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Stressed economies respond more strongly to climate extremes

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E-mail: anders.levermann@pik-potsdam.de**Keywords:** economic stress, Covid-19, climate impactsSupplementary material for this article is available [online](#)**Abstract**

Economies experience stress for various reasons such as the global Covid-19 pandemic beginning in 2020. The associated lock-downs caused local economic losses and the disruption of international supply chains. In addition, such stress alters the effects of short-term shocks as caused by climate extremes, especially their propagation through the economic network and the resulting repercussions. Here we show that adverse indirect impacts of tropical cyclones, river floods, and heat stress on global consumption are strongly enhanced when the economy is under stress. This compound effect results from aggravated scarcity causing higher consumer prices. Modeling climate impacts during Covid-19, we find that in a stressed economy with the current network structure, consumption losses due to climate extremes double in the USA and triple in China. The simulated effects intensify when climate shocks grow stronger. Our results emphasize the amplifying role of the interaction between climate change and its socioeconomic backdrop.

1. Introduction

Emissions of greenhouse gases (GHGs) due to human activity have increased Earth's mean surface temperature by more than 1 °C compared to pre-industrial levels [1]. As a result, intensity and frequency of extreme weather events have increased [2, 3] with adverse impacts on society [4]. Events like tropical cyclones (TCs) [5, 6], heat stress [7], and river floods [8] can hamper economic output, causing direct local economic shocks. This shock can propagate along supply chains through the global economy [9], resulting in additional indirect effects on production, final consumption (simply consumption hereafter) and prices elsewhere [10]. Quantifying the total effect, that is, the sum of direct and indirect economic impacts, is a difficult task due to uncertainty associated with the direct shock as well as the resulting complex interactions in the economic network [11]. For example, compound extreme events can cause stronger indirect impacts than the extremes

in isolation [12]. Complexity is further increased through the interaction with a multitude of socioeconomic factors that determine economic vulnerability and resilience [13]. Most studies assess indirect economic effects of climate extremes in an isolated fashion, not considering interaction with major concurrent socioeconomic events. However, global economic stress induced by, e.g. major international conflicts and crises reduces the economic capacity to cope with shocks induced by climate extremes. Here, we assess to what extent such global economic stress amplifies indirect effects from loss propagation induced by climate extremes. We focus on adverse repercussions on consumption, a measure that is commonly used in disaster impact analyses to investigate welfare impacts [14, 15].

In recent years, the most severe global economic shock resulted from the Covid-19 pandemic of 2020 and onward. Over 630 million confirmed cases and more than 6.5 million deaths globally were reported to the World Health Organization [16]. Most

governments took a wide range of measures against the spreading of the virus. These unprecedented societal interruptions took their toll on economic activity [17]. The gross domestic product (GDP) decreased globally by 3.3% in 2020 [18] with adverse effects on consumption [19, 20]. Model-based studies have shown that direct production losses due to containment measures can spread in the economic network, magnifying the overall adverse economic repercussions [21]. As a result, exports and trade decreased globally [22], disrupting international supply chains [23, 24]. Similar knock-on effects occur in response to climate extremes, whereby local production losses from disasters propagate along supply chains and cause additional indirect losses [8]. At the same time, unaffected production sites in the economic network can also flexibly mitigate direct production losses of individual disasters to a certain extent [25]. This becomes less viable in a situation of global economic stress like the pandemic, thus likely affecting indirect repercussions of local economic shocks due to climate extremes. Yet, while most climate-related research on Covid-19 focuses on the accompanying beneficial reduction of GHG emissions [26, 27], little research [28, 29] exists on possible amplifications of adverse climate impacts through the pandemic. Still, evidence for compounding impacts from the interplay of climate extremes and pandemic stress has been presented in a recent study by Hu *et al* [30], who model GDP impacts using a hypothetical economy, pandemic stress, and flood shock. Here, we take a less stylized approach to assess how global economic stress can alter indirect economic impacts from climate extremes, using the Covid-19 pandemic and its economic repercussions as an example for global stress.

2. Method overview

We use a global agent-based loss propagation model with myopic profit-optimizing producers [31], which simulates perturbations of quantities of trade, production, consumption, and their prices on the economic network (given by the EORA [32] multi-region input-output table) in response to direct local economic shocks. The model computes the global indirect effects in response to these direct shocks from the interaction of over 7000 agents with more than 1.8 million trade links on a daily time scale. Simulating a socio-economic system's complex dynamics with an agent-based approach is favorable, because stylized facts of macroeconomic systems emerge from the interplay of individual heterogeneous agents [33–35]. Especially in complex environments marked by deep uncertainty, myopic expectations of agents as in the model used here may serve as suitable behavioral guidelines, rather than more complex foresight strategies like rational expectations [36].

The setup of our simulations is inspired by a storyline approach, where the impacts of a historical reference event are compared to alternative realizations of this event under counterfactual climate or socio-economic conditions [37, 38]. Recent studies have further extended the concept of storylines by incorporating complex socio-economic impact chains of climate extremes [39]. Accordingly, we define two scenarios under which economic loss propagation from climate extremes is simulated, varying the socio-economic backdrop. The two scenarios are framed as a 'stressed economy' and a counterfactual 'unstressed economy' scenario, under which indirect economic impacts from climate extremes are simulated. The scenarios are defined by their respective baselines, i.e. an economic reference simulation without climate shocks. Impacts from climate extremes under the scenarios are then simulated by adding local economic shocks from climate extremes (simply called direct shocks, hereafter) on the respective baseline. The unstressed baseline is a simulation with full economic capacity of all agents and without stress impacts from the pandemic. In contrast to this, the stressed baseline experiences regionally decreased economic activity. Since the pandemic caused economic stress both on the supply and demand side [40, 41], both productive capacity and demand by final consumers are reduced for the stressed baseline. We derive this reduction in economic activity (cf equation (S.9)) using the daily stringency index from the Oxford Covid-19 Government Response Tracker project [42], a compound indicator for the strictness of government measures in response to Covid-19. This index represents the stringency of governmental containment and closure measures on a country and regional level (see methods supplement for details). We calibrate the decrease in economic activity such that our model best reproduces observed GDP for the United States (USA) and European Union (EU, 27 countries of the EU as of 2020 after withdrawal of the United Kingdom) during the years 2020 and 2021 (supplementary figures 1 and 2, supplementary table 1).

Under both scenarios, we simulate a global ensemble of heat stress, river flooding, and TCs, and the resulting impacts on consumption. The ensemble consists of 200 region and sector-specific time series of direct shocks as provided by Kuhla *et al* [12]. These time series are derived from projections of four global circulation models (GCMs) from the climate model intercomparison project (CMIP) 5 ensemble under representative concentration pathways 2.6 and 6.0. Regional heat stress-induced production reduction is based on empirical evidence [43] of sector-dependent productivity loss linear to daily mean temperatures above 27 °C. Further, production capacity is reduced in regions that experience floods or a TC wind speed above 64 kn, whereby affected grid cells are assumed to be out of operation for the time. Flooded areas

are derived from a river routing model [44], driven by discharge time series from the used GCMs which are coupled with five hydrological models. Five wind field realizations are computed from a probabilistic TC emulator [45, 46] driven by the used GCMs. The resulting direct shocks locally limit productive capacity of exposed sectors and regions for the time of the disaster. Note that, unlike the global economic stress in the stressed baseline, shocks from climate extremes affect only productive capacity and not final consumption, implying a supply shock only. For more details we refer to the methods supplement and Kuhla *et al* [12].

3. Results

We assess the impacts of climate extremes on global consumption and prices under both scenarios. To this end, we compute deviations from the respective baselines under both scenarios. Specifically, for the unstressed scenario, we compute the difference between simulations of climate extremes and the undisturbed economy. For the stressed scenario, we compute the difference between simulations of climate extremes in conjunction with global economic stress, and a reference simulation with global economic stress only. Thus, we isolate the economic impacts attributable to climate extremes under both scenarios. This allows us to assess the extent to which these isolated impacts change under global economic stress. In the following, different goods and services are aggregated across economic sectors (simply ‘goods’). All results are shown as mean values of the ensemble. Where provided, error bars denote the 66% ensemble range (i.e. the 16.7 and 83.3 percentiles). Aggregated numbers are aggregates over the 2 year period of 2020 and 2021. Our simulations are conducted on a 2015 economic network (due to availability of the EORA data) and therefore, absolute values are in US dollars of this year.

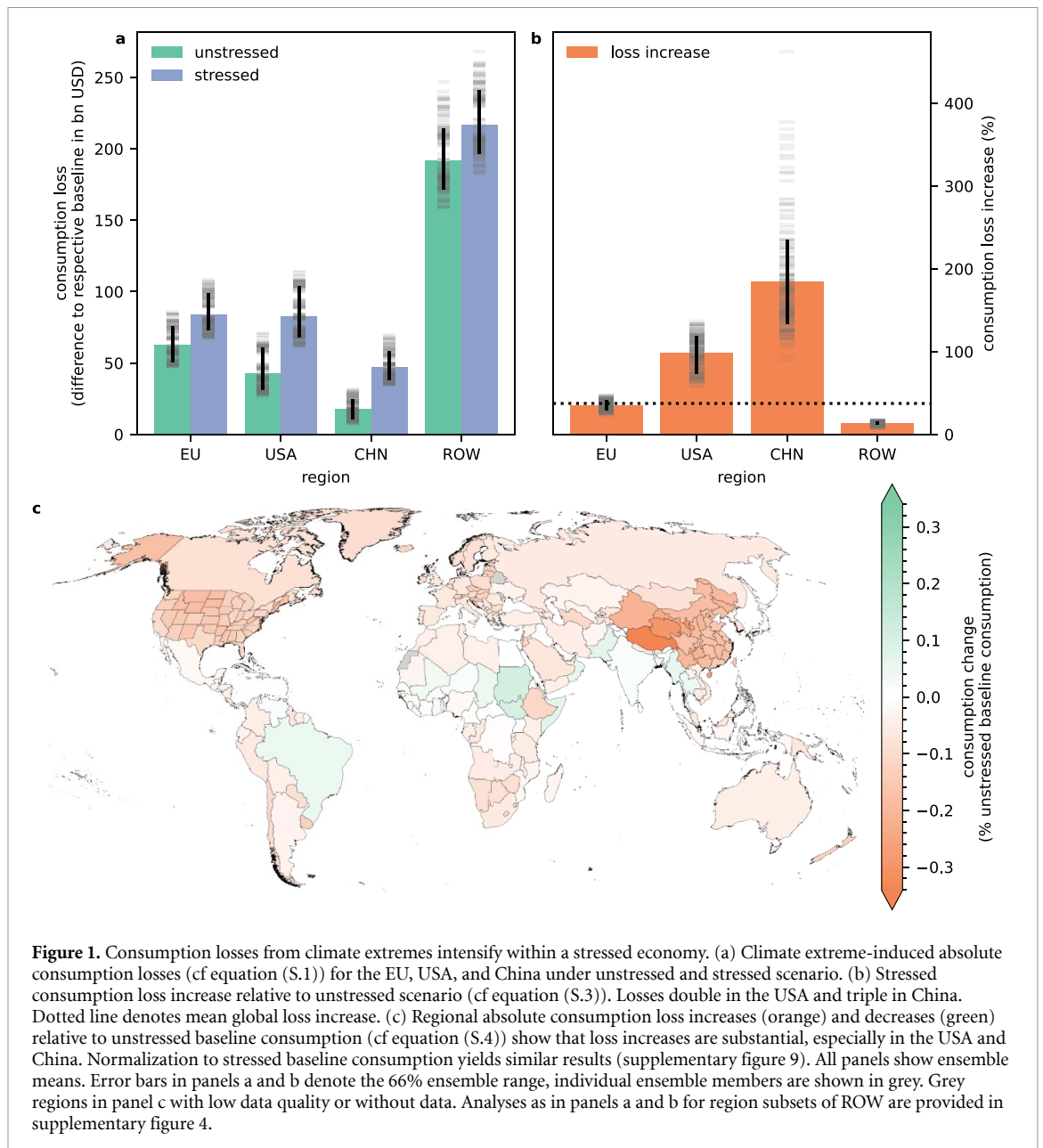
3.1. Consumption losses from climate extremes increase under global economic stress

Focusing on the three largest economies, we compute consumption losses for the EU, USA, and China (CHN), while aggregating the rest of the world (ROW). Additional analyses for a more detailed aggregation than ROW are provided in the supplementary information (see supplementary figures 3–7). A full regional breakdown of losses is provided in supplementary table 2. Lost consumption in response to climate extremes is the difference in consumption quantities to the respective scenario baseline consumption. Figure 1 shows consumption losses for both scenarios (panel (a)) and the relative loss increase from the unstressed to the stressed scenario (panel (b)) as well as the regional absolute increase relative to the unstressed baseline consumption (panel (c)).

Globally, losses amount to \$314bn in the unstressed and \$430bn in the stressed scenario, hence an increase of 37%. In both cases, ROW shows the largest consumption losses, also when normalizing to baseline consumption (supplementary figure 8). However, comparing between the scenarios, the impact of the global economic stress is strongest in the other regions, with consumption losses almost tripling in CHN, doubling in the USA and increasing by 35% in the EU. Note that these are averages across the ensemble and that the entire ensemble range contains much stronger increases, which is informative of possible extreme risk. The pronounced increase for the USA and CHN persists when normalizing to the unstressed baseline consumption of these regions, showing that the increase of consumption losses is substantial. Hence, vulnerability to consumption losses from climate extremes is strongly increased in the USA and CHN when the global economy is under stress. For example, while absolute consumption losses in the EU exceed those of the USA in the unstressed scenario, they are about equal in the stressed case. Notably, there are also few ROW regions where consumption losses decrease with the stressed scenario (green regions in figure 1(c), e.g. Brazil, countries in the the Sahel region, and South Asia; cf supplementary figure 4). In the economic network simulated here, agents decide on their production, purchase, and allocation of trade based on local optimization principles. This yields complex interactions on a daily basis, whereby reallocation of flows influences prices and consumption. This leaves some regions better off in the stressed compared to the unstressed scenario, e.g. when they can lower prices locally due to beneficial reorganization of domestic production in response to lower foreign demand. It should be noted that all regions with consumption increases are nonetheless in the ROW, which displays the largest consumption losses in both scenarios. Globally, net consumption losses yield an overall increase. Therefore, we further investigate the strong loss increases as shown in figure 1 and the underlying mechanisms, focusing on the EU, USA, and CHN as the world’s largest economies.

3.2. Loss increases result from amplified price response

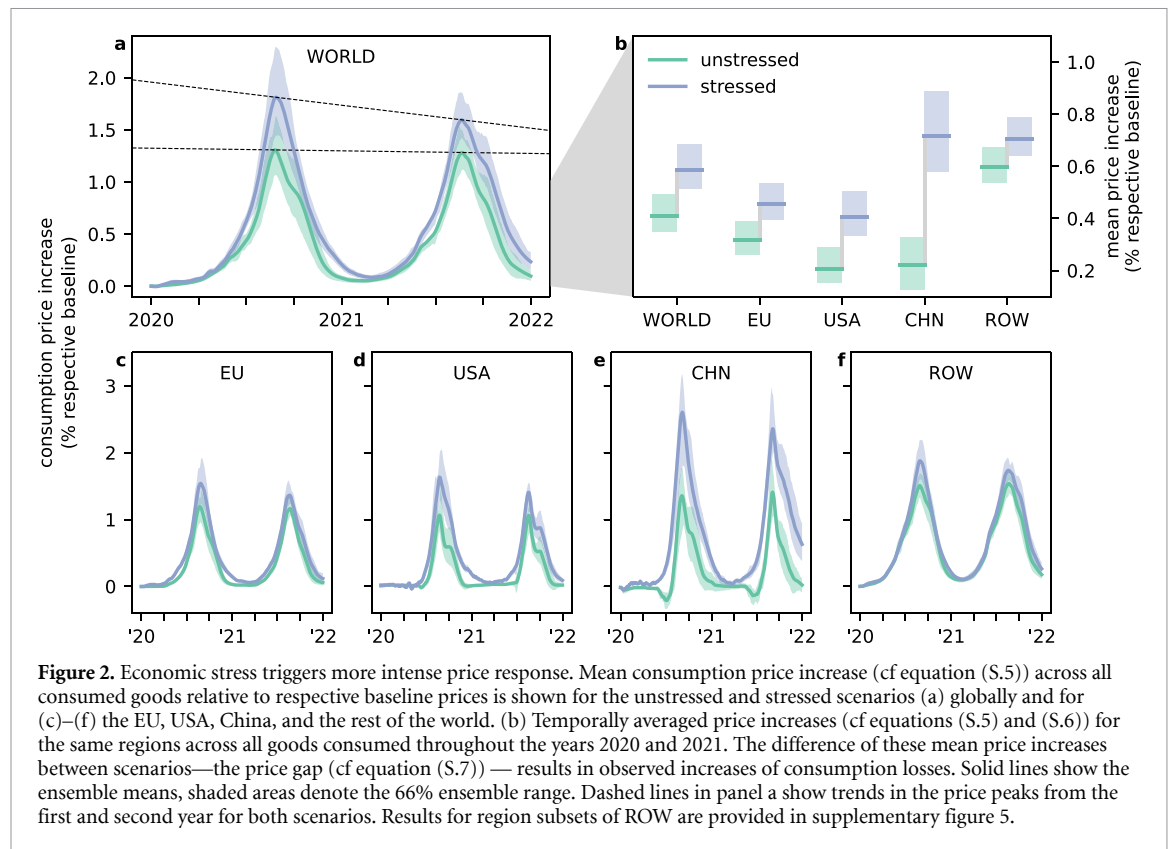
In both scenarios, production capacity is temporarily reduced in regions that suffer from direct shocks. This has effects on both their demand and the supply they can provide as well as the prices charged for produced goods. Reduced production capacity can—to a certain extent—be compensated through production extension. In production extension, marginal production costs increase, resulting in higher prices of the supplied goods. The amount of lost production from the shock that is not compensated this way results in decreased supply on the downstream side and reduced demand for intermediate goods on the



upstream side. Perturbations to the baseline are eventually passed on to final consumers in the form of prices who react by adjusting their purchasing behavior. Through differing exposure to climate extremes as well as economic linkages, prices and price changes can be regionally heterogeneous, resulting in regionally different consumption behavior. Figure 2 shows the temporal evolution (panels a, c–f, equation (S.5)) of consumption price changes and the 2 year average deviation (panel b) from the respective baseline price in response to the simulated climate extremes.

All regions show seasonal price behavior with peaks in the northern hemisphere summer, resulting from the seasonality in the climate extremes, in particular, heat stress [12]. Globally, consumption prices increase by up to 1.8% in the stressed but only up to 1.3% in the unstressed scenario. Comparing price spikes of 2020 and 2021 reveals

that this amplification abates with the global economic stress (dashed lines in figure 2(a)). We define the ‘price gap’ as the percentage point (‘pp’) difference in average price increases between scenarios (see equation (S.7)). Increasing consumption losses in the stressed scenario are caused by a larger price gap (supplementary figure 10), rather than the absolute level of consumption prices. For example, the price gap for China is about 0.5pp (figure 2(b), difference between the two scenarios’ average price increases), resulting in the largest consumption loss increase in the simulations (figure 1(b)). By contrast, ROW consumption prices in the stressed scenario are at the same level as those in China, but increase only slightly compared to the unstressed scenario. Therefore, consumption losses only increase moderately in ROW compared to other regions. However, it should be noted that ROW is only in a better position in a sense



that the consumption loss increase between scenarios is small (figure 1(b)) and not with regards to absolute consumption losses. Put differently, adverse consumption impacts from climate extremes in ROW regions are strongest, but intensify least with global economic stress. The USA and CHN show the opposite behavior. Here, consumption losses are smallest but increase the most under global economic stress.

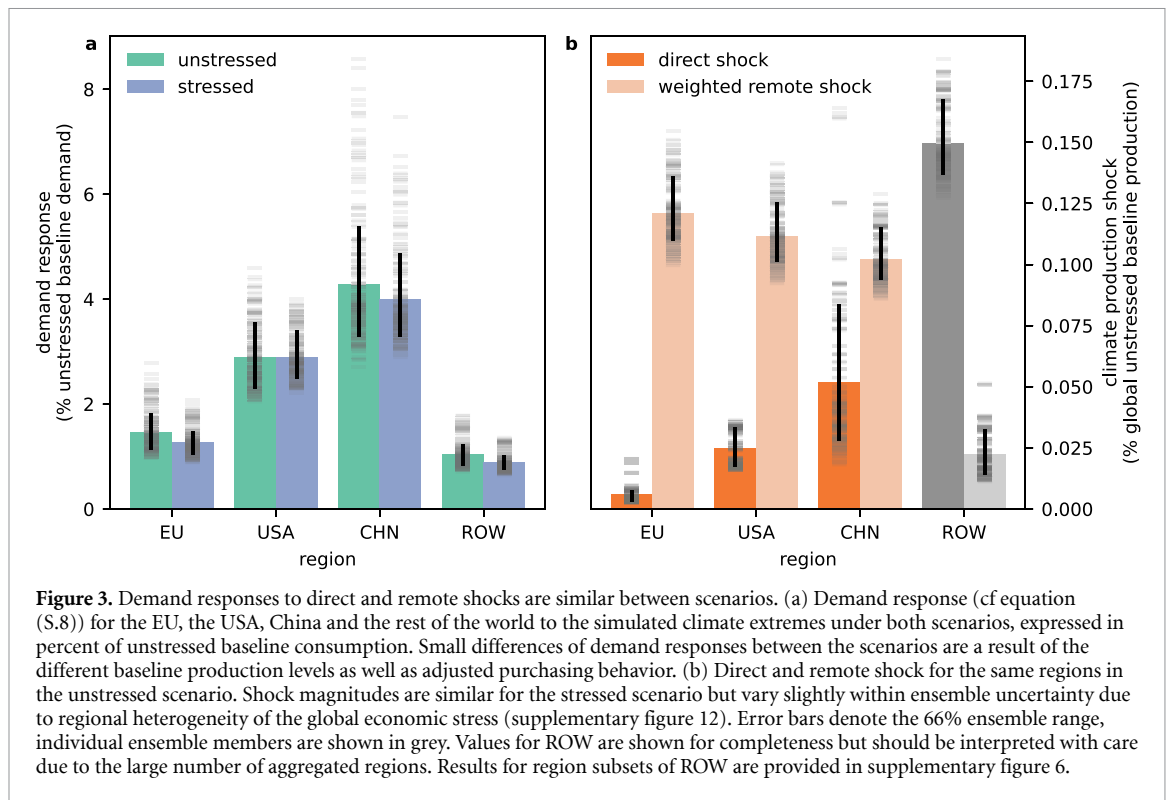
3.3. Aggravated supply–demand mismatch leads to higher prices

Price increases result from scarcity of goods in response to production losses due to climate extremes. This scarcity emerges from a mismatch of supply and demand and it is resolved by prices. We calculate the difference in demand for intermediate production goods (firm-to-firm demand) to the respective baseline demand. We express the demand difference relative to the unstressed baseline demand, which yields the region-specific demand response to the climate extremes (figure 3(a)).

Regardless whether economies are under global stress or not, the same climate extremes evoke similar demand responses. Note that the small differences of demand responses between the scenarios are a result of the different baseline production levels as well as adjusted purchasing behavior. In the stressed scenario, production capacity is globally hampered. With a similar increase in demand, yet lower capacity to supply goods, the imbalance between supply and demand is stronger than in the unstressed scenario.

To fulfill the same demand, economies would need to extend their production beyond baseline levels further than in the unstressed case. This aggravated supply–demand mismatch is resolved by a stronger price signal and final consumers cut their consumption according to their price elasticities. Since final consumption is primarily satisfied domestically (supplementary figure 11), the demand responses have a strong influence on regional consumption prices. Simulated consumption loss increases correspond to regional demand responses (figures 1(b), 3(a)); CHN and the USA, where consumption losses increase most with the stressed scenario, exhibit the strongest demand responses.

In the globalized economic network, demand for intermediate production goods is not only satisfied domestically but also through imports from around the globe. Therefore, while demand responses are generally reactions to climate extremes, on a regional level, they can be more specifically a reaction to climate shocks both locally and elsewhere, with an indefinite number of involved trade links. A region's vulnerability to consumption losses from climate extremes thus not only depends on how its economy can cope with local direct climate shocks, but also how it reacts to shocks of trade partners. Figure 3(b) displays the direct and weighted remote climate shocks. The direct shock (see equation (S.11)) is expressed as the share of global unstressed baseline production that is locally obstructed due to climate extremes. The weighted remote shock for a region (see equation



(S.12), simply ‘remote shock’ hereafter) is the average over all other regions’ direct shocks, weighted with the trade volume (imports and exports) with these regions. As such, it only includes direct supplier–buyer relationships, or tier one, as a first-order measure for indirect shocks from trade partners. Note that we here show shock magnitudes under the unstressed scenario, and that magnitudes slightly differ between scenarios because global economic stress due to the pandemic is regionally heterogeneous. However, differences are small and lie well within ensemble uncertainty (supplementary figure 12). While the EU, USA, and CHN are economically strongly interlinked, the remaining ROW regions are a large and not structurally coherent group of countries. Therefore, ROW trade volumes should be interpreted with care and shocks are only shown for the sake of completeness.

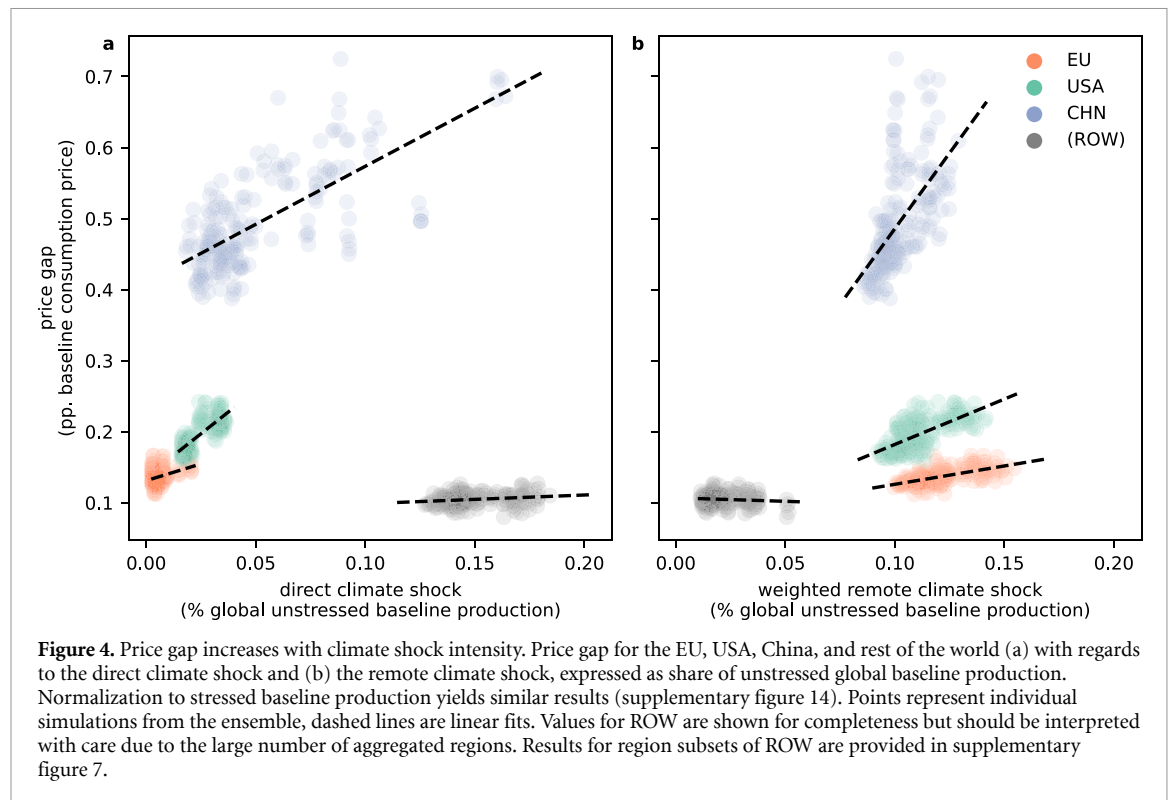
The direct climate shock is small in the EU, compared to the other regions. The USA and CHN show stronger direct shocks, with the shock in CHN about twice as strong as in the USA. The remote shock is pronounced for all three regions due to overall large direct shocks in ROW. It is strongest in the EU, due to the significant direct shocks in the USA and CHN. The computed demand response in the EU therefore results to a large extent from shocks to its trade partners. Possibly, buyers from affected regions switch to the EU as a supplier, requiring the EU to ramp up production and, in turn, demand. Simultaneously, EU demand that is usually directed to affected regions cannot be completely fulfilled anymore, further increasing scarcity. In the USA and CHN, also direct shocks are significant.

These two regions—due to geographical exposure to hazards and exposure in the economic network to remote shocks—experience the strongest aggravation of scarcity among scenarios, resulting in the largest price and consumption difference between scenarios.

3.4. Price gap increases with stronger climate shocks

Exposure to direct and remote shocks changes with spatial and temporal variability within the ensemble of simulated climate extremes. While both shock types are correlated (supplementary figure 13), their difference in magnitudes across the considered regions (figure 3(b)) suggests individual effects. Figure 4 shows the price gap between the scenarios in relation to the direct and remote climate shock magnitude. Shocks are normalized to global unstressed baseline production, but results are similar when normalizing shocks to global stressed production (supplementary figure 14). Again, ROW is only shown for completeness and should be interpreted carefully, especially with regards to the remote shock. An analysis for ROW subregions is provided in supplementary figure 7.

With more intense direct and remote climate shocks, the price gap widens in the EU, the USA, and CHN. Importantly, this does not merely indicate an increase in consumption losses with stronger climate extremes. Moreover, it entails a stronger amplification of consumption losses between scenarios, which again results from an aggravated supply–demand mismatch. However, unlike the change between scenarios, the increased scarcity with stronger climate



extremes does not result from altered supply capacity. Varying the intensity of climate shocks evokes demand response changes (supplementary figure 15), causing larger price gaps with stronger shocks. Hence, while global economic stress affects the supply-side of the supply–demand mismatch, the strength of climate extremes affects its demand-side. This effect on the demand response is regionally heterogeneous and differs between direct and remote shock, which suggests different regional vulnerability (in terms of consumption price reaction) with regards to changes in the two climate shock types. For example, the price gap increase is most pronounced for the USA with regards to the direct climate shock, while CHN exhibits the strongest reaction to a variation of the remote climate shock.

4. Discussion

Our findings show that economies are more vulnerable to consumption losses from climate extremes when the global economy is under stress, as simulated here for the example of the Covid-19 pandemic. Considering the largest economies, consumption losses due to tropical cyclones, heat stress, and river floods triple in CHN, double in the USA, and increase by 35% in the EU. Similarly, most regions in the ROW experience loss increases, but with smaller magnitude. Consumption losses decrease only in few regions under pandemic conditions, e.g. in several South Asian countries. We find that the overall larger consumption losses under global economic stress result from stronger price responses to climate

extremes in the stressed scenario. Under global economic stress, economies have less production capacity and thus, scarcity emerging from lost production due to the climate extremes is more pronounced. This leads to higher prices of final consumption and decreases in consumed quantities.

In this study, we cover one (economic) dimension of how a global pandemic can amplify adverse repercussions from climate extremes, not taking into account other possible impacts. For example, loss of life from climate extremes could be influenced by the pandemic due to stress exerted on health care systems. However, restricting our focus to economic impacts, we argue that the effects shown here likely also apply to other crises that globally reduce economic activity.

With ongoing climate change, the number [47, 48] and intensity [2] of weather extremes will likely increase. In the absence of adaptation, this will further intensify the effects computed here. While model projections for the extremes as simulated here are readily available until the end of the century, future global economic stressors and changes to the economic network structure are highly uncertain. Therefore, we refrained from simulating additional scenarios under future climate conditions. Yet, our findings on the responses to extremes with different intensity within the used model ensemble substantiate the expectation of a stronger interaction under climate change with intensifying extremes, both locally and remote.

We acknowledge that the representation of climate extremes based on model projections used here is imperfect, both with regards to physical impacts as well as the resulting economic losses. For example,

we calculate heat stress from an empirical relationship between temperature and productivity that was found for countries in the Caribbean and Central America [43]. While the underlying mechanisms plausibly apply to other regions, the extent to which productivity is affected by high temperatures likely differs. The derived local economic shocks and the simulated indirect effects should therefore be understood as a qualitative description of possible repercussions, rather than an accurate quantification of the past. For the latter, historical observations would be necessary. Notably, we here assess how indirect impacts change under the influence of global economic stress. To this end, the model projections allow the simulation of identical extremes under two different economic scenarios. Thus, the qualitative findings on increasing consumption losses under global economic stress are not affected by uncertainties of the direct impacts.

Using the stringency as a single index necessarily introduces uncertainties in the representation of economic stress during the pandemic. In particular, not all factors of government strictness that determine economic activity can be included in this index and economies react differently to the same restrictions. For example, differing levels of worker protection may cause labor markets in two countries with similar stringency indices to be impacted differently. However, our calibration to observed GDP warrants that the overall global economic stress situation is well reproduced. Remaining uncertainties can be justified, given that Covid-19 serves predominantly as an example of global economic stress and we do not focus on specific conditions of this pandemic. Similarly, the modeling chain of climate extremes as well as necessary assumptions on the economic behavior of agents in our model add to the uncertainty of the results. Nonetheless, such micro-economic assumptions on agent behavior are useful to model macro-economic behavior [49]. In this, we stress the qualitative nature of our results regarding the underlying economic effects.

Many previous studies have investigated propagation of climate impacts in the economic network. Furthermore, the need for analyses of impacts from consecutive and compound events, including the spreading of diseases, has been raised [50]. Our study addresses this need, thus adding on the literature of indirect impacts from climate extremes. We here show that the compound effect of climate extremes and global economic stress yields an amplification of adverse indirect impacts on consumption, in line with previous findings on amplified consumption losses from compound weather extremes [12]. We demonstrate that this amplification is a result of price anomalies, which have been acknowledged to play an important role in the aftermath of natural disasters [15]. Thus, we not only extend the literature on impacts from compound events, but also complement existing work on disaster price effects

and related consumption effects [51, 52]. Further, our work aligns well with recent results by Hu *et al* [30] who find that GDP impacts of a stylized flood are aggravated by hypothetical pandemic control measures. Yet, while the authors find that the compound GDP impact does not exceed the sum of impacts from both events simulated in isolation, we here show that this is the case for consumption losses in most regions. In particular, price increases as shown here can have a positive effect on GDP, while negatively affecting consumption. Moreover, stimulus effects as discussed in [30] are less viable when considering an ensemble of global climate extremes as opposed to a single hazard.

While we took the perspective of amplified climate extreme impacts through global economic stress, this could also be argued the other way around, as sustained by the demonstrated intensified amplification with stronger climate extremes. This compound impact reveals that cause and effect of interacting disasters are not easily disentangled. In particular, no single objective conclusion can be made on which of the two impacts—global economic stress or climate extremes—drives the interaction and intensifies the respective other repercussions. This adds an additional layer of complexity to the assessment of total impacts from climate extremes. We therefore stress the importance of further research focusing on the superposition of multiple crises.

Overall, our study shows that mitigation of and adaptation to climate risks not only entails the protection of regions prone to hazards. Moreover, increasing the resilience of trade relations is necessary to cope with shocks originating in other regions. In any case, the full impact of disasters can only be assessed by including the broader economic and societal backdrop against which the extremes unfold.

Data availability statements

The data that support the findings of this study are openly available at the following URL/DOI: <https://doi.org/10.5281/zenodo.7701637>. The Eora [32] multi-region input-output data is available from <https://worldmrio.com/>. Region shapefiles used for plotting are openly available from the GADM project [53] at <https://gadm.org/>.

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Code availability

The implementation of the *Acclimate* model is available as open source on <https://github.com/acclimate/acclimate> with identifier 10.5281/zenodo.853345. The implementation of the disaggregation algorithm can be found on <https://github.com/swillner/libmrio> with identifier 10.5281/zenodo.832052. The code to reproduce the analysis is available at the public repository for this publication: 10.5281/zenodo.7701637.

Author contribution

R M, SN W, and A L designed the research. SN W, C O and A L developed the *Acclimate* model. K K provided the climate extremes production shocks. R M conducted the analysis. R M wrote the manuscript with contributions from all authors. R M and L Q handled the manuscript revisions. All authors discussed the results.

Conflict of interest

The authors declare that they have no competing interests.

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