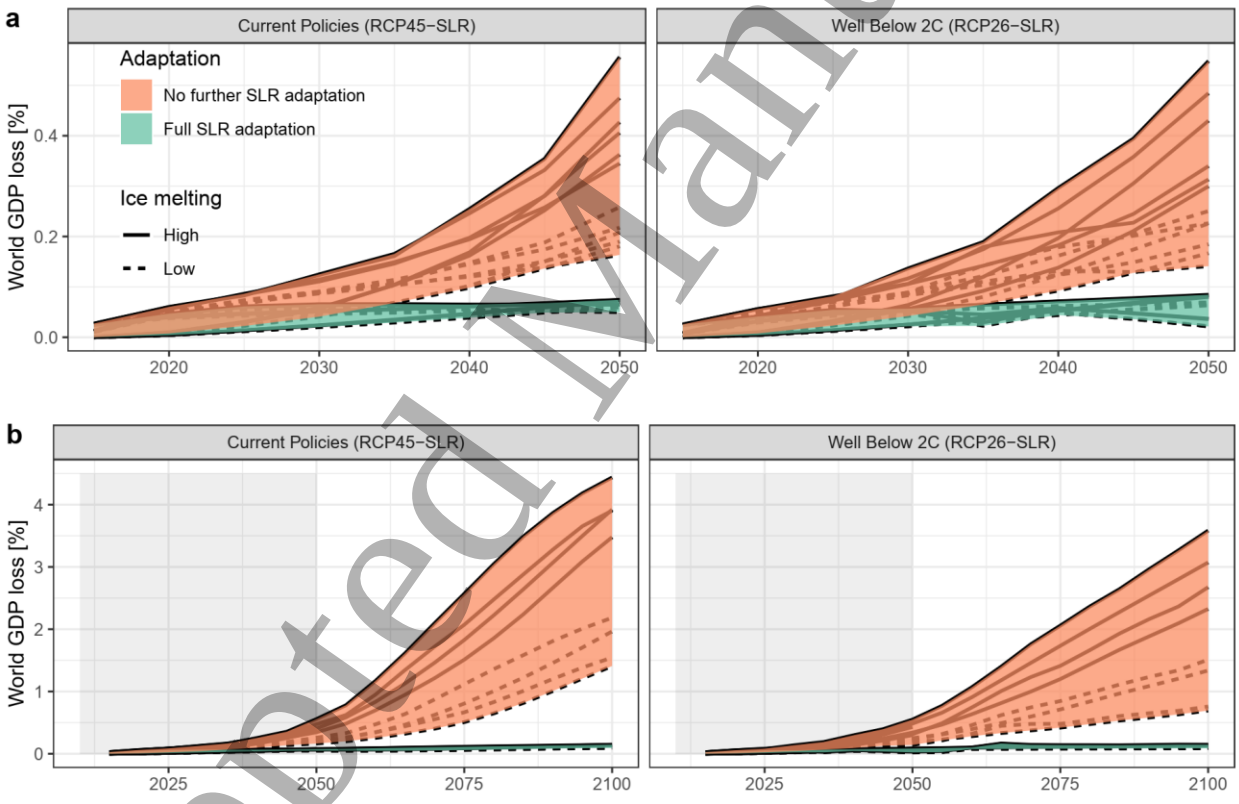


Fig. 2 World GDP loss from coastal flooding due to SLR across climate policy scenarios (RCP45-SLR and RCP26-SLR) and adaptation level until 2050 (top panels, a) and 2100 (bottom panels, b), relative to the respective reference climate policy implementation scenario without coastal flooding impacts (RCP45 and RCP26). The red and green uncertainty ranges account for FAIR, GEM-E3 and WITCH results, high and low ice-melting, and IPSL and MIROC climate projections. High ice-melting is highlighted by plain lines and low ice melting by dashed lines. Note: For the time horizon 2050, all three macroeconomic models have been used, while for 2100 only FAIR and WITCH were used.

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Projected global GDP losses are driven by the removal of available capital, a key productive resource of the economy, due to the expected annual damages by coastal flooding as a result of SLR. Fig. 3 shows that, especially in the short term, all models project that global GDP losses are lower than direct economic costs. In the CGE model GEM-E3, this is because macro-effects are somewhat counterbalancing direct coastal flooding impacts through substitution effects in production processes and via international trade effects. In FAIR and WITCH, this is a direct consequence of the type of production function used. This is a common finding in the literature as described for example in Bosello and De Cian (2014). Towards 2100, and in particular for high ice melting scenarios (panels on the left-hand side), both WITCH and FAIR project larger macroeconomic effects relative to direct impacts. This indicates that large disruptions of capital due to climate change can have an increasing impact on the productive capacity of the economy.

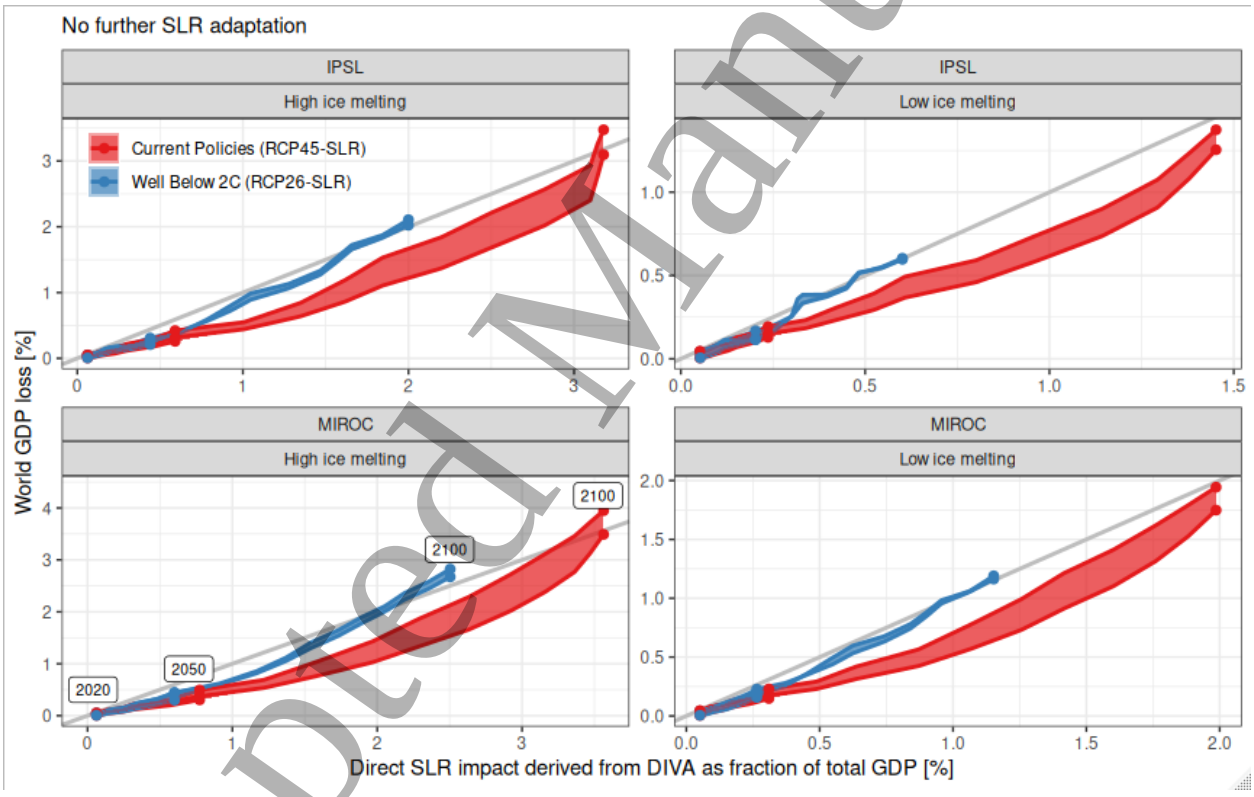


Fig. 3 Direct impacts from coastal flooding due to SLR (x-axis) vs. economy-wide effects (y-axis) from 2020 until 2100 across climate scenarios (RCP45-SLR (red) and RCP26-SLR (blue)) in the case of no further adaptation. World GDP impacts are expressed in relation to the respective reference scenario (RCP45 and RCP26). The red and blue uncertainty ranges represent the bandwidth of the results of our economic models. Panels show the results using impacts computed from two climate models (IPSL: top panels; MIROC: bottom panels) each in combination with high (left panels) and low (right panels) ice-melting. Note: For the time horizon 2050, all three macroeconomic models have been used, while for 2100 only FAIR and WITCH were used. In 2100, 1% direct SLR impact in terms of DIVA GDP is equal to 6.7 trillion USD_{2014}.

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In the well below 2°C scenario RCP26-SLR, macroeconomic impacts relative to direct impacts are higher because capital markets are already affected by mitigation measures, as the low-carbon transformation of the economy is a capital-intensive process. Thus, removing one unit of capital in a capital-intensive economy (i.e. an economy with a high capital-to-GDP ratio) has more detrimental effects and the additional effect of coastal flooding therefore has a relatively stronger indirect impact. While this finding is robust across all participating models, the specific values of the results differ (see Fig. S2 in the Supplementary Material). Moreover, we conducted a sensitivity analysis to clarify the robustness of this result for alternative socioeconomic development assumptions (i.e., running the two policy scenarios in combination with different SSPs). While we find that the pattern of how direct impacts relate to macroeconomic effects for the two policy scenarios (RCP45-SLR and RCP26-SLR) remains the same under alternative SSPs, the magnitude of the direct as well as the indirect impacts, expressed relative to the respective reference scenarios (RCP45 and RCP26), differs. This indicates the significance of socioeconomic assumptions in the assessment of climate costs (Fig. S3 in the Supplementary Material).

3.2. Regional and sectoral effects

Turning to regional effects, Fig. 4 presents the breakdown of the global economy-wide impacts of coastal flooding due to SLR for G20 countries for the cases of high-ice melting without any further adaptation. By 2050 (upper panels in Fig. 4), the highest levels of GDP loss are projected for China (0.8-0.9% under RCP26-SLR and 0.9-1.0% under RCP45-SLR) and India (0.5-0.6% under both scenarios), followed by Canada (0.3-0.4% under both scenarios) and Indonesia (0.2-0.3% under both scenarios). These are also the countries with the highest direct impacts according to DIVA model projections.

By 2100, the scale of economy-wide effects in G20 countries changes by an order of magnitude. China remains the G20 country with the highest projected GDP loss, which is now a factor of ten higher than it was in 2050 (9-10% under RCP26-SLR and 11-12% under RCP45-SLR). Other regions with high GDP losses by 2100 in the RCP45-SLR scenario are Japan (7-8%) and Europe (4-6%). However, this changes once stronger mitigation action is undertaken (RCP2.6-SLR), in which case Europe and Japan have relatively low GDP losses (see middle, right-hand panel in Fig. 4). Comparing the economic impacts between RCP45-SLR and RCP26-SLR indicates that strong decarbonization by the end of the century is highly effective in reducing potential future impacts, also at the level of individual G20 countries. Moreover, the lower panels in Fig. 4 indicate the effectiveness of comprehensive adaptation to coastal flooding due to SLR.

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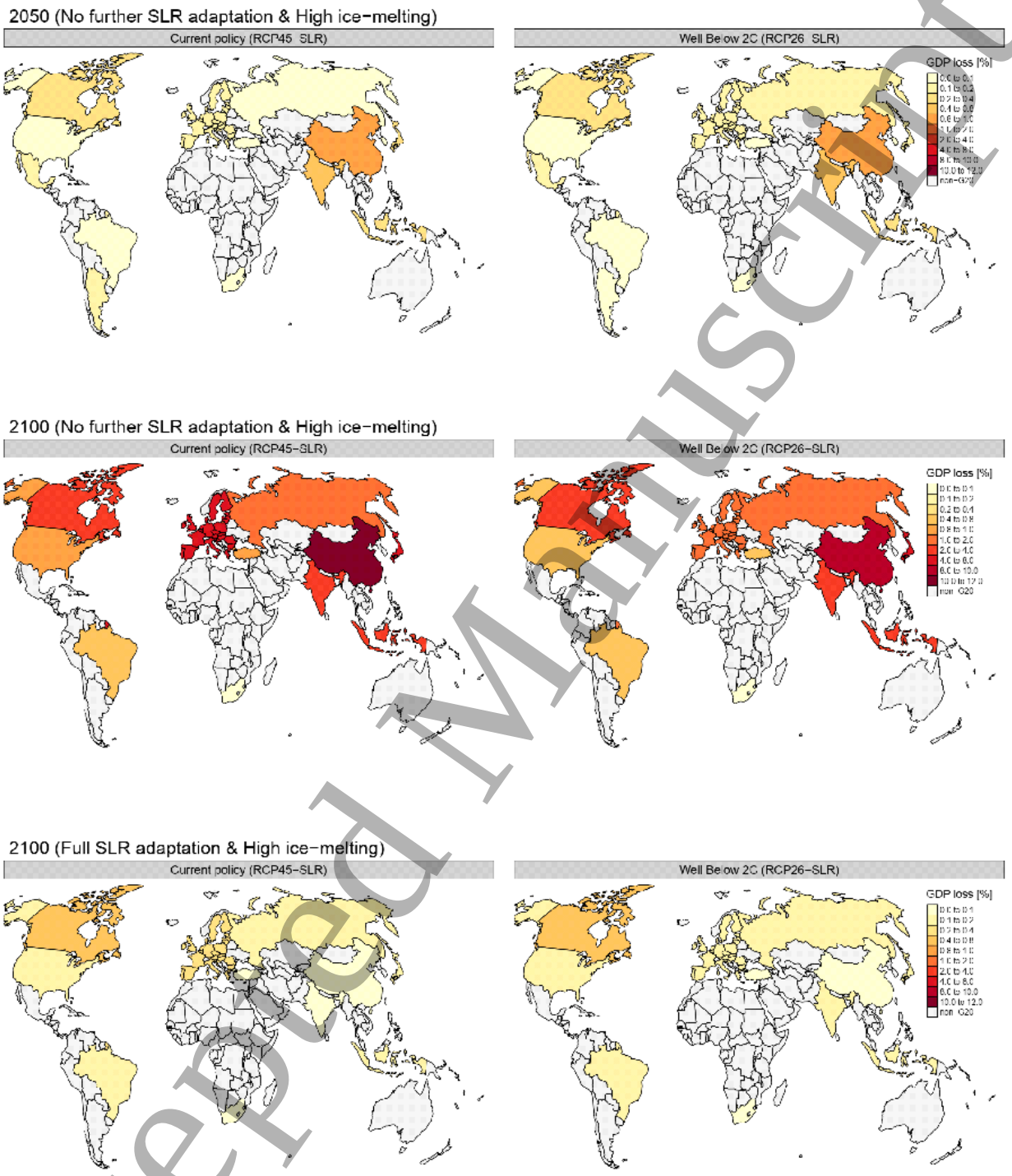


Fig. 4 GDP impacts due to coastal flooding in G20 countries for 2050 and 2100 across climate policy scenarios (RCP45-SLR and RCP26-SLR) in the cases of full and no further adaptation, and high ice-melting. GDP losses are expressed as an average of the different macroeconomic models, depending on regional detail, and are presented relative to the respective reference scenario (RCP45 and RCP26). Note:

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The number of macroeconomic models used for this visualization depends on the regional detail and time horizon of the respective model. For the time horizon 2050 all three macroeconomic models have been used, while for 2100 only FAIR and WITCH were used. Some G20 countries are missing from the map, since the regional aggregations in the models do not allow for a country-level assessment.

Overall, regional GDP impacts go in line with the regional distribution of direct impacts provided by DIVA. In particular, we find that GDP impacts are analogous to the share of direct damages to total capital stock of the economy, thus indicating that higher shares of destroyed capital stock result in more significant macroeconomic impacts.

A further key driver of the GDP effects is the regional allocation of mitigation efforts and SLR damages. We find that countries with high mitigation efforts (i.e. the biggest emitters, most notably China and India) coincide with the countries with the higher damages as a percentage of GDP. As these countries are also among the largest economies, this regional coincidence of mitigation efforts and SLR damages can have an important macroeconomic effect. In certain cases (i.e., specific regions, climatic or macroeconomic models), GDP changes due to coastal flooding impacts (RCP26-SLR and RCP45-SLR relative to RCP26 and RCP45, respectively), are higher in the RCP26-SLR scenario than in the RCP45-SLR one, despite that the level of direct damages is higher in the latter scenario (Fig. 5 and Fig. S5 and S6 in the Supplementary Material). This is mainly attributed to the disturbances of mitigation efforts to the overall economy and in particular to the increased capital requirements for the low-carbon transition. As a result of the ambitious mitigation efforts, GDP levels in the RCP2.6 scenario are slightly lower than in the RCP4.5 scenario. In particular, in GEM-E3 model we find that the economy of the RCP2.6 scenario becomes more capital intensive and thus the destruction of one unit of capital due to unavoided damages has a stronger effect on GDP. In FAIR and WITCH, mitigation actually leads to less productive capital and a further loss of productive capital due to sea level rise impacts, and therefore has a stronger impact on GDP. The strength of this effect has been analyzed in a separate artificial well below 2°C scenario run without mitigation costs using the FAIR model. This showed that the same level of direct damages has an approximately 5% larger global GDP impact in 2050 and 2100 when interaction with mitigation costs are accounted for, with higher differences for countries with higher mitigation costs (see Fig. S4 in the Supplementary Material). In the longer term up to 2100, the difference between the two climatic scenarios is amplified and thus results are generally as expected: higher impact ranges for RCP45-SLR than for RCP26-SLR.

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Fig. 5 Regional GDP impacts of coastal flooding due to SLR across climatic scenarios (RCP45-SLR and RCP26-SLR) for all macroeconomic and climate models, relative to the respective reference scenarios (RCP45 and RCP26). Lower values in the line range show the "full adaptation" case, higher values show the "no further adaptation" case. The shapes represent the economic models. Not all models are displayed in all panels, GEM-E3 provides information only for 2050 and WITCH does not provide information for Russia and Canada.

The GEM-E3 model further allows for a sectoral analysis of the impacts of coastal flooding and adaptation (Fig. 6). Although capital is assumed to be mobile across all sectors within a region in the GEM-E3 model, the impact of capital destruction from coastal flooding as a result of SLR differs by sector. This is mainly due to the different production structures of each sector, and in particular due to different levels of capital

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intensity and differences in the ability to substitute across production factors (see Table S11 of the SM for respective details). Thus, the result of different production structures is that changes in capital availability, hence the price of capital, affect each sector with a different intensity. Furthermore, the destruction of capital stock due to climate impacts implies a lower overall capital stock and thus lower investment requirements for the maintenance of capital. This lower demand for investments is another driver of changes in sectoral production, as lower demand in sectors that deliver investment goods reduced their overall production levels (see Table S11 of the SM for respective details).

Our results indicate that if no further adaptation measures are undertaken, 'construction', 'agriculture' and 'energy intensive industries' are the three hardest hit economic sectors on a global level, while the services sector is less affected due to the high elasticity of substitution and the respective demand for delivery to investments. The construction sector is also key in delivering investment goods and thus a lower investment demand for the maintenance of existing capital stock results in production losses. On the other hand, the agriculture sector is characterized by a capital intensive production process with low substitutability of capital and thus lower capital availability increases the cost of production and results in production losses. This holds for both climate policy scenarios, RCP26-SLR and RCP45-SLR, although certain differences may be noted across the two, depending on the relevant importance of a sector in each respective economy (e.g., bioenergy in RCP2.6 is more affected than in RCP4.5 as it becomes larger). On the contrary, the implementation of adaptation measures against coastal flooding (RCP45-SLR_adapt and RCP26-SLR_adapt) has positive effects on the 'construction' sector, which instead of being among those hit the hardest, is in this case among the sectors with the lowest negative impacts. This is mainly driven by the fact that the 'construction' sector is key to delivering services for adaptation and substantially expands its output level due to the high physical protection investments in the full adaptation scenario. In connection to the sectoral analysis, GEM-E3 further allows for an assessment of employment effects. The increased public demand for labor-intensive construction services initially raises demand for labor. However, coastal flood damages to the capital stock are translating into negative effects to the overall economic activity, which in turn leads to a slight reduction in total employment levels, despite the increase in construction activities for adaptation measures.

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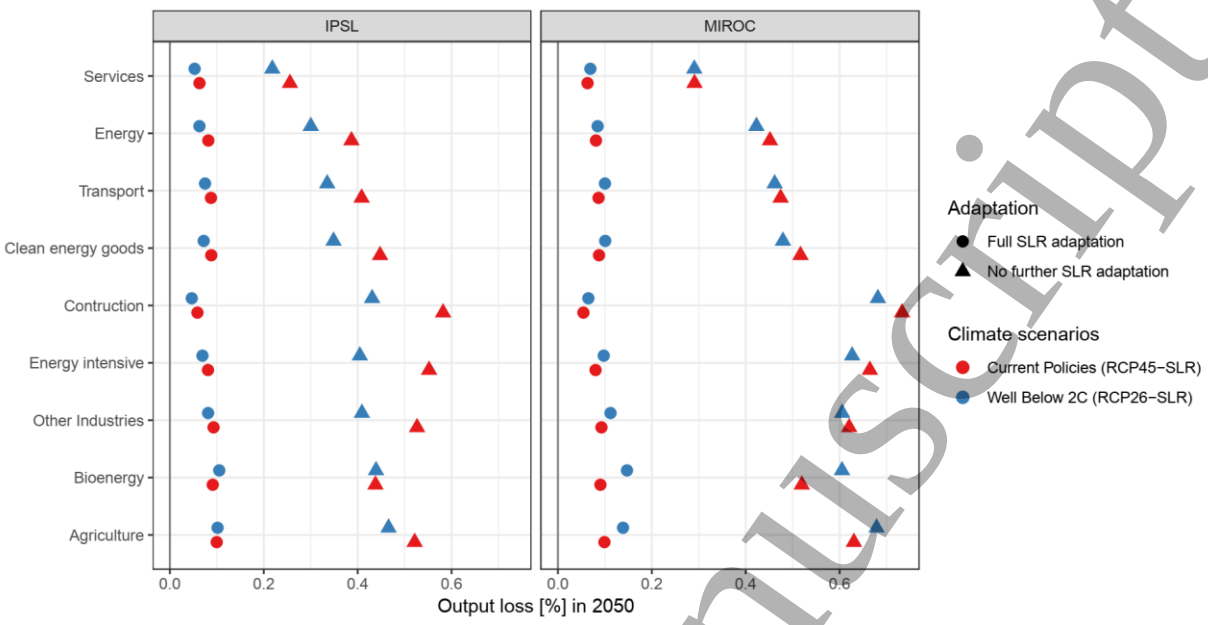


Fig. 6 Sectoral output effects triggered by coastal flooding impacts due to SLR across climate policy scenarios (RCP45-SLR and RCP26-SLR) with and without further adaptation, relative to the respective c reference scenarios (RCP45 and RCP26).

4. Discussion and conclusions

In this paper, we carried out a multi-model assessment of the macroeconomic impacts of coastal flooding due to SLR and the respective macroeconomic implications of adaptation measures for a RCP2.6 (equivalent to a 'well below 2°C') world compared to a RCP4.5 (or 'current policies') scenario. We combined our analysis, focusing on the global level, as well as on individual G20 countries, with corresponding stylized RCP2.6 and RCP4.5 mitigation efforts in order to understand the implications of interactions across mitigation, adaptation and SLR on a macroeconomic level. Overall, our multi-model analysis indicates that aggregate macroeconomic impacts are robust across the different model types, from simple optimal growth models (FAIR and WITCH) to more complex CGE models (GEM-E3).

Our results indicate that until the middle of this century, differences in macroeconomic impacts between the two climatic scenarios are small, but increase substantially towards the end of the century. Moreover, direct impacts can be partially absorbed by substitution effects in production processes and via international trade effects until 2050, resulting in GDP losses that are lower than direct damages. By 2100 however, we find that this effect is turned around and economy-wide effects become even larger than direct impacts. Within the G20, our results indicate that China, India and Canada will experience the

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highest macroeconomic impacts, with the two first large economies undertaking the highest mitigation efforts in a cost-efficient global climate action. In addition, we find that strengthening adaptation will be crucial for limiting direct as well as economy-wide impacts from coastal flooding already before 2050, but especially after mid-century. Particularly, the construction sector and other energy and capital-intensive industries will benefit directly and indirectly from fostering adaptation activities. It is important to note that in this study we only evaluate the performance of adaptation measures in terms of direct and indirect economic effects on GDP. It would be a fruitful area for future research to also consider further reaching co-benefits (such as triggering entrepreneurial activities and productive investments by lowering the imminent threat of losses from disasters) and co-costs (e.g. in the agricultural sector due to waterlogging induced by flood embankments) of adaptation (Surminski and Tanner 2016).

In contrast to the majority of the existing literature (e.g., Ciscar et al. 2011, 2012; Hinkel et al. 2013; OECD 2015; Diaz and Moore 2017), we implement the impacts from coastal flooding due to SLR in a 'well below 2°C' world, on top of the climate mitigation policies that lead to a reduction in GHG emissions and thus to the respective RCP2.6 scenarios. We find that the disturbances of mitigation efforts to the overall economy may in some regions lead to a counterintuitive result, namely to GDP losses that are higher in RCP26-SLR than in RCP45-SLR, despite that the direct coastal damages are higher in the latter scenario. This can be seen for certain model regions and only at the early period until 2050 when mitigation efforts are particularly high. As GDP is already reduced due to the mitigation effort, the removal of primary resources from the economy has a more noticeable effect when measured in relative terms of GDP. Even so, GDP losses in RCP26-SLR are bigger, even in absolute terms. For the CGE model GEM-E3, the explanation is that decarbonization efforts lead to a more capital-intensive economy in the RCP26 scenario, and thus the destruction of capital has a stronger effect on GDP. In addition, the rate of return of capital is higher in the RCP26 reference scenario, thus a reduction of one unit of capital corresponds to more loss of value and therefore bigger GDP losses. For the IAMs, FAIR and WITCH, mitigation actually leads to less productive capital and a further loss of productive capital due to sea level rise impacts, and therefore has a stronger impact on GDP. An important caveat to this result is that we do not take into account climate change impacts other than those resulting from coastal flooding due to SLR. If these other damages are higher in RCP45 than in RCP26, this would lead to more destruction of capital in RCP45, which in turn could dampen or reverse this effect. In the period after 2050 until the end of the century GDP losses are, as one would expect, for all regions higher in RCP45-SLR than in RCP26-SLR.

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It is important to note that all three macroeconomic models employed in this study are based on conventional neoclassical modeling techniques that assume optimality in the baseline. Any disturbance (e.g., a carbon tax) will therefore lead to negative macroeconomic effects, unless it counterbalances larger distortions that exist in the baseline (e.g., when recycling carbon taxes removes other taxes). This is especially important for assessing the regional macroeconomic impacts and in particular for the interpretation of our result that in some regions the medium-term macroeconomic impacts can be higher with higher mitigation efforts. This effect is particularly seen in relatively poor and emission-intensive regions (i.e., emissions as share of GDP) such as India and Russia, respectively, which further highlights the implications of mitigation effort-sharing decisions. This also implies that for the RCP26 scenario, the macroeconomic impacts of SLR partly depend on the regional distribution of mitigation efforts: if instead of a global carbon tax, a more equitable effort sharing scheme was implemented, leading to more equal mitigation costs across regions, the impacts of coastal flooding could also be alleviated in certain regions. For further multi-model assessment exercises we therefore suggest involving alternative, heterodox macroeconomic models in the portfolio and to apply different effort-sharing approaches. For example, post-Keynesian models that allow for initial capacity utilization rates lower than 1 or stock-flow consistent macroeconomic models that add the financial sector to 'real' economic activities, may both come to different results, since they allow for relaxing the capital scarcity assumption via intensifying the utilization of existing capacities or increasing debt, respectively). Moreover, a risk-based assessment capable of identifying and quantifying low-probability, high-impact events (see e.g., Hochrainer-Stigler et al. 2014) as a complement to this modeling exercise, which is based on expected values, could be another worthwhile addition to the set of models used.

As explained above, our finding that macroeconomic impacts under RCP2.6 can be higher than RCP4.5 due to distortion effects of mitigation may not be robust if other climate change impacts are taken into account. Hence, looking into further climate change impact sectors (e.g. health, agriculture, riverine flooding etc.) is another important extension for future multi-model assessment research. Here, an additional challenge will be to identify approaches that allow the macroeconomic model integration of direct impact estimates and adaptation costs in other sectors than coastal impacts. While we shocked total regional capital stocks in the macroeconomic models with the direct impacts from coastal flooding due to SLR as estimated by DIVA, the integration of willingness to pay estimates for public health damages, for example, will require quite different modeling approaches. Moreover, it would be very interesting to move the analysis further on a lower geographic level, with more details in terms of vulnerable economic activities and infrastructure that are potentially affected differently by SLR.

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Finally, a sensitivity analysis has shown that varying socioeconomic development assumptions (population and GDP growth rates according to different SSPs) has an impact on potential economic losses due to coastal flooding as indicated both by differences in direct and indirect impacts. Since the differences in direct biophysical model results, which in turn propagate into macroeconomic effects, are to a certain extent also driven by varying urbanization rates between levels assumed in the SSPs, we stress that uncontrolled urban development could substantially increase climate-related risk and hence jeopardize sustainable development. This finding is supported by earlier research (e.g. Merkens et al. 2016), which finds that regions where high coastal population growth and development is expected will face an increased exposure to coastal flooding. Moreover, the world is already committed to long-term SLR in the range of 1.2 to 2.2 meter under present levels of global warming (Hinkel et al. 2018) and even if global warming can be limited to well below 2°C by the end of the century, natural climate variability continues playing a role. Consequently, risk sensitized and climate proof (adaptation) investment in urban infrastructure is a crucial complement to ambitious mitigation efforts, in order not to increase risks related to natural hazards, by for example, situating infrastructure in flood prone areas, as was experienced in the past (The Economist Intelligence Unit 2016; Hochrainer-Stigler et al. 2017). This is particularly true for hot-spot countries, such as China, India and Japan, which we identified in this modeling exercise. Hence, regarding concrete policy suggestions, we put forward the idea of fostering climate-related-risk screening in investment appraisals, particularly in the identified hot-spot countries. While these results indicate that exposure as a driver of climate-related risks and related economic impacts has to be taken seriously to prevent jeopardizing the gains from ambitious climate change mitigation efforts, we do not want to give the impression that proper risk-sensitized investment efforts and adequate adaptation measures outweigh the role of climate change mitigation. This is due to the likely emergence of non-economic losses and damages that may arise after socioeconomic (soft) and physical (hard) limits to adaptation have been reached, and of potentially systemic risk that can only be prevented by substantial mitigation efforts. We therefore see our results as a strong signal to the international policy scene to strengthen the ambitions for climate change mitigation, but to do so by synergistically approaching climate change adaptation and risk-sensitizing socioeconomic development.

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Author contributions

The study was designed by T.S. with major contributions by L.D., Z.V., A.H. and J.M.. T.S., L.D., Z.V. and A.H. took the lead in interpreting the results and authoring the paper. J.H., V.B., K.F., D.v.V., D.L. and J.M. assisted the writing of the paper. L.D., Z.V., A.H., J.H., V.B., K.F., D.v.V. and D.L. developed and ran the models. L.D., assisted by T.S., Z.V. and A.H., developed the visualizations for the manuscript. T.S. edited the paper.

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