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The globalization of climate change: amplification of climate-related physical risks through input-output linkages

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Abstract

While global supply chains have recently gained attention in the context of the Covid-related crisis as well as the war in Ukraine, their role in transmitting and amplifying climate-related physical risks across countries has received surprisingly little attention. To address this shortcoming, this paper for the first time combines country-level GDP losses due to climate-related physical risks with a global Input-Output model. More specifically, climate-related GDP-at-risk data are used to quantify the potential direct impact of physical risks on GDP at the country or regional level. This direct impact on GDP is then used to shock a global Input-Output (IO) model so that the propagation of the initial shock to country-sectors around the world becomes observable. The findings suggest that direct GDP loss estimates can severely underestimate the ultimate impact of physical risk because trade can lead to losses that are up to 30 times higher in the EA than what looking at the direct impacts would suggest. However, trade can also mitigate losses if substitutability across country-sectors is possible. Future research should (i) develop more granular, holistic, and forward-looking global physical risk data and (ii) examine more closely the role of both partially substitutable outputs, and critical outputs that are less substitutable or not substitutable at all, such as in the food sector.

JEL Classification: E01, Q54, Q56, F18

Keywords: Supply chains, physical risk, climate change

Non-technical summary

The estimation of real-economic damages due to climate change physical risks remains an important challenge in the face of global warming. Many economic models make significant simplifications on the channels of transmission of climate physical risks across the globe, often giving the impression that the risks for the Euro Area will be relatively small. In particular, the role of global supply chains in the transmission and potential amplification of climate related physical risks has received little attention. This is relevant because climatologists predict that direct impacts from climate change-induced natural disasters will materialize mainly outside the Euro Area. The Euro Area could therefore import losses from abroad if its supply chains are disrupted, as it happened during the COVID-19 pandemic. Understanding potential real economy losses would also contribute to better portray the risks which could spill over into the financial system.

To address this shortcoming, this paper for the first time combines country-level GDP losses from the local realization of climate-related physical risks with a global Input-Output (IO) model at country-sector level. The IO methodology used to estimate the results relies on a bottom-up approach for finding feasible market allocations given the exogenous climate shocks, starting from a matrix of global trade flows. The data for such matrix are obtained from the OECD's Inter-Country Input-Output tables. Country-level GDP-at-risk data are retrieved from SPGlobal. The latter data cover most countries and are estimated without considering trade amplifications. The exogenous shocks are introduced into the IO model as a reduction in final demand and maximum productive capacity corresponding to the GDP-at risk values. The IO model also introduces the possibility for country-sectors to reallocate their input sourcing in the case they faced supply bottlenecks, which is a novelty for such models.

The results show that, if physical hazards under the Representative Concentration Pathway 8.5 scenario[1] in 2050 materialize globally at the same time, the aggregate GDP losses in the Euro Area are on average more than 10% of GDP, or around 15 times the expected direct climate shock for the Euro Area. The country-level breakdowns of the results show that the countries who will face the highest aggregate losses in the Euro Area belong to two groups: countries with high direct exposures to climate change physical risk, i.e. Mediterranean countries, and countries with large trade connections to regions of the world which will suffer high direct losses. For example, Germany and Luxembourg belong to the latter category. The three sectors which will face the largest aggregate losses in the Euro Area are wholesale

[1] RCP 8.5 is one of a suite of scenarios which describe potential future pathways based on greenhouse gas concentrations. RCP 8.5 delivers an increase of about 4.5˚C by 2100, which is considered adverse by climatologists.

and retail, real estate, and construction. The financial and insurance sector is also expected to face significant losses, increasing the potential spillover from real-economic to financial risk. The ease with which country-sectors can reallocate their input sourcing significantly affects the results, with higher (lower) possibility to reallocate input sourcing resulting in lower (higher) aggregate losses.

1. Introduction

Recent estimates of real-economic damages due to climate change physical risks do not appear incredibly worrying, not at least those for European countries. The Network for Greening the Financial System (NGFS, 2022) has recently published revised physical risk-related GDP scenarios:

"The new damage function estimates have been inputted into NiGEM, the macroeconomic model in the NGFS scenarios, to derive a set of impacts on GDP. [Global] GDP losses from chronic physical risks reach more than 6% in 2050, and up to 18% by the end of the century in the Current Policies scenario."

If productivity was to grow by 0.5%, which would be lower than the trend over the last decades, real GDP would still be higher in 2050 under the adverse NGFS scenario compared to today's GDP levels. In previous NGFS scenarios, damages were estimated to be around half of the new vintage estimates, i.e. for example less than 3% global GDP loss by 2050.

The ECB climate stress test of 2022 also finds relatively little impact from physical risks. The researchers estimate the expected losses for physical assets of firms to be less than 1.5% by 2050 in an adverse (hot house) scenario, considering direct (exposure and intensity of events) and indirect (regional-level reduction of GDP, chronic changes in temperature, precipitations, etc.) effects (Alogoskoufis et al., 2022, p.41, chart 26).

It is not surprising, that these kinds of scenarios have not scared policy makers or chief risk officers of financial institutions who have experienced larger shocks in 2008 or who must shock their systems with more adverse scenarios in regular stress testing exercises.

However, these estimates shall not give us much comfort. Estimating economic impacts from climate change has a long history of being unrealistically optimistic. Nordhaus' seminal 1991 paper was one of the first to estimate the effect of climate change on economic output (Nordhaus, 1991). A key assumption was that only economic activities that are exposed to the weather will be affected by climate change, namely agriculture, forestry, and fishery, while "for the bulk of the economy […] it is difficult to find major direct impacts of the projected climate changes over the next 50 to 75 years." This assumption appears absurd from today's perspective where droughts threaten the cooling of power plants (Turner et al. 2021), floods destroy not only agricultural production but also factories (Haraguchi & Lall, 2015), rising sea levels threaten the functioning of ports around the world (Noronha et al., 2023), and global food security could be jeopardised (Adams et al. 2021).

As many economic analyses of climate change have limited *a priori* the possible transmission channels from climate change to the economy (Keen 2022), overall policy conclusions are yet to take a more holistic approach, relativizing climate change impacts and letting economic assessments of climate change appear paradoxical. Consider for example the first paragraph of the IPCC's Executive Summary of Chapter 10 on key economic sectors and services from 2014 (Arent et al 2014)[2]:

"For most economic sectors, the impact of climate change will be small relative to the impacts of other drivers (medium evidence, high agreement). Changes in population, age, income, technology, relative prices, lifestyle, regulation, governance, and many other aspects of socioeconomic development will have an impact on the supply and demand of economic goods and services that is large relative to the impact of climate change."

Leaving aside the consideration that the "other factors" are themselves influenced by climate change, neglecting climate change impact on economic sectors seems unrealistic. Indeed, modern integrated assessment models (IAMs), like the ones employed by the NGFS or the IPCC[3], have moved beyond Nordhaus's original approach, including his own more recent research (Nordhaus, 2017; Nordhaus, 2018). Nevertheless, there are several elements that are not yet consistently accounted for when assessing the economic impacts of climate change. These include a realistic consideration of our world economy (Keen et al, 2021), wet bulb temperatures (Mora et al 2017), climate tipping points (Lenton et al 2008), the loss of biodiversity (Svartzman et al 2021) and, more generally speaking, globalization.

Regarding the latter, the IPCC states qualitatively (Pörtner et al, 2022, p.68):

"Interconnectedness and globalisation establish pathways for the transmission of climate-related risks across sectors and borders, through trade, finance, food, and ecosystems (high confidence). Flows of commodities and goods, as well as people, finance, and innovation, can be driven or disrupted by distant climate change impacts on rural populations, transport networks and commodity speculation (high confidence). For example, Europe faces climate risks from outside the area due to global supply chain positioning and shared resources (high confidence)"

In recent years, a growing body of research has tried to address some of these shortcomings directly or has made further progress with data and models required as input or basis for the question at hand. Consequently, this paper connects to three streams in the literature. First, our paper relates to the literature on the welfare effects of trade shocks. In the wake of the COVID-19 pandemic, the Russia-Ukraine war, and high inflation levels in many countries, resurgent attention has been directed at

[2] Note that the mentioned changes in population, regulation etc. can potentially all be affected by climate change.
[3] See for example the recent IPCC report (Pörtner et al, 2022, p.67), where "under high warming (>4°C) and limited adaptation, the magnitude of decline in annual global GDP in 2100 relative to a non-global-warming scenario could exceed economic losses during the Great Recession in 2008– 2009 and the COVID-19 pandemic in 2020."

understanding how supply chains shocks percolate through the world economy (see Paul et al., 2021, Bachmann et al., 2022, Weber et al., 2022) and how firms react to supply chain risks (Ersahin et al, 2024). Consequently, input-output methodologies have also seen a growing interest and were extended, also allowing for the analysis of the interrelated shocks of the recent years (see Baqaee & Farhi, 2018, Pichler et al., 2022) as well as for the analysis of more long-term structural issues like US-China trade relationships (Feenstra and Sasahara, 2018).

Elements of input-output models have also been incorporated into more traditional general equilibrium macro models. Baqaee and Farhi (2023) develop a large computable general equilibrium model that contains micro-founded elasticities of substitution (see also Baqaee and Farhi, 2019) and mark-up pricing mechanisms (Sornette and Senner, 2019). Moreover, and in contrast to earlier neoclassical trade models, the model has room for unemployment as well as changes in the income distribution, both of which are essential to study the welfare effects of global trade (Capaldo and Izurieta, 2018). Since equilibrium prices are part of the model, not only quantity but also price changes after trade-related shocks can be analyzed. Attinasi et al (2023), for example, use the model of Baqaee and Farhi (2023) to investigate the consequences of supply-chain decoupling along geopolitical blocks or strategic sectors, and find higher inflation (price-changes) and lower output (quantity changes). While in principle, the application of such models to study physical risk transmission appears fruitful, our paper does not use such a large-scale general equilibrium model for two reasons. First, since we are interested in informing the debate with empirical estimates, a large and consistent macroeconomic dataset at the country or regional level would be needed regarding prices, employment, elasticities and so forth. To our knowledge, such a dataset is not readily available. Second, since this paper aims at informing not only academics but also policymakers, we prefer to provide a traceable approach that can, with all its limiting assumptions, be quickly understood to illustrate the simple yet underdeveloped finding that physical risk can only be grasped after taking supply-chains into account.

Second, our paper relates to the literature that has started to analyse the transmission of climate risks across borders. In this strand, however, the focus remains mostly on transition risks (Devulder & Lisack, 2020, Frankovic, 2022, Krivorotov, 2022). The ECB/ESRB (2022) analyse how transition shocks transmit through IO linkages as well as a financial contagion model. More specifically, two stylized transition shocks, a negative supply shock to reduce fossil fuels and a policy shock that reduces global demand for fossil fuels by 10 to 30 percent over five years are considered. The researchers find that:

"Up to 20% of banks' Risk Weighted Assets (RWAs) are estimated to fall below the MDA (Maximum Distributable Amount) when considering a 30% reduction in global demand for fossil fuels combined with a Probability of Default (PD) increase of 300%, applied to sectors with a GVA loss of 0.5

percentage points (Chart A.3). In the case of a 30% reduction in fossil fuel production factors, up to 12.5% of banks' RWAs are estimated to fall below the MDA with a 300% PD increase" (Ap. 1.3, ECB 2022)

Similarly, Espagne et al. (2023) analyse the cross-border risks that could result from a decarbonization of the world economy using a global macro-econometric model which in turn also builds on IO data. Campiglio et al (2022) develop a macro model to study how carbon pricing policies can affect the global economy via international production networks and Hambel et al (2021) take trade into account when calculating the global social cost of carbon. The large part of the transition risk literature, much like the physical risk literature, still focuses on purely domestic effects. Krivorotov (2022) analyses sectoral transition risk in the US using a general equilibrium production network that captures the entire supply chain. Aguilar et al (2023), for example, build a model in the spirit of Baqaee and Fahri (2023) to study transition risks and calibrate the model to the Spanish economy and Fried et al (2022) develop a transition risk model and calibrate it to the US economy. Ciola et al (2023) develop an agent-based model of the US economy and analyze how this adaptive and complex system reacts to energy shocks.

Third, we connect to the literature on the study of the propagation of climate physical risks across borders, which remains underdeveloped. Such analyses require the combination of the following three elements, which are difficult to integrate: (i) forward-looking climate-related hazard scenarios at the country or regional level for the whole world, (ii) the economic impact of such scenarios on the economies (damage functions), and (iii) a trade model to be shocked with these economic damages. To our knowledge this paper is the first to apply IO modelling with physical risks on a global scale. The analysis by Lepore and Fernando (2023) appears similar by also considering supply chains and climate risk at a global level. However, the authors use a general equilibrium modelling approach and estimate how sectoral changes in productivity due to physical climate risks affect a global, multisectoral, intertemporal general equilibrium model. Also related, the World Bank Group has started to consider IO-related supply-chain aspects within individual countries to get more comprehensive climate risk assessments (see for example World Bank Group 2023, 32). Moreover, other scholars have investigated how *specific* climate disasters transmit across global supply chains. Forslid and Sanctuary (2022) for example examine the effect of Thailand's 2011 flood on Swedish importing firms. Finck and Tillmann (2022) analyse how the supply shocks resulting from the Tohoku earthquake in 2011, the Suez Canal disruption in 2021, and the Shanghai backlog in 2022 affect euro area economic activity. Naturally, the literature on the propagation of physical risks across borders builds on studies of purely domestic climate-related impacts, see for example Hsiang et al (2017) for the US economy. However, the literature on domestic impacts of hazards is often purely backward-looking. Dell et al. (2012) for example study historical temperature and economic growth relationships. On the theoretical side, there have also been studies to integrate input-output relationships across borders into the complexity of climate risk transmission chains, including mitigation and adaptation policies, but without an empirical estimation of the global effects (Challinor et al., 2018 and Carter et al., 2021).

Finally, it is worth mentioning that scholars have started to investigate how nature-related risks transmit across global supply chains, see Almeida and Senni (2023) for a review of this literature.

This paper aims at making economic impact assessments of climate change more realistic by incorporating a key element of globalization. More specifically, this paper is the first to analyse the transmission of GDP losses from climate change related physical risks through global country-sector input-output linkages. While we do not consider other important aspects of globalization (finance, migration, social order etc.), this paper makes a first important step towards getting a more realistic picture of the risks arising from climate change.

This paper is structured as follows. Section two gives an overview of our modelling approach. Section three presents the data used and section four describes the model in detail. Sections five presents the findings and discusses them. Section six concludes.

2. Integrating Input-Output into climate risk analysis

Physical risks describe the increased risk of natural hazards or risk associated with the chronic worsening of the physical conditions for living on the planet derived from climate change (Dikau & Volz, 2019). Chronic damages are related to the average increase in global temperatures. The natural hazards influenced by climate change are many and include floods and inundations, droughts, heatwaves, windstorms, and wildfires. For the scope of this paper, we rely on data which include all these hazards. Importantly, physical risks do not only have a direct impact on the economy, as cascading or amplifying effects are also possible through input-output linkages.

In general, the global economy is exposed to physical risks which generate GDP losses. Given that the domestic production of goods and services relies on inputs produced in other parts of the world, the realisation of local or regional GDP losses generates further GDP loss around the world due to input-output linkages along global value chains (GVCs). For example, heat stress-related GDP losses in South Asia could lower GDP in Europe due to a decrease in goods flows to Europe, which are necessary for European production. Moreover, disruptions to parts of the GVCs which are more difficult to substitute lead to higher contagion from the initial shock (consider for example the disruption caused by the temporary closure of the Suez Canal in 2021 (Finck and Tillmann, 2022), or the shortages in microchips supply in 2022).

In this paper, regional GDP-at-risk metrics are combined with a global input-output model at the country-sector level to analyse contagion in the real economy and the propagation of exogenous climate change-induced physical risk shocks. Specifically, SPGlobal GDP-at-risk data are used to quantify the potential direct impact of physical risks on GDP at the country level. The direct impact on GDP is then used to shock an Input-Output (IO) model so that the propagation of this shock to country-sectors around the world becomes observable.

To investigate IO linkages between country-sectors, conventional IO models are extended to simulate supply and demand shocks simultaneously and to account for substitution effects. This is done to account for the fact that the realization of physical risks from climate change reduces both domestic final demand and production capacity (Feng and Li, 2021). As an example, the realization of a climate change related hazard in South Asia will result in less final demand in South Asia for the output produced domestically and abroad, because of the reduction in population and incomes which are likely to follow the occurrence of natural disasters. Moreover, production sites in South Asia will also be damaged or destroyed, reducing their productive capacity – in other words, there will also be a supply shock. To assess the shock amplification due to input-output interconnections, we build a simulation-based IO methodology, which allows to model the propagation of simultaneous supply and demand shocks. Our model is inspired by the ones developed in Pichler and Farmer (2022) and Pichler et al. (2022).

A key feature of our modelling approach is that we depart from a pure Leontief production functions framework (Baldwin et al., 2022), where there is no elasticity of substitution between the production inputs from each country-sector. Instead, we use a modified Leontief production function where the elasticity of substitution is zero across global sectors (steel and energy, for example), but non-zero within each global sector. In this sense, we assume that the production of every country-sector output needs a specific ratio of inputs from each global sector, but we allow for the possibility to source these inputs from different countries. The degree to which inputs can be substituted across countries ranges from 0 to 100 percent and has a substantial effect on total GDP losses. Put differently, there is a space of possibilities for each country-sector to reallocate their input sourcing in case they were to face input bottlenecks.

We start from the assumption that country-sectors produce goods already at equilibrium, so that global demand equals global supply, and there are no inventories in the global system. After the introduction of exogenous shocks, a first round of transmission will take place. The country-sectors whose output supply is now higher than the post-shock aggregate demand they receive, will build up inventories.

These inventories can be used to satisfy additional demand within a global production sector. For example, the European automotive industry, faced with a reduction in inputs received from the steel producers in South Asia, can shift its sourcing of steel to North America, if the steel producers in North America have built up inventories. We define *trade reallocation capacity* as the percentage of missing input goods whose sourcing can be reallocated within a global production sector at no cost. Higher trade reallocation capacity can mitigate the amplification of the losses through input-output linkages.

3. Data

3.1 Input-Output Data

The 2021 edition of the OECD Inter-Country Input-Output (ICIO) tables captures information on annual symmetric industry-by-industry trade volumes in goods and services between 66 countries, divided into 45 unique industries based on ISIC Revision 4 (Martins Guilhoto et al. 2022). The tables are provided for the years 1995 to 2018. For the scope of this paper, we refer to the most recent available data, i.e. for the year 2018. The structure of the ICIO input output data is exemplified in figure 1. Each row of the ICIO tables reports the distribution of value added (at basic prices) produced by each country-sector.

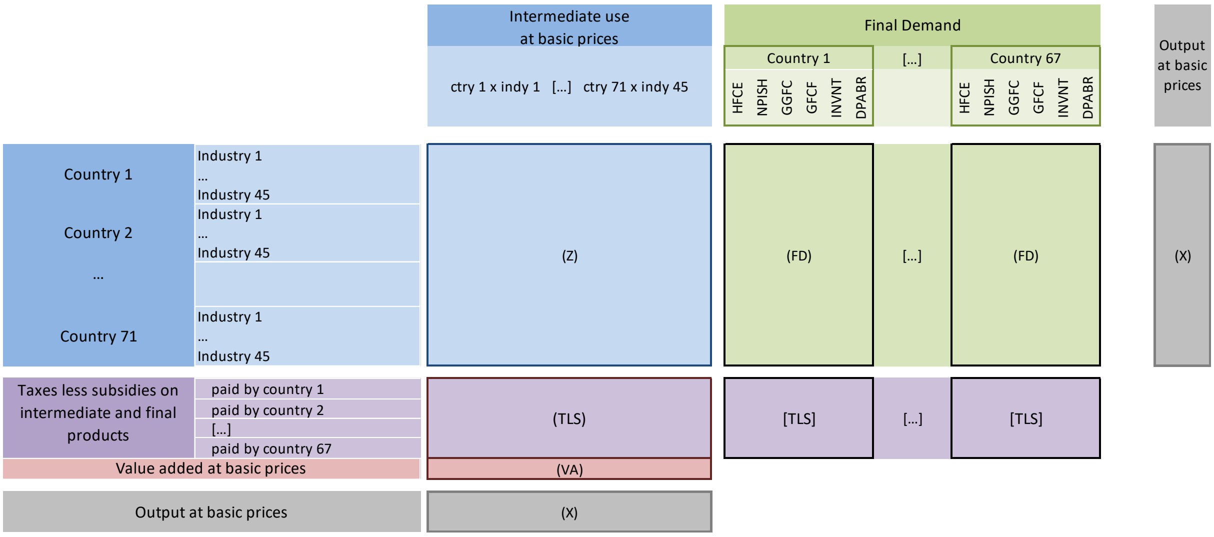

Figure 1: OECD, Inter-Country Input-Output Tables, 2021 edition (million USD)

Source: OECD

The Z matrix captures intermediate, intra-industry consumption; that is, the flow of intermediate output from each country-sector on the vertical axis to each country-sector on the horizontal axis. The FD matrix captures the flow of goods and services which satisfy final demand of households, firms, and the government. The X matrix captures total aggregated output produced at basic prices by each country-sector. Each column of the ICIO tables represents the sourcing of inputs by each country-sector. In this sense, the Z matrix can also be understood to capture how much input from country-sectors on the vertical axis does each country-sector on the horizontal axis need for their production. The TLS matrix provides information on the total taxes and subsidies which influence the total value added of each industry. Lastly, matrix VA collects the difference between the total output produced by each country-sector and the sum of Z and TLS. The VA matrix therefore collects the part of value added used for basic production inputs, i.e. labour costs, remunerating shareholders, etc. The flows between country-sectors are perfectly symmetrical, meaning that every dollar of value added flowing out of a country-sector must flow in somewhere else, and the corresponding revenue used to remunerate intermediate and basic inputs, or taxes.

A frequent assumption in Input-Output modelling is that country-sectors produce according to Leontief production functions, that is, the ratio of each input factor to total output produced is constant and there is no substitutability across input factor (Baldwin, 2022). The traditional Input-Output Leontief models derive a matrix A which captures the *input-output coefficients*, i.e. input to total output ratios, by dividing the matrix X by the matrix Z. Any input-shortage faced by any country-sector would reduce their total production according to this matrix. This is an assumption that we will relax in the development of the model used in this paper.

3.2 Climate-related GDP-at-risk data

To analyse the amplification of physical risks across country-sectors with the help of input-output data, ideally country-sector level data with GDP losses for different scenarios and for different hazards would be available. However, despite the growing body of knowledge and research on climate change, there have been surprisingly few efforts to produce such datasets. Many datasets are not granular enough, i.e. on a global scale only, or focus on individual countries, regions or ecosystems. NGFS (2021), for example, has global GDP losses but nothing on a granular or regional level, and it does not include damages from extreme hazards beyond average temperatures growth. Once more granular or more detailed physical risk related GDP-at-risk data become available, the methodology proposed in this paper can simply use these new data as an input. For now, a dataset of country-level estimates of GDP-at-risk from SPGlobal (2022) appears to be the best available one for our purposes.

SPGlobal (2022) GDP-at-risk data are quantified combining (i) physical risk exposure metrics for droughts, wind, floods, and heatwaves in the RCP 8.5 scenario by the year 2050 with (ii) historically estimated physical hazard losses per exposed GDP. Representative Concentration Pathways (RCP) are “scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases (GHGs) and aerosols and chemically active gases, as well as land use/land cover” (Moss et al., 2008). The RCP 8.5 scenario sees GHG emissions growing through the whole century, that is, no serious emissions abatement policies are introduced across the globe.

To assess which share of GDP is exposed to a specific hazard, SPGlobal (2022) uses the SPGlobal Trucost Index, which in turn uses different datasets and internal models to estimate scenarios until 2050, for 135 countries. For the percentages of GDP that would get lost if hazards realize, SPGlobal (2022) builds on the results of Formetta and Feyen (2019) who use historical MunichRe event studies for drought, wind, and flooding. To estimate the GDP impact of droughts, SPGlobal (2022) analyses the impact on labour productivity for three sectors (agriculture, industry, and services), based on Roson and Sartori (2016).

Moreover, SPGlobal GDP-at-risk data are quantified using a static approach, so that second-round effects including IO linkages are not considered. Consequently, potential risks of double counting are avoided. Figure 2 illustrates SPGlobal data aggregated at the regional level, while we use individual data for 128 countries.

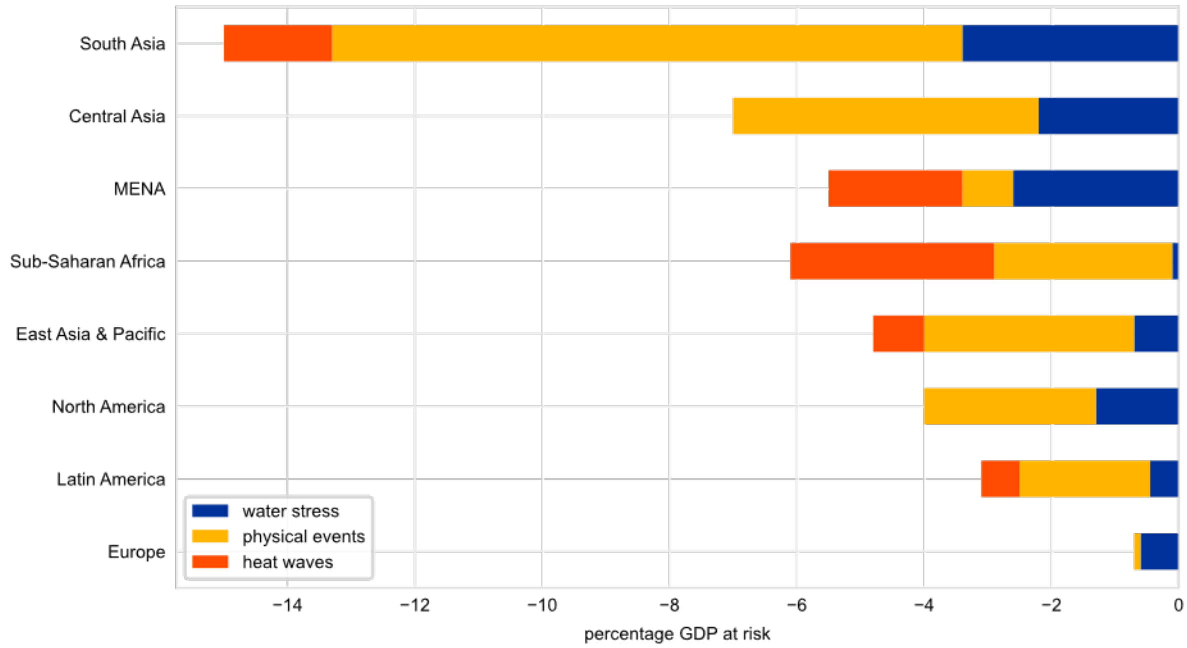

Figure 2: GDP at risk from climate change-related physical risks, RCP 8.5 scenario

Source: SP Global and ECB

3.3 Modelling climate shocks

The IO tables system is initially in equilibrium. The realisation of climate change physical risk events affects both final demand in countries hit, as well as the productive capacity of industries residing in those countries (Hallegatte et al., 2008; Ciccarelli et al., 2024). The realisation of climate hazards, therefore, creates two shock channels: the first, acting on the demand side of the tables; the second, acting on the supply side. For the analysis of this paper, we apply the two shocks simultaneously. The shocks are operationalised by using GDP-at-risk data from SPGlobal to reduce both final demand FD as well as total gross output X in the IO model, thus capturing both demand and supply effects. In the current formulation, we introduce the shock by reducing final demand and productive capacity of all the sectors residing in each country by the estimated losses for that country in the SPGlobal data[4]. The next section describes the model mechanism in more detail.

4. Model description

We will start by providing a general overview of the model dynamics before describing the dynamics of the physical risk shocks in more detail. The initial ICIO tables allocation represents a global economy in equilibrium, where all available inputs are transformed into outputs. Building on Pichler and Farmer (2022), the model we develop relies on a bottom-up approach for finding feasible market allocations given the exogenous shocks to final demands and maximum productive capacities. Conceptually, country-sectors place orders to their suppliers based on the incoming total demand they face. Because suppliers' production capacity can be constrained, either directly by the exogenous production shock or by insufficient inputs, they might not be able to satisfy the orders they receive. For the purpose of the model, we assume that country-sectors who cannot fully satisfy their customers demand share the restriction equally across all their deliveries. In addition, we assume that country-sectors who face new demands which are less than their production capacity accumulate inventories without incurring additional costs. Lastly, we assume that country-sectors which are input-constrained can shift their input sourcing from output-constrained country-sectors to other country-sectors which operate in the same global sector (e.g. steel production) and have accumulated inventories. A key component of this mechanism of the model is the *trade reallocation capacity* parameter, which determines the ease of reallocating input sourcing withing global sectors. We expect that the reallocation of trade would reduce the impact from the simultaneous shock that could be realised by a model such as Pichler and Farmer (2022) with fixed Leontief production functions.

Research about vulnerabilities and reallocation of global supply chains has increased recently due to climate change, the US-China trade conflict, and the COVID-19 pandemic (Bown et al 2018). Alfaro and Chor (2023) show how friendshoring, nearshoring, and reshoring of supply chains related to the US

[4] In reality, different industries will be affected differently depending on factors such as their geographical location, dependence weather conditions, insurance protection, etc. This simplifying assumption allows nonetheless to grasp the amplification effects through trade connections.

has been a reality for many decades. More generally, Baldwin et al. (2023) also follows a holistic approach in analysing supply chains by using input-output data, showing how the location of the production of intermediate goods and final goods has varied over time. In other words, trade reallocation has continuously occurred in the past, and it is also realistic to assume that future climate shocks will come along with certain reallocations.

Following conventional IO notation, we separate total gross output X[5], a vector of the size of the number of countries times sectors, into intermediate use A·X and final use FD (see for example Baldwin et al (2022) and figure 1 for reference):

$$X = A \cdot X + FD$$

Note that AX equals matrix Z in figure 1. The entries of matrix A are called input-output coefficients and are ratios. A_{ij}, for example, represents the units of inputs from sector i., e.g. metal parts, that sector j has to acquire in order to produce one unit of its good, e.g. a car. Each column of matrix A, i.e. A_j, represent the total collection of input ratios for the production function of country-sector *j*. Throughout the rest of the paper, we use the subscript i to refer to producing/selling sectors and the subscript j to refer to using/buying sectors. Rearranging the identity is useful to understand the output of each sector needed to produce a given vector of final demands FD:

$$X = (I - A)^{-1} \cdot FD$$

Where I is the identity matrix, and $L = (I - A)^{-1}$ is typically called Leontief inverse. One way to analyse climate shocks would be to shock FD and then infer a new equilibrium vector of total outputs using the Leontief inverse. This approach is commonly referred to as the "demand-driven" Leontief model, and it represents the classical approach to input-output modelling (Oosterhaven, 1996). The shock would transmit through backward-linkages, e.g. showing how a loss in final demand in Asia causes lower output in Europe, because less goods are now demanded overall. However, climate change-related natural hazards also affect the productive capacity of countries they hit, thus constraining gross output, and creating supply-side shortages. To account for these forward-linkages, we therefore go beyond the pure Leontief approach by adding a simultaneous productive capacity shock.

4.1 Shock propagation algorithm

[5] Gross output does not equal GDP, i.e. not only the value added, but the sum over all the things that the country buys domestically or abroad, both intermediate and final demand.

Initially, an exogenous set of climate-related shocks is introduced to final demand and total production capacity. We assume this is the immediate result of the realisation of natural hazard risk from climate change, where all risks realise simulateneously and in a deterministic manner. The post-shock global final demands vector is defined as

$$fd^{max} = FD \cdot (1 - d_{shock}),$$

where FD is the aggregate final demand taken from the input-output data, and d_{shock} is the column vector of demand shocks. The vector d_{shock} is constructed by assuming that a loss in purchasing power in country results in relative reduction in demand for all goods homogeneously.

Similarly, the post-shock maximum production capacity is given by vector

$$x^{max} = X \cdot (1 - p_{shock}),$$

where X is the aggregate final demand taken from the input-output data, and p_{shock} is the column vector of production shocks, also constructed to be homogenous at country level[6]. After the shocks are introduced, the propagation algorithm is set in motion.

As a first step, country-sectors determine the total gross output they need to produce given the demand shock, as if there were no supply-side constraints, i.e.

$$x^{md} = L \cdot fd^{max} \quad (1)$$

where x^{md} stands for output for maximum demand and L is the Leontief inverse. Note that this is how the traditional Leontief model would be solved, without considering forward-propagating shocks, i.e. assuming that each country-sector can still satisfy 100 percent of incoming demand despite having received a physical risk shock. However, following the approach of Pichler and Farmer (2022) we postulate that country-sectors can only satisfy the new incoming demand up to the supply ceiling determined by vector x^{max}.

As a second step, therefore, country-sectors determine if they can satisfy the new incoming demand, and consequently distribute the potentially scarce output among their customers. If a country-sector *i* can satisfy demand only partially, it will create a supply bottleneck to other industries due to proportional rationing. We can then calculate the vector *r*, which contains the fraction of total demand received that each country-sector *i* can satisfy. Each element of *r* is between 0 and 1 and is given by:

[6] Once more granular data will be available, shock vectors with country-sector specific shock can also be simulated.

$$r_i = \frac{x_i^{max}}{x_i^{md}} \quad (2)$$

Where x_i^{max} is the maximum productive capacity of country-sector *i* and x_i^{md} is the maximum demand country-sector *i* receives under the pure Leontief solution. We assume that in cases where rationing was needed, country-sectors would distribute output proportionally to their customers' demand, where no distinction is made between intermediate and final customers. Therefore, if a country-sector's constrained output is smaller than incoming demand, it will supply to customer j not the full desired amount but the demand of j times r_i.

As a third step, we calculate what would happen if country-sectors' productive capacity were defined by a Leontief production function with zero substitutability between any of the input factors[7]. In this case, the largest input bottleneck each country-sector faces will be the binding constraint for their total production. Given that A_j is the vector of technical coefficients of country-sector j, extrapolated from the matrix of technical coefficients A,[8] we can calculate the vector of production constraints for all country-sectors due to input bottlenecks. Each element of vector *s* is between 0 and 1 corresponds to the largest production constraints among all of j's suppliers such that:

$$s_j = \min_{i:A_{i,j}>0} \{r_i\} \quad (3)$$

The fourth step is to calculate the new hypothetical distribution of intermediate outputs across the whole country-sector network that would realise if country-sectors used pure Leontief production recipes. The constrained input-output matrix Z^{cons} represents the new pure Leontief allocation of output given demand reduction and production constraints. The new input-output matrix is obtained by multiplying each of the intermediate output quantities coming from the ICIO data (*Z*) by what represents the most sizeable constraint between the direct production shock and the input bottleneck constraint faced by country-sector *i*. Each row of the Z^{cons} can be then determined as:

$$Z_i^{cons} = Z_i \cdot \min\{s_i, (1 - p_{shock_i})\} \quad (4)$$

As a fifth step, we can calculate another hypothetical distribution matrix, which represents the intermediate output distribution that would be needed to satisfy aggregate demand x^{md} given a pure Leontief allocation. We call this matrix Z^{need} and, noting that the matrix A is the matrix of pure Leontief

[7] Under the original Leontief framework, country-sector A1 cannot substitute imports of steel from country B with imports of steel from country C. If country-sector A1 receives 10% less steel from country B, it will be able to produce 10% less of its output, no matter the quantity of steel coming from country C.
[8] This is discussed in the section on Input-Output data.

technical coefficient, we can extrapolate each of its elements such that:

$$Z_{i,j}^{need} = A_{i,j} \cdot \min\{x_j^{max}, x_j^{md}\} \quad (5)$$

The difference between Z^{need} and Z^{cons} gives us the matrix of unfulfilled intermediate inputs demand. Each element of the matrix of unfulfilled demands represents the extra demand that country-sector *j* would have for inputs for sector i, if the Z^{cons} allocation was to realise. This passage is important, because it shows the incentive for country-sectors to try and restructure their import sourcing: they face incoming demand larger than what they would be able to produce without restructuring imports. If they were able to restructure their input sourcing, they would increase their sales, given that demand is there. From the Z^{need} matrix, we can extrapolate the matrix of unfulfilled (extra) demands exD for inputs across the whole system. Each row of exD captures the extra demands received by each country-sector *i* from all the country-sectors *j*. Each row is given by:

$$exD_i = Z_i^{need} - Z_i^{cons} \quad (6)$$

For the sixth step, we calculate the difference between the total production capacity of each sector and the total demand that they would face if the pure Leontief Z^{cons} allocation was to realise. We assume that this difference can be collected as inventories[9]. The inventories of country-sector *i* represent the difference between what could be produced by sector *i* after the supply shock realised and the demand they would face if a pure Leontief reorganisation of the global economy were to happen. Inventories are output which is not wanted anymore but was produced. For each country-sector i, inventories are calculated as:

$$inv_i = \max\{x_i^{max} - fd_i^{max} - \sum Z_i^{cons}, 0\} \quad (7)$$

We now know which country-sectors across the globe have a stock of intermediate goods which could be accessed by input-constrained country-sectors. To allow for the reorganization of supply networks, we relax the assumption that each country-sector *i* produces according to a pure Leontief production function where the inputs of each country-sector *j* are not substitutable. Instead, we assume that the Leontief production structure remains, but inputs are not substitutable only *across* global sectors, while there is perfect substitutability for the inputs *within* a global production sector. To make an example, this means that the auto industry in Germany needs a minimum quantity of steel to produce a unit of its output, but it does not matter what the composition of the supply of steel is (whether it comes from North America, Europe or Asia). With this assumption, country-sectors have the possibility to reallocate

[9] For the scope of this analysis, we abstract from the accounting for the costs related to inventories.

the supply side of their Global Value Chain to mitigate the input bottlenecks they face. The reallocation can only take place towards country-sectors that have accumulated inventories. By repeating the example above, the German auto industry can overcome an input bottleneck caused by the decrease in delivery of steel from North America by sourcing steel from Europe, if Europe has available output inventories. To summarize, reallocation of supply chains happens because country-sectors could sell more of their output if they were able to produce it, and the lines along which reallocation can happen depend on the inventories country-sectors have accumulated. To our knowledge, this reallocation mechanisms is a novel contribution that our model makes to the literature.

The seventh step in the propagation of the shocks is to calculate a vector sub where each element is the ratio of total inventories that a global sector has accumulated over the extra demand that the global sector faces. We use the subscript sec to refer to global supply sectors. A global supply sector collects all the country-sectors i which produce the same goods category, e.g. steel. The vector sub has the same length as the number of global sectors recorded in the IO matrix. We name this vector sub, because it represents the ratio of unfulfilled demand that can be met by *substitution,* i.e. relocation of input sourcing within a global sector. Each element of the vector is calculated as:

$$sub_{sec} = \sum_{i \in sec} \frac{inv_i}{\sum exD_i} \tag{8}$$

The eight step is to reallocate inventories across global sectors to reduce supply bottlenecks, knowing how much of the aggregate extra demand can be satisfied by inventories for each global sector. We then calculate a new output allocation matrix Z^{new} where each element is given by:

$$Z_{i,j}^{new} = \min\{Z_{i,j}^{cons}, Z_{i,j}^{need}\} + \gamma \cdot \frac{inv_i}{inv^{sec}} \cdot exD_j^{sec} \cdot sub_{sec} \tag{9}$$

where inv_i are the extra inventories of country-sector i, inv^{sec} are the total inventories of the global sector to which i belongs, and exD_j^{sec} is the aggregate extra demand from country-sector j for the global sector to which i belongs. This formulation allows to shift supply that was previously coming from countries who are now not able to produce anymore to countries that have available inventories. The parameter γ introduces the *trade reallocation capacity*, that is, the ratio of inputs that each country-sector can reallocate in the supply GVC network without cost. The parameter can range between 0 and 100 percent, where 0 means no capacity to reallocate trade networks, while 100 means perfect ease of movement[10]. In the current implementation of the model, all country-sectors have the same trade reallocation capacity. Moreover, available inventories are proportionally allocated across all the

[10] We are aware that in reality this parameter would be endogenous. However, for the scope of this analysis we set its value and test the sensitivity of results to its changes.

demanding country-sectors.

Figure 3 illustrates the working of the trade reallocation mechanism in more detail and provides an example. On the left-hand side we find the hypothetical Z^{cons} matrix, with the red circles annotating how much extra demand each country-sector j has for each input-producing country-sector i. The matrix also reports the total inventories that each producing sector has accumulated as well as the aggregate demand from all country-sectors j for the global steel production sector, of which all the i country-sectors are part. In the example, the total aggregate demand for steel is the same as the total inventories in the steel sector, therefore all the extra demand could be satisfied if there was perfect trade reallocation capacity. The right-hand side of the figure reports two potential reallocation outcomes. The top matrix derives from a system where there is 100 percent trade reallocation capacity, while the bottom one from a system with only 50 percent. One can note how India's steel sector, which is subject to significant extra demand but has no inventories to satisfy it ends up with no additional trade allocated to it. The extra demand for its output is instead captured by the other steel producers, proportionally to the inventories they had accumulated.

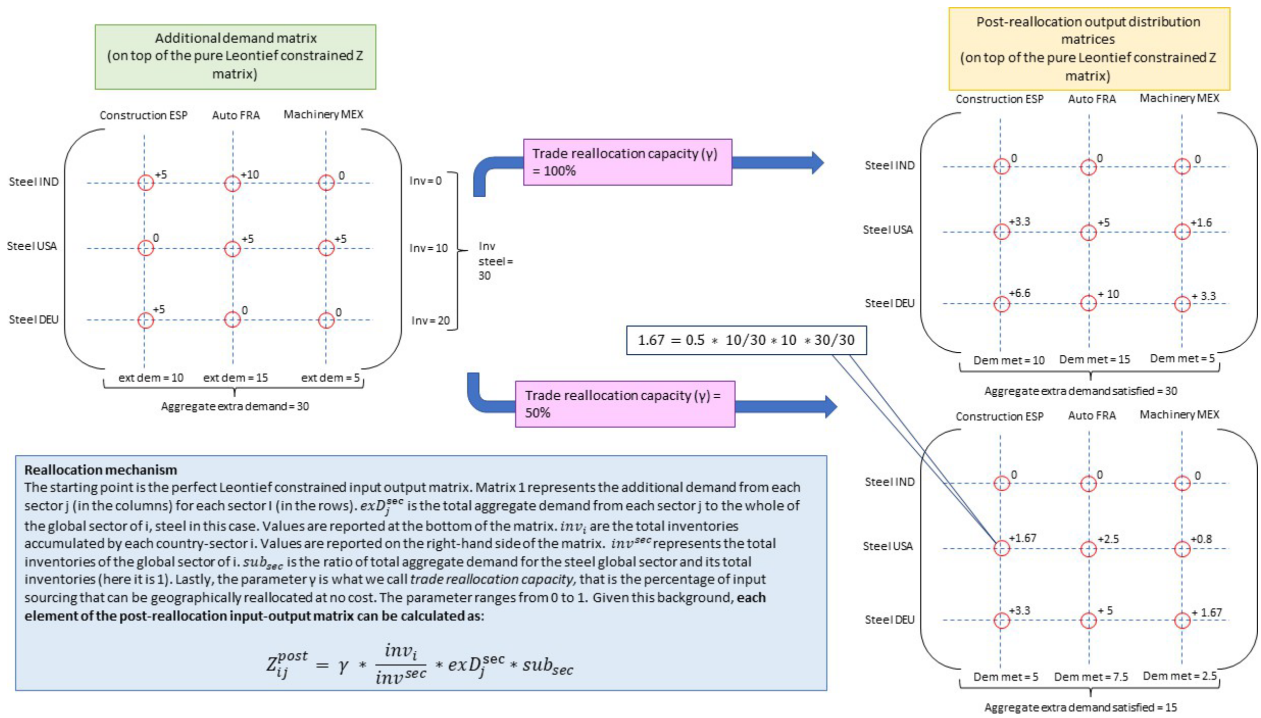

Figure 3: Illustration of the trade reallocation mechanism

Source: ECB

For the ninth step, we need to calculate how much output each country-sector i can produce after the restructuring of supply chains. To leverage on the possibility for trade reallocation, we extrapolate an intermediate output matrix where global sectors are aggregated, which we label ZG. This matrix is obtained by summing all rows that belong to the same global sector in the original Z matrix, so that we go from a (3195 x 3195) matrix to a (45 x 3195) matrix. This is used to calculate total output reflecting the global Leontief production function where there is no substitutability only at global sectors level. From the ZG matrix, we can extrapolate a global sectors technical coefficients matrix AG, which reports the ratio of each global sector inputs to output produced for each country-sector.

From the final input-output matrix Z^{new} we can extrapolate a matrix where global sectors are aggregated ZG^{new}, calculated in the same fashion as the matrix ZG. By using the global technical coefficients matrix AG, which can be extrapolated from ZG in the same way as A can be extrapolated from Z, we can calculate the final output that each sector produces, based on the minimum of its global production function inputs. Each element of the aggregate output vector is obtained as:

$$x_j^{new} = \min_{i:ZG_{i,j}^{new}>0 \wedge AG_{i,j}>0} \{\frac{ZG_{i,j}^{new}}{AG_{i,j}}\} \tag{9}$$

For the tenth and final step, given the new vector of gross outputs, we need to check whether this completely satisfies the post-shock aggregate demand d^{new}. If this is not the case, we are basically faced with a further reduction of aggregate demand. Therefore, we calculate a new vector of aggregate demands d^{new}, equivalent to the new total outputs and we reiterate through the algorithm again, starting from equation (1). The iteration through the algorithm continues until the condition is met. At this point, we have the final distribution of outputs following the propagation of simultaneous final demand and production shocks.

5. Results

5.1 GDP Losses

Before showing the empirical results of the model, we quickly recap the key assumptions of the model. First, we consider GDP-at-risk by 2050 under an adverse RCP 8.5 scenario. We assume that these GDP-at-risk numbers affect today's input-output (IO) relationships. If all hazards realized simultaneously, the GDP-at-risk numbers become actual GDP losses. Second, we assume that the hazards affect both the supply and demand side of today's global IO relationships, and we assume a variable degree of trade reallocation. With no trade reallocation, the decline in production and demand in one country can significantly alter the output and demand in other countries because we do not allow for any substitution. Third, the model abstracts from the effects of physical risk on other macroeconomic variables besides

IO quantities, like prices, employment, financial flows, or distributional aspects. Against the backdrop of these assumptions, we find that direct output losses due to physical hazards are amplified many-fold by IO linkages. We consider the most adverse scenario, where all physical hazards under the RCP 8.5 scenario in 2050 materialize globally. In this scenario, the GDP in the global regions falls by their respective direct GDP-at-risk value (see Figure 1, and figure 4, in yellow). South Asia is the most affected region, with GDP declining by 15 percent due to direct physical hazards. Countries in Central Asia, Sub-Saharan Africa, and the MENA region experience the second largest GDP shock due to physical hazards. Countries in Europe experience a direct climate GDP shock of 0.7 percent because they are relatively less exposed to extreme hazards. Note that these regional numbers are averages and that GDP-at-risk can vary considerably across countries within these regions.

Once these initial shocks propagate through IO-linkages, GDP-losses are amplified manifolds. Figure 4 reports the total GDP losses per region after accounting for trade interconnections. Note that these numbers can alternatively also be interpreted as the GDP-at-risk. The loss estimates vary depending on the global *trade reallocation capacity,* where the figure shows the two extreme cases, a capacity of 0% or 100%. The former case can be considered a worst-case scenario, while the latter a hypothetical best case. The red dots in figure 4 also report the average values of GDP losses (respectively GDP-at-risk values), obtained from a sensitivity analysis over the whole parameter space for the trade reallocation capacity. Sub-Saharan Africa is the region that suffers the highest losses from the IO amplification, with the best-case scenario showing losses of around 9% of GDP on average for the region. The high loss happens despite the relatively low direct shock. A counter example is South Asia, the region with the highest direct climate shock, which faces a relatively negligible amplification of losses through IO linkages. In the EA, the amplified GDP loss is on average more than 15 times the direct climate shock, with a worst-case scenario showing aggregate losses of around 20% of GDP.

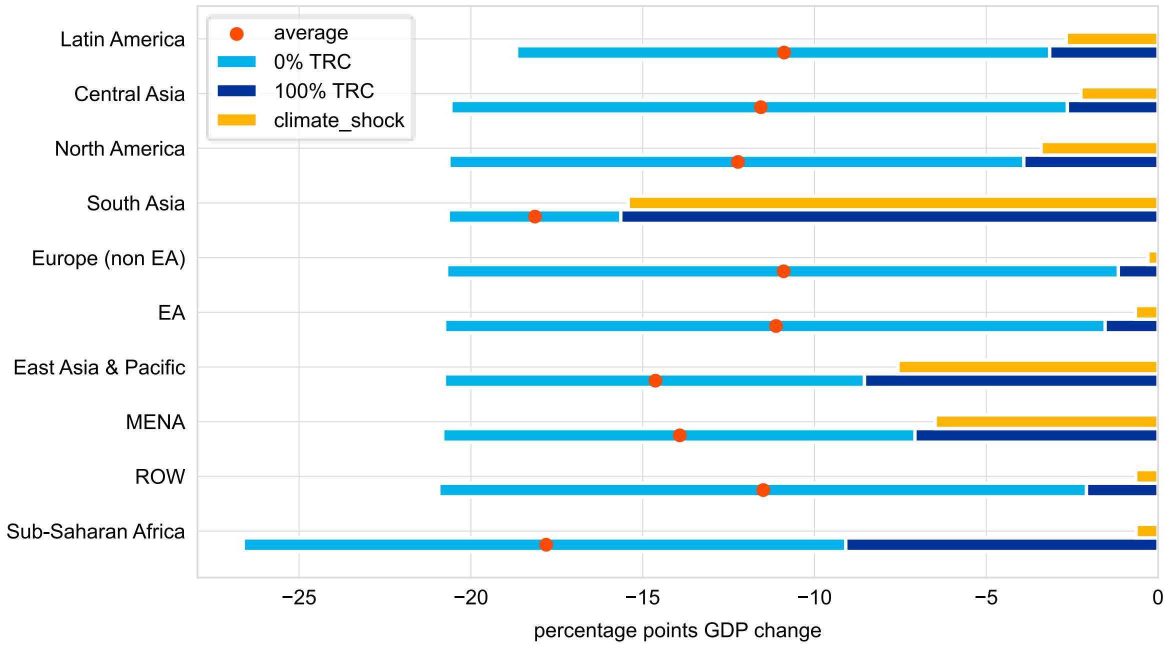

Figure 4: GDP-at-risk resulting from IO amplification of physical risks under the RCP 8.5 scenario. If all hazards were to realise simultaneously, which would be a very adverse scenario, the graph would indicate the associated realized GDP losses.
Source: SPGlobal, OECD ICIO, ECB calculations.

Figure 5 presents a breakdown of IO-amplified losses for EA countries, which varying climate shocks in the range between zero and 2.3 percent of GDP. Countries in Southern Europe, alongside the Netherlands and Belgium, are expected to suffer the highest direct losses from physical risks. On the other hand, several countries are expected to suffer close to zero direct losses in our adverse scenario. Under the adverse RCP 8.5 scenario and assuming that all hazards realized simultaneously, on average, the aggregate EA losses from the amplification through IO linkages are more than 11 percent of GDP, with the best- and worst-case scenarios losses ranging between 2 and 22 percent of GDP. The losses are heterogeneously distributed across EA countries, especially under perfect reallocation capacity. Here, Italy is the worst performer, showing almost double the loss than the best performer, Croatia. Considering the average losses, the field is more even, with every EA country showing aggregate losses of more than 10 percent of GDP. Some countries, like Germany and Luxembourg, see losses increase more than other countries for worsening trade reallocation conditions despite lower direct climate losses, showing the effects of their economies' dependence on trade.

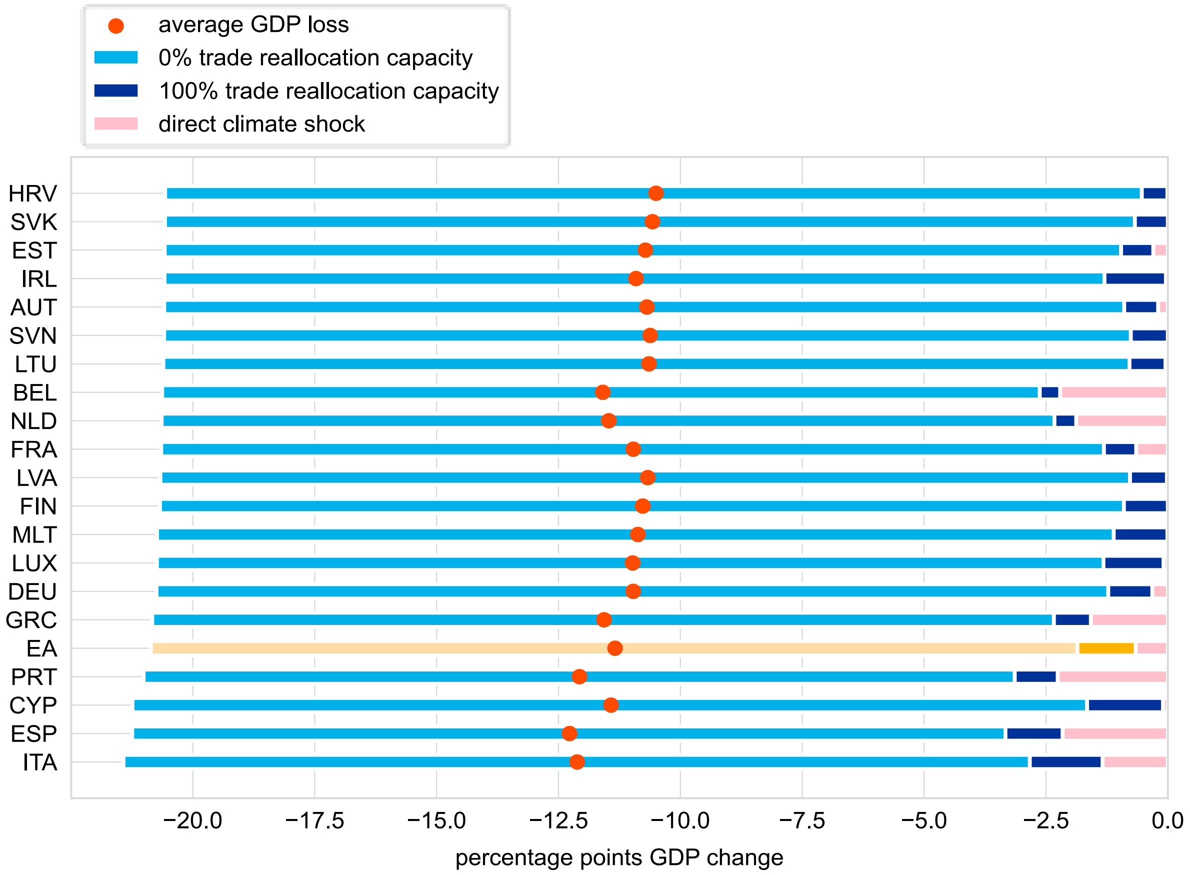

Figure 5: GDP-at-risk resulting from IO amplification of physical risks under the RCP 8.5 scenario. If all hazards were to realized simultaneously, which would be a very adverse scenario, the graph would indicate the associated realized GDP losses in Euro Area countries

Source: SPGlobal, OECD ICIO, ECB calculations.

5.2 Sectoral losses

Figure 6 presents a breakdown of the most affected sectors in the EA, in terms of Gross Value Added (GVA) losses, again considering the most adverse RCP 8.5 scenario where all hazards realize simultaneously (the numbers can thus also be interpreted as the GVA-at-risk). The results are computed by assuming a trade reallocation capacity of 50%. The wholesale and retail trade sector shows the most significant losses by far. A detailed analysis shows that the loss in GVA in these two sectors is due to a production shortage caused by a global shortage of two key sectoral inputs: IT products and raw materials produced in the mining sector. In general, the global production of technology largely depends on input production which takes place in countries in Asia. Therefore, the realisation of climate change physical risks will have a large impact on those sectors, in turn affecting the sectors in the European area that depend on technological inputs, as it is the case for the wholesale and retail and the real estate sectors.

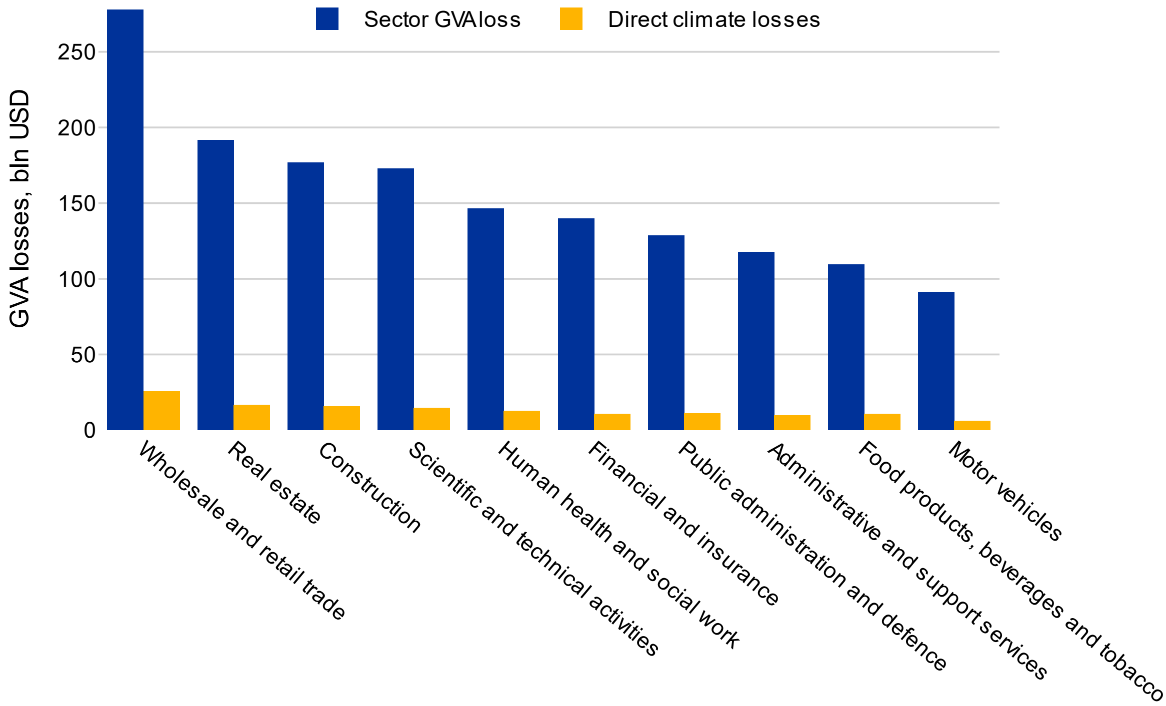

Figure 6: GVA-at-risk for the 10 most affected sectors, aggregated at EA level, under the RCP 8.5 scenario. If all hazards were to realize simultaneously, the numbers would indicate actual GVA losses.
Source: SPGlobal, OECD ICIO, ECB calculations.

Interestingly, sectors such as construction, finance and insurance, and the public administration are expected to face significant losses. These sectors are key for the delivery of climate risk mitigation and adaptation policies. Significant losses in the wake of the realisation of climate physical risks could create a vicious cycle were those productive sectors which could act as barriers to the cascading impact of climate risks find themselves unable to intervene because of their reduced economic capacity. Similarly, the high expected losses for the health and social work sector could compound the existing vulnerability of people's health to physical risk impacts. Understanding these interlinkages is key for developing sound risk management plans for the future.

5.3 Discussion and assessment of the quantitative results

How do our results compare to those in the literature? The purely domestic shocks taken from SPGlobal are largely in line with the existing literature and do not appear to be particularly conservative. Naturally, they are in line with Formetta and Feyen (2019) as well as Roson and Sartori (2016) since these studies have been used to develop the dataset in the first place. Moreover, the NGFS (2022) for example expects global GDP to decline by 5 per cent by 2050, whereas the data by SPGlobal estimate the decline to be slightly more optimistic with only around 4 percent. The country-level shocks are also roughly in line with existing literature. We shock US GDP by 4.1 percent, whereas Nordhaus (2017) expects US GDP to decline by 3.2 percent. Hsiang et al (2017) estimate for the US is "roughly 1.2% of gross domestic product per +1°C on average". In our RCP 8.5 scenario, temperatures would increase by around 2-3 degrees Celsius by 2050, so that the authors would predict losses amounting to 2.4 to 4 percent of GDP. This also appears in line with our data, where we appear to be on the conservative end of the authors' spectrum. Note that for many countries, climate-related GDP impacts are not readily available as they require both forward-looking climate scenarios as well as the associated damage functions. For Switzerland, for example, as well as many other countries, such scenarios do not currently exist (SNB, 2024). Note that the input shock of our model, i.e., domestic physical risk effects, can easily be updated once novel data becomes available. Similarly to how countries across the globe fail to achieve measurable CO2 targets, they also appear to fail in producing globally consistent and granular climate-related scenarios.

Once IO-linkages are taken into account, our estimated GDP-at-risk or GDP losses are way higher. Given the novelty of our research in taking these effects into account, it is obviously difficult to compare them to any existing literature. SwissRe (2021) is an exception as they capture supply chains, although through more ad-hoc expert judgments. The Swiss insurer finds that GDP could globally decline by up to 18 percent in the "severe case", which is similar to the RCP 8.5 scenario that we consider. Our findings of around 20 percent GDP losses are thus in line with this exceptional study of SwissRe.

Why are our GDP losses or GDP-at-risk numbers larger than those typically considered, as in NGFS (2022)? Since our purely domestic shocks are roughly in line with the literature, the higher magnitudes can largely be associated to the way we model IO linkages. While the relatively high numbers might appear surprising at first sight, they are indeed intuitive once we recap the structure of our global economy. The trend of globalization that has accelerated with the opening of China a few decades ago led to trade in goods and services now making up more than 20 percent of GDP. Supply-chains can easily span across dozens of countries. If such an interconnected structure is hit, the domestic effects can be manifold higher. The ability to source from other country-sectors can significantly reduce this effect, so that our estimates for a trade reallocation capacity of 0 percent appear clearly too conservative. On the other hand, it is also clear that certain inputs and outputs are, at least in the short-term, not substitutable. We leave it to future research to empirically estimate the trade reallocation capacity.

Besides the large variability of our results depending on the possibility to reallocate trade, we also must keep in mind that our IO model does abstract from important macroeconomic effects. Effects that could both, aggravate and mediate the risks. Consider the following four key assumptions:

(i) Prices including exchange rates as well as financial flows do not change: in reality, shortages in goods and services would cause prices to adjust, which are, in monetary market economies, an important signal for producers and consumers to adjust their behaviour, likely mitigating welfare losses. Moreover, exchange rates and capital flows would react. These flows could worsen losses if e.g. foreign investors quickly want to leave a damaged country. If, however, private or public capital is mobilized for reconstruction or mitigation, GDP losses could be smaller.

(ii) No policy responses: in reality, governments would likely hardly act before such hazards realize, but would act with certainty once such adverse scenarios realized. Mobilization of fiscal resources, the military, new laws relating to rationing or price controls as well as redistributional policies would be possible and could mitigate impacts.

(iii) No dynamic adjustment: our model is not dynamic although today's IO structure could change until the projected hazards realized. It is also unlikely that all hazards realize at the same time. It is more likely that they occur over the scope of several years, and that economic networks will adjust accordingly. For example, if a factory has been destroyed by a flood, the owner is likely to rebuild it at another less risky place. Future shocks might thus have a smaller effect. Moreover, elasticities of substitution are not part of the model, or are limited to the trade reallocation capacity, but would be important in reality and can also change over time.

(iv) Other macroeconomic variables are not affected: in reality, the realization of adverse climate scenarios would also affect employment, productivity, health and geopolitical structures. All of them are not taken into account in the model but need to be kept in mind when drawing policy conclusions.

6 Concluding Remarks

This paper for the first time combines country-level GDP-at-risk data due to climate-related physical risks with a global country-sector-level Input-Output model. The findings are very intuitive: climate-related hazards can damage GDP significantly more heavily once global supply-chains are taken into account.

Nevertheless, the absolute numbers presented in this paper should be treated with caution or seen as GDP-at-risk. The key idea of this paper is rather to show that amplification matters. In this light, the amplification factors presented in this paper should be seen as possible ranges for how global supply chains can aggravate the situation, rather than precise estimates. For more reliable absolute GDP losses a couple of extensions would be needed.

On the one hand, consider the following effects that may lead to GDP impacts that are smaller than suggested in this paper: not all hazards may occur at the same time but may realize over several months or years – the probability for a certain hazard and thus GDP loss to occur in a specific point in time are not known on a global scale. Moreover, hazard impacts are not necessarily additive, i.e. if a flood destroys a field, a drought cannot destroy it a second time. In addition, adaption across various dimensions can lower GDP impacts. In particular, firms could change their input composition to produce similar outputs, i.e. deviate from today's Leontief production function with constant coefficients. Future models could include relative price changes to understand this channel in more detail. Lastly, some firms have an existing stock of inventories that could delay or mitigate the impact.

On the other hand, there are a couple of effects that can lead to larger GDP impacts. Tipping points, interdependent hazards as well as wildfires are not part of the physical risk data used. Similarly, migration, diseases and political instability are not accounted for but could significantly lower GDP. Finally, GPD losses can feed into financial sector losses, which can in turn have an effect on the real economy. Future models could try to implement the potential contagion between the real and financial sphere.

One of the important parameters that can increase or decrease hazard-related GDP impact is the substitutability across country-sectors. Future research should examine more closely the role of both partially substitutable inputs, and critical inputs that are less substitutable or not substitutable at all, such as in the food sector or specific technologies. This could be done along the lines of Pichler et al (2022, appendix C), who use survey data to estimate critical vs. non-critical inputs during a lockdown in the UK, or along the lines of more complex general equilibrium models in the spirit of Baqaee and Fahri (2023).

Looking ahead, the bottleneck to more realistic climate change assessments appear to be the availability of granular, hazard-level physical risk data that are forward-looking and cover different, including adverse, scenarios. However, not analysing the amplification of climate risks through supply chains for lack of data could lead to a large underestimation of the risks posed by climate change for economic and financial stability.

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Appendix A. Indicators of vulnerability: looking beyond trade size

The implementation of the IO model allows to capture losses incurred by each country due to the vulnerability of the whole network of supply chains, which go beyond the direct exposure to high physical risk countries. To substantiate this intuition, we develop two metrics:

- Trade Risk Index (TRI): the percentage difference between each country's trade to GDP ratio adjusted and non-adjusted by physical risk exposure from SP global. Trade reallocation is assumed to be zero.
- First-order (trade-related) GDP losses (FGL): for each country, we shock exports and imports by their respective trade partners' SPGlobal shock (if Germany imports from Italy, and Italy is hit by 0.5%, then imports from Italy go down by 0.5%). It does not include second order effects, nor do we allow for trade reallocation.

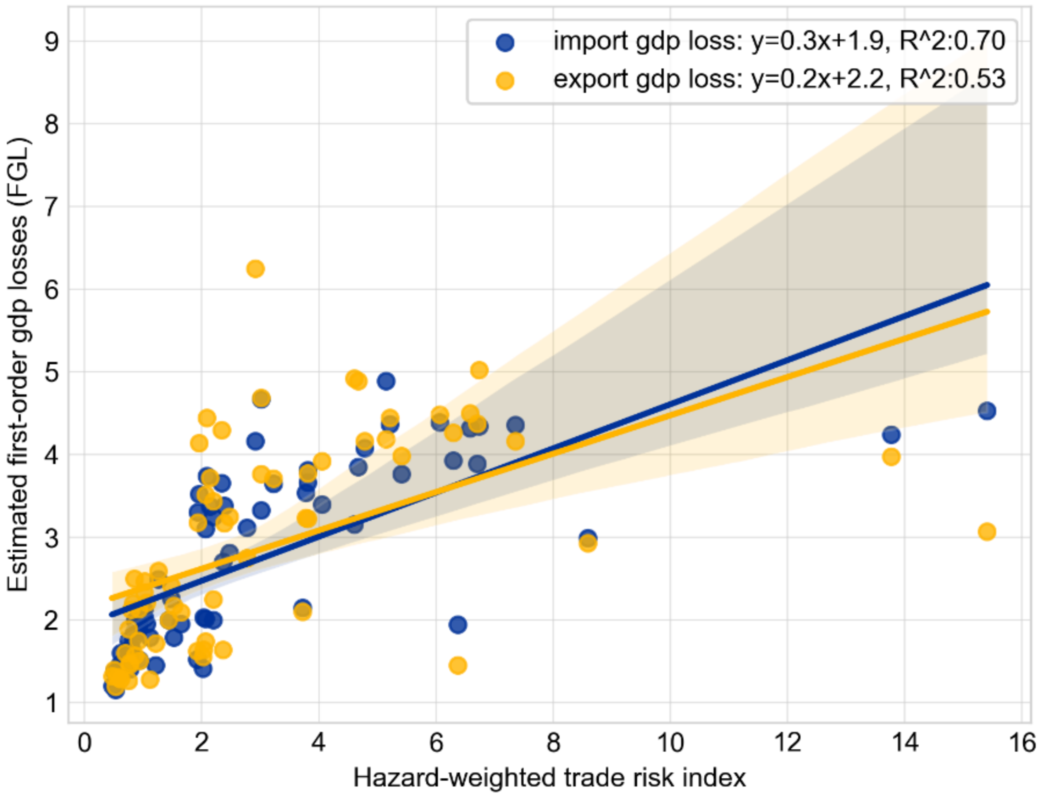

Figure 7: Correlation between hazard-weighted trade risk index and first-order GDP losses through trade.
Source: SPGlobal, OECD ICIO, ECB calculations.

Figure 7 plots the correlation between TRI and FGLs, divided between losses through imports and exports, for the 71 countries in the OECD sample. The correlation between the two indicators is significant and relatively large. This shows that countries who have a larger portion of their trade relations directed or incoming from countries exposed to physical risk will suffer higher first-order

GDP losses.

Figure 8, on the other hand, shows the correlation between the TRI index and the GDP losses at country level computed through the IO model for different values of the trade reallocation capacity parameter. The relationship is still significant, but of a much lower magnitude. In this sense, the exposure to physical risks of direct trading partners is a limited indicator for the amplification of losses through global value chains. This is because IO relationship takes into account the composition of the whole value chain and not only the exposures of direct trading partners.

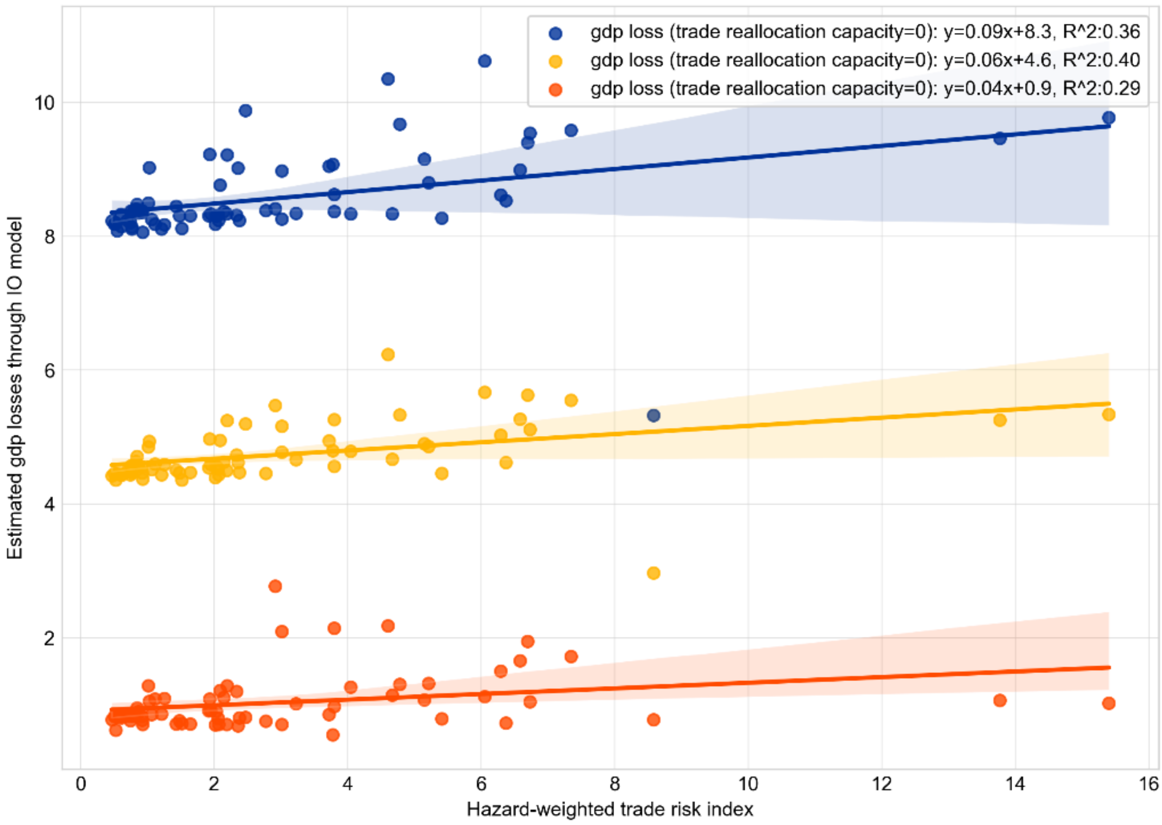

Figure 8: Correlation between hazard weighted trade risk index and GDP losses calculated through IO exposures
Source: SPGlobal, OECD ICIO, ECB calculations.

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