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Risks on global financial stability induced by climate change: the case of flood risks.

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Abstract There is increasing concern among financial regulators that changes in the distribution and frequency of extreme weather events induced by climate change could pose a threat to global financial stability. We assess this risk, for the case of floods, by developing a simple model of the propagation of climate-induced shocks through financial networks. We show that the magnitude of global risks is determined by the interplay between the exposure of countries to climate-related natural hazards and their financial leverage. Climate change induces a shift in the distribution of impacts towards high-income countries and thus larger amplification of impacts as the financial sectors of high-income countries are more leveraged. Conversely, high-income countries are more exposed to financial shocks. In high-end climate scenarios, this could lead to the emergence of systemic risk as total impacts become commensurate with the capital of the banking sectors of countries that are hubs of the global financial network. Adaptation policy, or the lack thereof, appears to be one of the key risk drivers as it determines the future exposure of high-income coun-

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tries. This implies in particular that the avoided costs in terms of financial stability should be weighted in as benefits of adaptation policy.

Keywords Financial Stability · Climate Impacts · Flood Risks

1 Introduction

There is increasing concern among financial regulators that changes in the frequency and intensity of extreme weather events induced by climate change could pose a threat to global financial stability in the medium to long term [1,2]. This concern partly hinges on the precedent of the 2007-2008 financial crisis, which saw a massive amplification of losses through financial interdependencies. Estimates of direct losses of the financial system on the US subprime mortgage market amount to 500 billion USD [3]. Yet, the subprime crisis eventually triggered losses one order of magnitude greater within the financial system and almost two orders of magnitude greater for the global economy [4,5]. In this paper, we seek to provide an estimate of the financial risks induced by climate change, which account for the amplification of direct impacts through global financial interlinkages. The paper focuses more specifically on global coastal and river flood risks. Coastal floods primarily occur due to storm surges whose magnitude and impacts are expected to increase due to sea-level rise [6]. The magnitude and impacts of riverine flooding is expected to increase through climate-induced changes in precipitations [7]. Our analysis is not comprehensive as far as climate impact domains are concerned but it covers, among climate-related natural hazards on which the future impacts of climate change are likely or very likely [8], a large share of direct impacts on physical assets (see discussion section).

Scientific evidence about the magnitude and the drivers of climate-induced financial risks is scarce. The existing literature mainly focuses on risks induced by mitigation, also referred to as transition risks [9,10]. The interplay between physical risks and financial stability has mainly been approached from the macro-economic perspective [11–14]. In particular, Dietz et al. [11] propose a top-down measure of climate value at risk using GDP projections derived from the DICE integrated assessment model [15]. This approach fails, in particular, to account for the actual impact of shocks on the balance sheet of financial actors and for dynamics within the financial system. Furthermore, the value at risk derived in [11] captures the risk related to the uncertainty about the DICE model's parameters (productivity growth, climate sensitivity and climate damages) rather than that related to the distribution of climate impacts.

Against this background, this paper aims to provide a data-driven assessment of climate financial risks. In this perspective, we have to address three major conceptual and empirical issues: (i) quantify the impacts of flood events on financial assets, (ii) estimate the allocation of the induced losses among financial actors and their propagation across financial networks, and (iii) determine relevant measures of the impacts attributable to climate change.

With respect to the first issue, existing results on the economic impacts of natural hazards are partly ambiguous. Although natural hazards have a clear short-term negative impact on supply chains and financial stability [16, 17], their medium and long-term impacts on growth differ across types of disasters, sectors and economies [18, 19]. Yet, one fact is unambiguous. If a natural disaster induces the destruction of physical assets, the corresponding losses must be accounted for on the balance sheet of some economic actors and thus affect the value of their liabilities. This is the starting point of our analysis. We focus on floods, which have a clear impact on physical assets, and model the allocation of these impacts among domestic institutional sectors, i.e. private sector, public sector, and financial sector (distinguishing between insurance and the rest of the financial sector).

The second issue is that the analysis of financial contagion requires detailed data on financial interdependencies. In this respect, we build on a new dataset of cross-border exposures [20], which allows us to reconstruct the global financial network at the level of institutional sectors. We then use the debtrank algorithm [21] to estimate the propagation and the amplification of shocks through this network.

The third issue is that an assessment of climate-induced financial risks must address the attribution question [22], i.e., one must quantify the part of the risk actually induced by climate change. We address this issue by comparing the risk prevailing under the historical distribution of damages with that obtained for a range of future climate and socio-economic scenarios for time-horizons 2030, 2050, 2080. This approach requires quantitative projections of the impacts of climate change on the distribution of extreme events. To the best of our knowledge, such projections are available on a global level only for the impact domains we consider, i.e. river and coastal flood risks [6, 7, 23, 24].

Our analysis first allows us to identify the major determinants of climate-induced financial risks at the country-level: the evolution of the distribution of hazards, the financial leverage, i.e. the ratio between the global financial exposure of the financial sector and its capital, and the adaptation policy [25]. Second, we identify which countries are the major sources of climate-induced risks for the global financial system. Third, we use financial risk metrics to track the evolution of risk for a range of climate scenarios. We find that a high-end climate scenario, without adaptation, could indeed lead to systemic financial risk as it shifts the distribution of impacts towards high-income countries and makes the magnitude of impacts commensurate with the capital of their financial sectors. Following the approach by Ciscar et al. [26, 27], our analysis is performed considering future climate impacts apply to the current financial network and thus discard potential changes in its structure.

Approaching the issue of the economic impacts of climate change from the perspective of induced financial risks also allows us to address some of the recurring critiques to integrated assessment models. First, a financial risk perspective puts the emphasis on the tail of the distribution of damages rather than on its expected value [28]. Second, building a bottom-up assessment of risks from the actual distribution of damages allows to dispense from arbi-

trary assumptions about damage functions [29]. Third, focusing on measures of future risks, which can be expressed in terms of future GDP, allows us to overcome the debate about the appropriate discount rate to be used. [30,31].

Methods

We consider two polar scenarios for socioeconomic and climate dynamics¹. First, a scenario with rapid and emission intensive economic growth, i.e. combining SSP 5 and RCP 8.5 [32,33]. We refer to this scenario as "high-impact" as it combines high hazard rates, because of climate-induced changes in the distribution of extreme events, and high exposure, because of the growth in value of economic assets. Second, a scenario with low-carbon and sustainable economic growth, i.e. combining SSP 1 and RCP 2.6. We refer to this scenario as "low-impact" as it combines low hazard rates and balanced economic growth. For both scenarios, we consider two variants: i) *without adaptation*, in which protection structures remain constant and thus protection level declines over time ; and ii) *with adaptation*, in which flood protection structures are upgraded to maintain constant protection level (see detailed methods below for details).

Our analysis focuses on a set of 109 countries for which data about bilateral financial exposures are available (see subsection 2.3.1 in detailed methods below and subsection 1.1.1.in the SI). This set of countries accounts for 95 % of global GDP and can thus be considered as representative of the current global economy. For each country in the sample and for each scenario, we obtain estimates of the distribution of direct impacts, i.e. the yearly value of damages on physical capital, at the horizons 2030, 2050 and 2080, measured as a share of world GDP at the corresponding date. The estimates for coastal flood risk are derived by aggregating risks assessed at the level of about 12,000 coastline segments with the DIVA model by Hinkel et al. [6] (see detailed methods 2.2 below). River flood risk is simulated using the cascade of models of the GLOFRIS framework[24,34,7], combining inundation maps (30 x 30), land-use maps and depth-damage functions (see detailed methods 2.1 below).

Using country-level data on insurance coverage and fiscal position by country, we develop a simple linear model of the allocation of direct damages among the private sector, the public sector and the insurance sector (see Subsection 2.3 in detailed methods below).

Each of the institutional sectors that receives a share of the direct impacts is linked to the financial sector, which is the core focus of our analysis. First and foremost, the financial sector is the key provider of credit to the public and private sectors. Second, the insurance and financial sectors are strongly interlinked via ownership links (financial conglomerates), credit risk transfer instruments and mutual asset exposure [35]. To estimate the domestic propagation of shocks through the credit channel, we follow a standard approach

¹ This section gives a general overview of methods. Detailed Material and Methods are provided below.

used in the literature on systemic risk [21,36]. We assume that the default probability of the counterparties of the financial sector increases proportionally to the share of their capital eroded by the initial shock. The expected value of the assets of the financial sector decreases accordingly (see subsection 2.3.2 in detailed methods below). We follow a similar approach to estimate the propagation of shocks from the insurance sector and assume that it transmits to the financial sector a share of the shocks that it faces proportional to the erosion of its capital buffer (see also subsection 2.3.2 in detailed methods below). Domestic impact on the financial sector then depends on: (i) the direct impact of climate shocks on the public, private and insurance sectors; (ii) the financial leverage of these sectors; and (iii) the exposure of the financial sector, i.e. the sectoral composition of its balance sheet. Overall, impacts transmitted to the domestic financial sector amount to 35 to 45 % of total domestic impacts (see subsection 2.3 in detailed methods below, Figure 3 as well as Table 7 and Figure 8 in the supplementary material).

Large correlated shocks on a set of financial institutions, such as the ones induced by tail climate impact events, can lead to systemic risks if they ignite a sequence of reassessments by financial institutions of the risk of their counterparties, notably these in the financial sector, which have been directly or indirectly affected by the initial shocks [37]. The aftermath of Hurricane Katrina illustrates the potential unfolding of events. First, Massa et al. [38] show that the liquidations of bond holdings by property and reinsurance companies created a persistent negative price impact on bond prices. Second, Schuwer et al. [39] emphasises that the uninsured part of damages to property led to unexpected losses for banks and that major rating agencies announced a close monitoring of affected banks. Further propagation, which didn't materialize in the case of Katrina, would occur if the loss to capital ratio were sufficient to trigger massive credit downgrades. In order to model the amplification of risk induced by this process through global financial interlinkages, we use the debtrank algorithm [21]. When a climate shock hits the financial sector of a country, its capital is eroded. This erosion leads to a decrease of the value of its liabilities towards the financial sectors of connected countries, hence eroding their capital and further propagating the shocks via their liabilities (see subsection 2.3.4 in detailed methods for details). In order to quantify this effect, we build on a new dataset [20] to reconstruct the global network of bilateral financial exposures at the institutional sector level (see subsection 2.3.4 in detailed methods below). This first allows us to estimate the transmission of direct damages from the public and private sectors of each country to their international creditors. More importantly, this allows us to simulate and estimate the propagation and the amplification of shocks through international exposures between financial sectors, i.e. through the global financial network. In this framework, the total impact induced by a climate shock depends on the exposure (assets potentially affected by the hazards) and vulnerability (the conditions that determine the losses for a given level of hazard and exposure) of the impacted country on the one hand and on its leverage and centrality in the global financial network on the other hand (see Figure 1 and Figure 9

in the SI). As illustrated in Figure 1, high-income countries are clearly more central and more financially leveraged. Notably, the financial sectors of high-income European countries have a leverage ratio that is an order of magnitude greater than that of low and middle income countries.

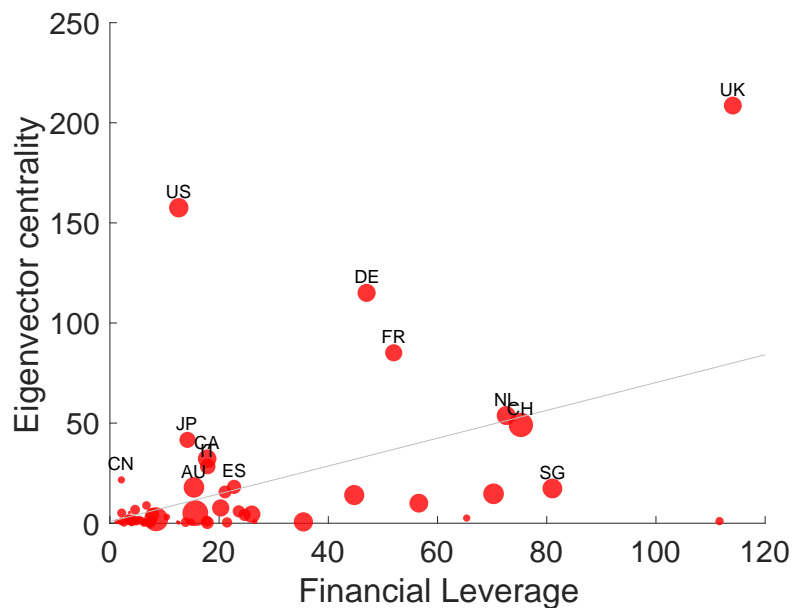


Fig. 1 Relation between (i) a country financial leverage measured as assets outstanding of the country's financial sector on foreign financial sectors in percentage of GDP and eigenvector centrality of the country in the network of bilateral exposures between financial sectors. ISO 3166-2 Country codes are indicated for most central countries and detailed in subsection A1 of the SI. Node size is proportional to GDP per capita.

2 Results

Using this model of the propagation of climate-induced shocks in financial networks, we perform two series of analysis. On the one hand, we assess the risk induced by individual countries by measuring the global impact induced by

a shock occurring in the country. On the other hand, we measure the exposure of each country’s financial system to global climate risks through a series of simulations in which we draw the realizations of global damages and simulate propagation of shocks through financial interlinkages (see subsection 2.3.4 in detailed methods below). In both cases, the shock in a given country is drawn from a distribution of yearly damages).

Our assessment of country-induced risk is based on the measure of the total loss of capital for the private and financial sectors induced by the realization of a 95th percentile event (in terms of yearly damage) in the country and its global propagation. This impact can be interpreted as the value at risk induced by a given country on the global financial system. Table 1 reports the impacts induced by the most risky countries from this perspective for the historical and high-impact scenarios. Results for coastal and river floods are qualitatively similar. Under the historical distribution of events, large low and middle-income countries, notably Brazil, China and India, are the major sources of risk. In the future scenarios with adaptation, these large low and middle income countries remain the major sources of risk. The increase in risk is sizeable (in the order of 50 % on average, excluding the increase in river flood risk in India, which is a clear outlier) but commensurate with present risks. In a scenario without adaptation, there is a radical change of regime, most notably for coastal floods. Both the sources and the magnitude of risks change drastically. High-income countries, notably West European countries, become major sources of risk from coastal flooding. The global level of risk increases by up to an order of magnitude. Results for the low impact scenario and for time-horizons 2030 and 2050 are qualitatively similar although of lesser magnitude, see subsections 1.2 and 1.3 of the SI

Historical scenario				SSP5 2080 with adaptation				SSP5 2080 without adaptation			
Coastal		River		Coastal		River		Coastal		River	
Country	Impact	Country	Impact	Country	Impact	Country	Impact	Country	Impact	Country	Impact
CN	16.5	BR	14.9	CN	21.5	IN	66	UK	244.7	CN	101.6
UK	8.6	IN	14.1	UK	10.5	BR	18.9	CN	196.2	IN	81.2
DE	5.1	CN	6.7	US	6.5	CN	12.8	JP	130.5	BR	26.9
US	2.8	ID	3.8	DE	5.7	EG	8.6	US	86.3	US	14.5
FR	2.5	EG	2.9	FR	3	BD	8.4	DE	61.8	EG	13.2
CA	1.2	MX	2.8	IT	2.8	ID	8	FR	61.1	CA	12.9
IT	1.1	PH	2.2	NO	2.6	TH	6.8	CA	37.8	TH	12.5
DK	1.1	AR	2.6	EG	2.5	KH	5.1	SG	33.2	AU	10.5
NO	0.7	TH	1.8	IN	2.3	PH	3.8	IT	27.8	ID	8.6
IN	0.7	IQ	1.7	CA	2.2	MX	3.3	DK	27.3	BD	8.4

Table 1 Top 10 countries in terms of total impact induced by coastal and river floods in the historical and high-impact scenarios. Total impact corresponds to the sum of the domestic impact on private and financial sectors and of its global propagation through financial networks. Impact is measured in basis-point of world GDP. Countries are designated using ISO 3166-2 code (see subsection 1.1.1. in SI).

Figure 2 highlights the drivers of this major shift in climate-induced financial risks. Without adaptation, high-income countries as well as certain countries in Africa and East Asia become much more exposed to climate impacts. High income countries also are much more financially leveraged and much more central in the global financial network (see Figure 1). Therefore,

the financial amplification of risk, i.e. the ratio between total impacts induced by financial propagation and the direct climate impacts in the source country, is much higher in this scenario. This leads to the major increase in the magnitude of global risks observed. In a nutshell, climate risk has turned into a financial risk.

Note that the propagation of risks is related to the specific features of financial institutions, notably their leverage and their role as financial intermediaries. Accordingly, the relevant propagation network is that of bilateral exposures between financial institutions rather than the broader network of financial exposures between countries. The major differences between high-income countries on the one hand and that of low and middle income countries on the other hand, is thus explained by the much larger relative size of the financial sector for the former group of countries. Also note that large holdings of foreign assets by governments or central banks, e.g. in China, are not a source of financial propagation in our setting.

The second part of our analysis focuses on the risk faced by the financial system of each country through both its domestic and global exposure to climate impacts. In order to perform this analysis, we run a series of Monte-Carlo simulations in which the realizations of direct climate impact are drawn independently in each country and then propagate through the global financial network (see subsection 2.3.4 in detailed methods below). We focus on the resulting distribution of losses for each country and for the global financial system.

We find that the level of adaptation is the major determinant of the magnitude of the increase in risk. For example, at the horizon 2080, the mean value of global risk would amount to 1.13% of global GDP with adaptation and to 7.1% of global GDP without adaptation. These correspond respectively to a 50 % and a 10-fold increase with respect to the mean present risk, which amounts to 0.76% of global GDP. More broadly, we observe a monotonic increase in risks with the stringency of the climate scenario considered, the horizon, and the presence or the lack of adaptation policy. The increase is consistent across all risk-measures. In relative terms, the increase is larger for the lower percentile of the distribution and up to the 70th percentile (see Figures 10 To 12 and Table 12 in SI)

Figure 3 highlights the structure of risks for the high-impact scenario with adaptation (that is representative in this respect). On average, the insurance sector accounts for 8%, the governmental sector for 13% and the private sector for 24% of the global risk while domestic and global propagation to the financial sector account respectively for 16% and 39% of the risk. Overall, financial interlinkages amplify the risk by a factor of 2, in line with analyses of financial amplification mechanisms in other contexts [21,9].

In order to assess country-specific risk levels as well as the possibility of occurrence of a systemic event, we compare climate risk faced by a country's financial system to the value of its capital/equity. The results of this analysis are reported in Figure 4 for the high-impact scenario with adaptation. We consider as a measure of risk the conditional value at risk at the 95th

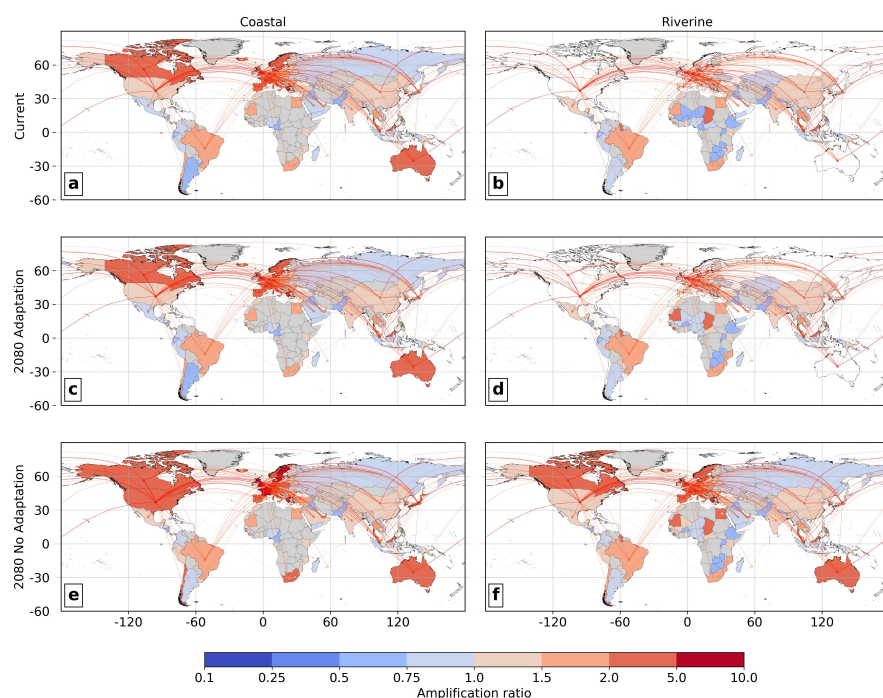


Fig. 2 Heatmap of country-induced financial amplification of climate damages. Each country is colored according to its financial amplification ratio, i.e. the ratio between the total impacts induced by a *95th* percentile event in the country and the corresponding domestic impacts. Results are reported for coastal/river floods in the historical scenario (panels a/b), the high-impact scenario with adaptation (panels c/d) and the high-impact scenario without adaptation (panels e/f). The map also displays the network of mutual exposure between financial sectors. A link represents an exposure of at least 1 million US\$ between the financial sectors of the corresponding countries. The map underlines in particular the close relationship between financial amplification ratio and centrality in financial network.

percentile, that is the expected loss conditional on the realization of a *95th* percentile event at the global scale. Our analysis distinguishes domestic and global impacts, which correspond respectively to domestic and global climate damages. It thus highlights how differences in the international financial position of countries affect the structure of the risks they face. A first set of countries whose financial sectors play a limited role in global financial intermediation, including India and China, mostly face domestic impacts. The majority of countries are mostly exposed to global impacts, i.e. these induced by global financial propagation of shocks. They face a substantial risk, which however remains below a threshold corresponding to 50% of the capital of their financial sectors. Finally, the most exposed group of countries is formed by a set of mostly North-Western European countries (among which France, Germany, Netherlands, Switzerland, UK) that are characterized by high financial

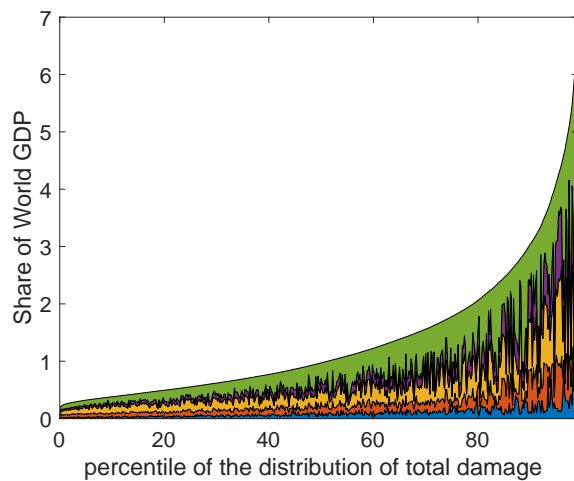


Fig. 3 Components of the global impact of floods for a sample of events from the high-impact scenario with adaptation at horizon 2080. The sample is drawn between the 10th and 90th percentiles of a distribution of direct impacts obtained through 50000 Monte-Carlo draws, with independent draws of damages in each country. The total height of the graph corresponds to total damages. It is allocated between the insurance sector (blue), the governmental sector (red), private sector (yellow), direct (domestic) impacts on the financial sector (purple) and indirect impacts on the financial sector (green) induced by network-based shock propagation.

leverage and high centrality in the global financial network (see Figure 1). For these countries, the risk is commensurate with the size of the capital buffer (*ceteris paribus*). Taken together with the centrality of these countries in the global financial network, this fact suggests that in a high-impact scenario, a climate-driven systemic financial event cannot be excluded *à priori*.

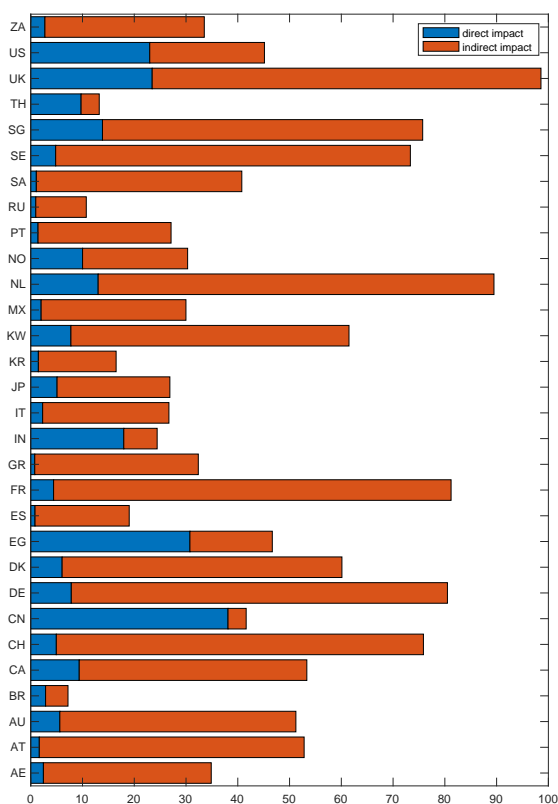


Fig. 4 Conditional value at risk at the 95th percentile for direct and indirect impacts of floods as percentage of capital of the financial sector for the 30 countries facing the largest absolute impact. Results are reported for the high-impact scenario with adaptation at the horizon 2080.

Discussion

Our analysis first highlights that climate impacts can be massively amplified by financial interlinkages. On average, financial propagation of shocks amplifies risks by a factor of 2, but for certain countries and scenarios, e.g. for coastal flood risks in the U.K in a high-impact scenario without adaptation, the amplification ratio can reach a factor of 10. Macro-economic disaster impact assessments provide a useful benchmark for these results. Notably, a commonly used metric in the related literature is the economic amplification ratio, or disaster multiplier, which is the ratio of the overall production losses over the direct economic losses [40]. Previous studies mostly presented am-

plification ratios varying between 1 and 2 [41,42], with some studies showing outliers slightly below and above [43]. Hence, financial amplification ratios can be substantially higher than purely economic ones. A crucial driver of this difference is the role played by leverage in financial networks: the vulnerability of financial intermediaries is proportional to their capital whereas the impact they propagate is proportional to the size of their balance-sheet. The ratio between the latter and the former is above 10 for the financial sectors of some countries that serve as hubs in the global financial network (e.g. the UK), which explains the high amplification ratios observed. In fact, our estimate of the risk is rather conservative as we neglect financial amplifications within domestic financial networks.

However, an important caveat is that the financial amplification of shocks is conditional on the reaction of actors in the financial system, as opposed to the economic propagation of shocks through input-output relationships, which is more mechanical. Indeed, the propagation mechanism is driven by the sequential reassessment by financial institutions of the risk associated to their counterparties, notably those in the financial sector [37]. Such processes are generally triggered by large correlated shocks [37]. Our analysis therefore focuses on the tail of the distribution of climate impacts rather than on its average. In this respect, our analysis partly addresses existing concerns in the literature about the need to refocus climate impact assessment on the risk of catastrophic outcomes [28,29].

Our analysis provides a dual perspective on the risks induced by "physical climate risks" on financial stability. On the one hand, we identify which countries are the major sources of risks from the financial perspective. On the other hand, we identify which countries are the most vulnerable to these financial risks and thus potential spreaders of systemic risks.

With respect to the sources and the magnitude of risk, our results emphasize the crucial role of adaptation. There is up to an order of magnitude of difference in the scale of impacts between the scenarios with and without adaptation. This difference partly hinges on the level of direct damages but the crucial driver of the results is the fact that, in the absence of adaptation, the relative exposure of high-income countries increases massively. As these high-income countries are highly financially leveraged and very central in global financial networks, especially the Western European ones, the financial amplification ratio increases as they are more substantially affected by climate impacts.

Financial leverage is also a key determinant of the vulnerability to climate-induced financial risks. Hubs of the global financial network, such as the U.K. or Switzerland, are highly exposed to external climate risks through global financial interlinkages. In line with the concerns of financial supervisors [1], we find that in a high-end scenario, climate impacts in the tail of the event distribution generate risks for the financial sectors of these countries that are commensurate with capital buffers. Thus, a high-end climate change scenario appears as a potential source of systemic risk in the medium to long-term.

From a policy oriented perspective, our results point to two main conclusions. On the one hand, the need of a risk-management framework for climate-related financial risks. On the other hand, the crucial role of adaptation policy.

The management of climate-related financial risks can be approached both at the macro and the micro level. At the macro-level, an analysis of the sensitivity of our results to the mode of allocation of domestic damages (see Tables 13 and 14 in the supplementary information) highlights the major role of insurance to limit the propagation of climate impacts. If insurance is provided by private actors, the size of the insurance buffer is crucial to limit the propagation of shocks. In particular, capital requirements shall be updated in a forward-looking manner to avoid propagation of risks from the insurance to the financial sector [44]. Insurance can also be provided (implicitly) by the public sector. This reduced the financial amplification of climate impacts as long as the public sector is less financially fragile than the (non-financial) private sector. If the governmental sector ought to keep an insurance role, budgetary provisions must be made to ensure that the increased scale of damages does not jeopardize the sustainability of sovereign debt. At the micro-level, we found that climate-induced risks can be a source of systemic risk for the financial sectors of the most leveraged countries, mostly in Western Europe. This highlights the need for financial institutions to integrate climate change in the risk-management framework of financial institutions, as recently put forward by the "Central Banks and Supervisors Network for Greening the Financial System" [45]. More broadly, this questions the potential distortions on the allocation of global risks induced by the very large size of the financial sectors of certain countries. A salient fact in this respect is the dominant position of European reinsurance companies on the global market.

With respect to adaptation policy, our results point to the following conclusions. First, investments in adaptation will have large co-benefits in terms of financial stability. Such investments are particularly relevant in countries that are more leveraged and more central in global financial networks. Furthermore, as for mitigation, a clear and credible adaptation policy is required for investors to accurately account for physical risks (or the absence thereof) in their long-term investment decisions and thereby to reduce future exposure. Such a clear adaptation policy is, however, found wanting in many coastal countries, not in the least due to large upfront investments required for coastal protection and the deep uncertainty associated with future sea-level rise [46]. In this respect, the main implication of our results on the interactions between adaptation policy and climate-induced financial instability is that the avoided costs in terms of financial stability should be weighted in as benefits of adaptation policy. This finding can be seen as the contraposition of the claim that adaptation is a necessary condition for the future insurability of climate-related risks [47]. As emphasised in our sensitivity analysis (see subsection 1.5 in SI), with reduced insurability, a larger share of the risk would threaten the balance sheet of (non-insurance) financial institutions and thus financial stability. A natural follow-up question is that of global cooperation on adaptation. Indeed, not only are there bilateral externalities, as climate impacts in one country poten-

tially affect financial stability in another, but the recent financial crisis and its aftermath have definitively shown that financial stability is a global public good [48,49]. The literature suggests that existing mechanisms did not succeed in building a fair and efficient mechanism for the financing of adaptation [50]. Financial regulation could contribute to this objective by incentivising financial institutions, e.g. by weighting-in climate risk in capital requirements, to finance and/or monitor adaptation in order to reduce the risk weighting on long-term projects.

A priori, a limitation of our analysis is that it only accounts for coastal and riverine flood risks. Nevertheless, we find that climate-induced changes on the distribution of coastal and river floods have very similar effect on financial stability. This result is likely to extend to other impact domains if climate induced changes in the distribution of damages are similar. In this respect, according to Munich Re² (one of the major global reinsurer), over the period 2013-2018, the share of overall losses for natural events worldwide by type of disaster were 9% for geophysical events, 15 % for climatological events (mainly droughts and fires), 20% for hydrological events (mainly riverine floods) and 56% for meteorological events (storms, including storm surges). Moreover, according to [51], approximately 60 % of losses from hurricanes and tropical storms are due to coastal flooding. Furthermore, whereas impact of climate change on coastal flooding through sea-level rise is recognised as very likely[8], there is no clear evidence on the impact of climate change through changes in the intensity or frequency of storms through the wind component per se [8,52]. Overall, coastal and riverine flooding represent the large majority of direct impacts on physical assets from hazards on which the future impacts of climate change are likely or very likely.

The main climate-related impacts excluded from our analysis thus are wildfires, droughts and heatwaves. Our analysis could in principle be easily extended to wildfires but there is to our knowledge no global projections of future distributions of wildfires and few studies available in the literature on their costs . Droughts, which impact directly agriculture and indirectly non-agricultural sectors through availability of water supply[53], rather have an impact on revenues than on capital (physical assets). Beyond data on the magnitude of these impacts, one would need to model the impact of changes in revenues on the creditworthiness of economic actors to include them in our framework. Finally, heatwaves are more likely to have an impact on the liability than on the asset side of the balance sheet of financial institutions. Thus accounting for their impact in our setting would require a more elaborate model of the functioning of financial institutions considering the interplay between the asset and the liability side of the balance sheet. Slow onset events (increasing temperatures; desertification; loss of biodiversity; land and forest degradation; glacial retreat and related impacts; ocean acidification; sea level rise; and salinization) also are likely to have an impact on financial stability

² data has been retrieved from Munich Re's NatCatService, <https://www.munichre.com/en/solutions/for-industry-clients/natcatservice.html>, which is however offline at the time of writing.

by deteriorating the financial balance of sectors whose assets or revenues are impacted by these processes, (e.g. tourism, agriculture or forestry). Namely, they might lead to a "slow onset" deterioration of the balance sheet of the corresponding actors. The quantitative evaluation of their indirect impact on financial stability seem however extremely difficult.

Another limitation of our analysis is that we do not account indirect impacts through global supply chains or prices. Although these might be important, the level of uncertainty associated to the magnitude and direction of impacts is too large to be included in our analysis [19], which aims to be more data than model driven. A similar remark applies to demand-driven effects. Shocks on financial institutions are likely to propagate to households through the liabilities of financial institutions, e.g. pension funds. The resulting wealth and/or income effects could generate a negative macro-economic feedback [54] that will further amplify the impacts on the financial system.

Another shortcoming of our analysis is that, in our assessment of global risks, we consider the realisation of hazards across countries to be independent. This is clearly an over-simplification but can not be currently overcome given the absence of models taking into account the spatial correlation of hazards in the existing literature (the topic is currently under investigation, including by some of the authors of the present paper). This likely leads us to underestimate the magnitude of events in the tail of the distribution of global impacts as correlated shocks would lead to both higher direct impacts and further propagation.

Furthermore, we consider that the characteristics of countries in terms of leverage and position in the global financial networks are fixed. This is clearly a counterfactual assumption and we acknowledge that this implies that we in fact perform an as if analysis, as in [26]. Overcoming this simplifying assumption would require to develop micro-founded quantifications of socio-economic scenarios describing the evolutions of economic and financial relationships consistent with the different SSPs. Scenarios with lower level of global interaction such as SSP3 would likely limit the financial amplification of shocks while in scenarios with sustained or increased global connectedness, such as SSP4 or SSP5, financial amplification mechanisms are likely to increase. In particular, if the leverage or the centrality of countries highly exposed to climate impacts were to increase, it would have a substantial effect on climate-induced financial instability.

Detailed Materials and Methods

Figure 5 illustrates the modelling workflow used in the paper and refer to relevant subsection of this section.

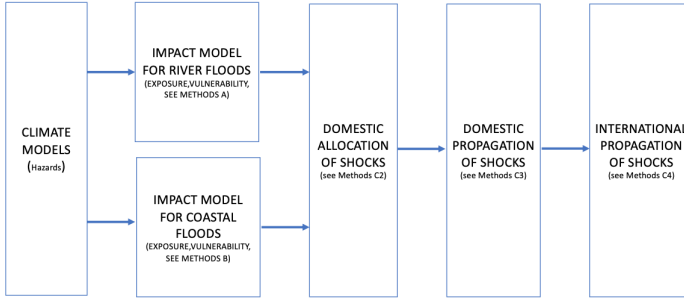


Fig. 5 Modelling framework used for the analysis.

2.1 Direct impacts of river floods under climate change on physical capital

River flood risk was simulated using the cascade of models of the GLOFRIS framework. The original model setup is described in [34], and was extended for future projections in [24] and for adaptation through structural measures in [7]. For this study, we used an updated version of the modelling framework described in Ward et al. (2020). In brief, GLOFRIS simulates flood risk by combining information on hazard, exposure, and vulnerability. Hazard is represented by inundation maps (30 x 30) showing inundation extent and depth for floods of the following return periods: 2, 5, 10, 25, 50, 100, 250, 500, and 1000 years. These are simulated using the methodology described in [55], using the new version of the hydrological model PCR-GLOBWB [56] to daily overbank flows, and a volume conserving flood-spreading algorithm to convert flood volumes to inundation depths. The hydrological model is forced by meteorological data from the EU-WATCH project [57]. For calculating economic damage, exposure is represented by land-use maps showing the percentage of built-up area per cell (30 x 30) from HYDE [58]. For each cell that contains built-up area, we assume that 75% of the built-up area is residential, 15% commercial and 10% industrial respectively, following [59]. Maximum damage values are assigned per country for each of these classes, using the values from [59]. Vulnerability is represented through depth-damage functions, which show the percentage of the maximum damage that would actually occur for different inundation depths; these depth-damage functions are only applied for the urban damage risk indicator, and are also taken from [59]. Economic impact damage per grid-cell is calculated per return period by combining these different datasets using the following equation:

$$I_{\theta}(p) = \theta_r(p)M_r + \theta_c(p)M_c + \theta_i(p)M_i \quad (1)$$

where I_{θ} is the economic impact damage of a cell at inundation depth of the exceedance probability p , θ is the vulnerability and M the maximum damage assigned to residential (r), commercial (c) and industrial (i) occupancy types.

Estimates of current protection standard per subnational region are estimated using the FLOPROS model [60]. For the future simulations, changes in hazard are simulated by forcing the hydrological model PCR-GLOBWB with bias-corrected future climate data from five General Circulation Models (GCMs) taken from ISI-MIP [61]. Changes in exposure are simulated by using the SSPs to project future changes in built-up area, using the methodology of Jongman et al [62]. Future maximum damages are scaled according to the change in GDP per capita between the current and future conditions under the relevant SSP. In our simulations, the vulnerability curves are held constant in the future. Current and future gridded GDP values are taken from [63], which uses the national GDP per capita from the SSP database as input.

2.2 Direct impacts of coastal floods and sea-level rise on physical capital

Current and future direct impacts on physical capital in the coastal zone are assessed using the DIVA coastal flooding framework [6]. Impacts are assessed on the level of the global coastal segmentation of Vafeidis et al. [64], which divides the world's coast into about 12,000 coastal floodplains that are homogeneous in their biophysical and socio-economic characteristics. For each coastline segment, we first assess population exposure by overlaying elevation data from the Shuttle Radar Topography Mission (SRTM) [65] with spatial population data from the Global Rural-Urban Mapping Project (GRUMP) [66]. Second, we translate population exposure into physical capital exposure by applying sub-national GDP per capita rates [64] and an assets-to-GDP ratio of 2.8 [67]. Third, we compute flood damages for flood events with return periods of 2, 5, 10, 25, 50, 100, 250, 500 and 1000 years by integrating over all elevation levels affected by the flood event and applying depth-damage functions. Extreme water levels are taken from the GTSR database [68] and are assumed to uniformly increase with sea-level rise, following 20th century observations [69]. Sea-level rise scenarios are taken from [6]. For each RCP used in this study (RCP2.6 and RCP8.5) sea-level rise has been computed for four global climate models (HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM, NorESM1-M) using the 50th percentile of ice sheet contributions. Finally, we average across the four climate models and aggregate damages assessed on the level of coast-line segments to national levels.

The computation of flood damages takes into account current and future protection levels. Current protection levels are taken from [70] who complemented protection levels for the biggest 136 coastal cities of [67] with expert judgement for segments not associated to these cities (Table 2.2). Protection level zero is assumed if the population density in the 1-in-100-years floodplain is lower than 30 people per km². In unprotected areas it is assumed that nobody lives below the 1-in-1-years water level. For the no adaptation scenario, coastal protection is not upgraded and hence the protection levels decline over time with rising sea levels. For the adaptation scenario, protection levels are

kept constant over time and hence protection infrastructure is upgraded to keep pace with sea-level rise.

class (annual income per capita)	urban	rural	uninhabited
Low income ($\leq \$1035$)	1:10	None	None
Lower middle income ($\$1036 - \4085)	1:25	None	None
Upper middle income ($\$4086 - \12615)	1:100	1:20	None
High income ($> \$12615$)	1:200	1:50	None
special case: Netherlands	1:10.000		
special case: 136 coastal megacities	taken from Hallegatte, 2013		

Table 2 Stylized protection model used in this study.

2.3 Model of financial propagation

2.3.1 Characteristics of the model and data sources

We focus on the set of $N = 109$ countries for which data on global financial interlinkages is available in the JRC Finflows database [20]. This set contains in particular all OECD countries and the major low and middle income countries (see subsection 1.1.1 in SI for details). Each country is partitioned into four institutional sectors: the insurance sector, the governmental sector, the private sector and the financial sector (other than insurance).

The insurance sector of country n is characterised by the share of insured losses for hydrological events $\sigma_n \in [0, 1]$, which is obtained from the Munich Re NatCat database [71], and by the size of its capital buffer $I_n \in \mathbb{R}_+$, which is set equal, by default, to the 99.5th percentile of the (insured) loss distribution, consistently with Solvency II requirements [72].

The governmental sector of country n is characterized by the total level of public debt D_n , obtained from the IMF global debt database [73], the maximum sustainable level of public debt \bar{D}_n (set by default to 200% of GDP consistently with the maximal values observed in [73]) and the fiscal space which is set equal to a share $\beta \in [0, 1]$ of GDP (set by default to $\beta = 6\%$ consistently with the largest fiscal costs incurred for natural hazards reported in [74]). Furthermore, as explicitly specified in the legislation of high-income countries on natural catastrophes and empirically observed in low and middle income countries [75, 76], the state has an insurance role that we represent by setting a target share $\tau \in [0, 1]$ of losses that ought to be covered by private insurance or governmental support, conditional on fiscal space (τ is set by default to 0.5 in simulations).

The private sector of country n is characterized by the value of its stock of physical assets $K_n \in \mathbb{R}_+$, which is obtained from the World Bank 2018 wealth of nations database [77]. The value of the equity of the private sector E_n is equal to the difference between the capital and the total value of credit to the private sector C_n^{pr} (see below).

The financial sector of country n is characterized on the one hand by the total bank capital B_n and on the other hand by the total value of credit to the domestic private and public sectors, denoted respectively by C_n^{pr} and C_n^{pb} . All values are obtained from the World Bank global financial development database [78].

In the following, unless otherwise specified, all values are expressed in terms of share of GDP and a generic country is denoted by the index n .

2.3.2 Domestic allocation of shocks

We first consider the allocation and propagation of shocks among domestic institutional sectors. In this respect, we take as given the realization of a vector of (yearly) shocks on physical assets (S_1, \dots, S_N) per country. In the computation of the country-induced value at risk, a single country is shocked at a given percentile of its direct damage distribution. In the computation of the global financial risks induced by climate change, we perform a series of Monte-Carlo simulations in each of which a shock is drawn independently at random in each country according to the direct damage distribution. In either cases, the shock S_n is first allocated among the domestic institutional sectors of country n as follows.

A share σ_n of the shock is insured and thus allocated to the insurance sector, up to its capital buffer. That is the insured part of the shock is given by $S_n^{ins} = \min(I_n, \sigma_n S_n)$.

The government then covers the non-insured part of the shock up to the share τ of the total shock, conditional on its fiscal space. Namely, the part of the shock covered by the government is given by $S_n^{pb} := \min(\beta, \tau S_n - S_n^{ins})$. This accounts for the role of the government both in developing countries with low insurance penetration where the state is the de facto insurer [75] and in developed countries where there exist legal provisions for the covering by the state of a share of the damages due to natural disaster [76].

The residual part of the shock $S_n^{pr} = S_n - S_n^{ins} - S_n^{pb}$ is assigned to the private sector.

2.3.3 Impact on the domestic financial sector

After its direct impact, the shock propagates towards the domestic financial sector. The main channel of propagation is the decrease in value of the liabilities of the governmental and private sectors induced by the deterioration of their balance sheet [21, 79].

First, following Battiston et al. [21, 79], we assume that the value of the private sector's liabilities decrease as a function of the change in equity induced by the shock. More precisely, we assume that the value of the private sector's liabilities towards the domestic financial sector, following the shock S_n , is given by $(\frac{E_n - S_n^{pr}}{E_n})C_n^{pr}$. This amounts to consider that the value of the liabilities of the private sector are given by their expected value under a default

probability that is proportional to the equity or equivalently the probability of an idiosyncratic shock leading to default is uniformly distributed over $[0, E_n]$ [80].

Second, we assume that the value of government's liabilities decrease proportionally to the level of public debt, i.e. the values of government's liabilities towards the domestic financial sector, following the shock S_n , is given by $\frac{\bar{D}_n - D_n - S_n^{pb}}{\bar{D}_n - D_n} C_n^{pb}$. This amounts to consider that the value of the liabilities of the governmental sector are given by their expected value under a default probability that is proportional to the ratio between the current and the maximal sustainable level of debt.

Finally, to account for the fact that large shocks increase the probability of default of the insurance sector, we further consider that a part of the shock faced by the insurance sector can be transmitted to the financial sector. More precisely, given a share S_n^{ins} of damages covered by the insurance sector, we assume that a share $\rho^{S_n^{ins}}/I_n$ is propagated towards the financial sector where I_n is the capital buffer of the insurance sector and $\rho \in [0, 1]$ is a parameter (set to 1 by default). In particular, if $I_n = S_n$, the shock completely depletes the capital buffer and the shock is fully propagated to the financial sector. This parametric approach is used to account for the huge uncertainties associated to the actual exposures between the financial and the insurance sectors given the variety of potential channels of propagation involved [81].

Overall, the impact of domestic climate shocks on the financial sector amounts to

$$S_n^{fin} = \rho \frac{S_n^{ins}}{I_n} + \frac{S_n^{pb}}{\bar{D}_n - D_n} C_n^{pb} + \frac{S_n^{pr}}{E_n} C_n^{pr}. \quad (2)$$

This impact leads to a deterioration of the financial sector's balance sheet. Namely, the capital of the financial sector of country n after the domestic propagation of the shock S_n is given by $B_n - S_n^{fin}$.

2.3.4 International propagation of shocks

Domestic shocks propagate at the global scale according to three main channels: (i) from the domestic private sector to the international private sector via FDI and equity holdings, (ii) from the domestic private and governmental sector through international debt holdings (mainly bonds), (iii) from the domestic to the international financial sectors through claims and liabilities of internationally active banks. The JRC Finflows database [20] provides detailed statistics on these cross-border exposures, in particular for each pair of countries i, j : (i) the value $A_{i,j}^{pr}$ of FDI and equity holdings of entities (private sector) of country i in entities (private sector) of country j , (ii) the value of portfolio debt $A_{i,j}^{db}$ held by entities (financial sector) of country i on entities (private sector) of country j , (iii) the residual value of claims $A_{i,j}^{fin}$ held by the financial sector of country i on the financial sector of country j , which is inferred from the BIS locational banking statistics [82]. Furthermore,

the World Bank global financial development database provides the relative shares $\alpha_j \in [0, 1]$ and $1 - \alpha_j$ of public and private debt in the international debt liabilities of country j .

In this context, the private sector of each country is further impacted by the shocks received through its equity holdings, leading to a total impact of

$$S_n^{intpr} = \sum_{j \neq n} A_{n,j}^{pr} \frac{S_j^{pr}}{E_j} \quad (3)$$

Moreover, the financial sector of a country is impacted by its cross-border debt holdings on public and private sectors as well as through indirect exposure via FDI and equity holdings of the private sectors. Namely, the impact of international climate shocks on the financial sector of country n is given by

$$S_n^{intfin} = \sum_{j \neq n} \left(\alpha_j \frac{S_j^{pb}}{\bar{D}_j - D_j} + (1 - \alpha_j) \frac{S_j^{pr}}{K_j} \right) A_{n,j}^{db} + \frac{S_n^{intpr}}{E_n} C_n^{pr}. \quad (4)$$

where the first term of the sum corresponds to the impact via international debt holdings and the second term to the impact mediated by international FDI and equity holdings. This international propagation of shocks leads to a further deterioration of the private financial sector's balance sheet. Namely, the capital of the financial sector in country n following the global propagation of shocks is given by $B_n - S_n^{fin} - S_n^{intfin}$.

2.3.5 Financial contagion

Further to the international propagation of shocks through cross-border equity and debt holdings, a well-identified source of systemic risk is the endogenous amplification of shocks within financial networks [21]. The BIS locational banking statistics, captured in the adjacency matrix $(A_{i,j}^{fin})_{i,j=1,\dots,N}$ provides a detailed representation of the network of financial interdependencies at the country-scale. Building on this dataset, we simulate the amplification of shocks through the global financial network by applying the debtrank algorithm [21]. More precisely, we consider that:

- The book value of the interbank claims of country n on country j is initially equal to its nominal value, that is

$$\mathcal{A}_{n,j}(0) = A_{n,j}^{fin}$$

- The “equity” of the financial sector of country n in period 0 equal to

$$\mathcal{E}_n(0) = B_n + \sum_{j \neq N} \mathcal{A}_{n,j}^{fin}(0) - \sum_{j \neq N} A_{j,n}^{fin}$$

- The financial sector of country n can be in either of three states: undistressed (\mathcal{U}), distressed (\mathcal{D}) or inactive (\mathcal{I}). Initially, the financial sector of each country n is undistressed,

$$\mathcal{S}_n(0) = \mathcal{U}.$$

- The “equity” of the financial sector of country n in period 1 is equal to

$$\mathcal{E}_n(1) = \mathcal{E}_n(0) - S_n^{fin} - S_n^{intfin}$$

The algorithm then unfolds as follows for every $t \geq 2$:

- Each actor distressed in the previous period becomes inactive

$$\mathcal{S}_n(t) = \mathcal{D} \Rightarrow \mathcal{S}_n(t) = \mathcal{I}.$$

- Each undistressed actor that faced a shock in the preceding period becomes distressed:

$$(\mathcal{S}_n(t-1) = \mathcal{U} \wedge \mathcal{E}_n(t-1) < \mathcal{E}_n(t-2)) \Rightarrow \mathcal{S}_n(t) = \mathcal{D}$$

- The value of the liabilities of distressed actors decrease proportionally to their loss of equity, i.e. for all n, j one has:

$$\mathcal{A}_{j,n}^{fin}(t) = \frac{\mathcal{E}_n(t-1)}{\mathcal{E}_n(t-2)} \mathcal{A}_{j,n}^{fin}(t-1) \quad (5)$$

so that $\mathcal{A}_{j,n}^{fin}(t) \neq \mathcal{A}_{j,n}^{fin}(t-1)$ if and only if $\mathcal{S}_n(t) = \mathcal{D}$.

- The equity of (undistressed) actors are updated accordingly, i.e. if $\mathcal{S}_j(t) = \mathcal{U}$, one has:

$$\mathcal{E}_j(t) = \mathcal{E}_j(t-1) + \sum_{n \neq j} \mathcal{A}_{j,n}^{fin}(t) - \sum_{j \neq N} \mathcal{A}_{j,n}^{fin}$$

and $\mathcal{E}_j(t) = \mathcal{E}_j(t-1)$ otherwise.

Hence, distress propagates sequentially across the network through financial exposures. The value of the liabilities of a distressed actor decreases thus putting in distress its creditors. The algorithm stops when all actors are either inactive or undistressed, i.e. at the date T such that for all n , $\mathcal{S}_n(T) \in \{\mathcal{I}, \mathcal{U}\}$. A key feature of the version of the debtrank algorithm we use is that an actor stays in distress for a single period and then becomes inactive. This leads to a conservative estimate of the losses induced through financial propagation compared to other variants of the algorithm (see [79] for a detailed discussion). The linear impact of the value of equity on the value of liabilities implemented in Equation 5 amount to consider that (i) beyond climate-induced shocks, financial actors in each country n face idiosyncratic shocks distributed uniformly over $[0, K_n]$ with $K_n > \mathcal{E}_n(0)$, (ii) actors are risk-neutral and evaluate their assets by assuming they receive zero payment from defaulted counterparties, i.e. these such that $\mathcal{E}_j < 0$.

2.4 Measures of risk

Our analysis refers to the following measures of risks:

- The value at risk of order α , $var_X(\alpha)$, for a random variable X , representing potential losses, is the value v such that the incurred loss is less than v with probability α , or equivalently the α th percentile of the loss distribution, that is

$$var_X(\alpha) = V \text{ where } P(X \leq V) = \alpha$$

- The conditional value at risk (or expected shortfall) of order α for a random variable X representing potential losses, $cvar_X(\alpha)$, is the expected loss incurred conditional on the loss being greater than the value at risk of order α , that is:

$$cvar_X(\alpha) = \mathbb{E}(X \mid W \geq var_X(\alpha))$$

- A random variable X first-order stochastically dominates a random variable Y , or equivalently is less risky in the sense of first order stochastic dominance if for all $x \in \mathbb{R}$, one has

$$P(X \geq x) \geq P(Y \geq x)$$

or equivalently for all $x \in \mathbb{R}$, one has

$$F_X(x) \leq F_Y(x)$$

where F_X denotes the cumulative distribution function of X . It is well-known [83] that X first-order stochastically dominates Y if and only if for every weakly increasing utility function, one has $\mathbb{E}(u(X)) \geq \mathbb{E}(u(Y))$.

Data availability statement

All data is publicly available from referenced sources

Conflict of interest

The authors declare that they have no conflict of interest.

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