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Wave-like global economic ripple response to Hurricane Sandy

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Abstract

Tropical cyclones range among the costliest disasters on Earth. Their economic repercussions along the supply and trade network also affect remote economies that are not directly affected. We here simulate possible global repercussions on consumption for the example case of Hurricane Sandy in the US (2012) using the shock-propagation model *Acclimate*. The modeled shock yields a global three-phase ripple: an initial production demand reduction and associated consumption price decrease, followed by a supply shortage with increasing prices, and finally a recovery phase. Regions with strong trade relations to the US experience strong magnitudes of the ripple. A dominating demand reduction or supply shortage leads to overall consumption gains or losses of a region, respectively. While finding these repercussions in historic data is challenging due to strong volatility of economic interactions, numerical models like ours can help to identify them by approaching the problem from an exploratory angle, isolating the effect of interest. For this, our model simulates the economic interactions of over 7000 regional economic sectors, interlinked through about 1.8 million trade relations. Under global warming, the wave-like structures of the economic response to major hurricanes like the one simulated here are likely to intensify and potentially overlap with other weather extremes.

1. Introduction

Globally, tropical cyclones range among the costliest and deadliest natural disasters. While they constitute only 16.5% of all recorded billion-dollar events in the United States between 1980 and 2018, they are responsible for more than half of the costs resulting from all extreme weather events combined [1, 2]. Their frequency is expected to decrease or to remain static under global warming but most projections anticipate an increase in intensity of the most extreme tropical cyclones [3], especially in the Atlantic basin [4] (where tropical cyclones are called hurricanes). In consequence, economic losses in hurricane-prone regions are expected to increase in the future due to climate change [5–8] through higher storm intensity [9] and sea level rise [10] but also due to changes in the economic values at risk [11, 12]. Local economies can be affected through destroyed capital stock (stock losses or damages) or through lost production output (flow losses). Since we do not consider damages in this work, we here generally imply lost production in the notion of loss. In particular, we refer to losses in a region that is directly affected by a hurricane as direct losses. However, losses can spread through the supply network, which is then referred to as higher-order losses [13–15]. We here refer to the latter as indirect losses. These may represent a substantial or even dominant share of total economic disaster losses [16–18]. Indirect losses can result from supply shortages due to direct losses that propagate downstream along supply chains. Direct losses and an associated production decrease may also lead to reduced demand (production demand, generally in contrast to final demand for household consumption) which propagates upstream in the

supply network. These downstream and upstream effects are also called forward and backward propagation [19] or ripple effects [20]. Here, we investigate the possible ripple response to Hurricane Sandy (2012) and its effect on global consumption expenditure.

There is good consensus in the literature that extreme weather events have adverse effects on household consumption [21], which is commonly used in economic models as a measure for societal welfare [22] and is therefore often regarded in disaster impact analyses. In this study, we refer to the latter as final consumption or simply consumption where we also include government spending. In a globalized world, local disasters can have global economic repercussions [23], one prime example being the COVID-19 pandemic [24] with huge estimated indirect consumption losses worldwide [25]. However, most studies [26–29] on the impacts of historic extreme weather events focus on the local economic impacts of the disaster and therefore miss the global dimension [23].

With this work, we choose a different scope of analysis and investigate a single historic hurricane's possible impact on consumption on a global scale. We simulate the potential global indirect impacts on consumption that a major hurricane in the United States can have globally, using an agent-based network model. We choose a modeling approach because this allows us to investigate aspects of higher-order effects of a single event that cannot be found in historic data. While local effects of hurricanes are — in large parts — well-studied [30–32], higher-order effects and the way they propagate in the trade network are still poorly understood. Lenzen [14] conducted a study on the higher-order indirect effects of a single hurricane in Australia but focus on national spillover effects. Other studies [7, 33, 34] give a global perspective but cannot link effects to single historic events or do not consider indirect losses. We here propose one means to study loss propagation and global effects on consumption after a single historic major hurricane. As a case study, we choose Hurricane Sandy which made landfall in the US in 2012.

Sandy severely hit the US and in particular the states of New York (NY) and New Jersey (NJ) in 2012. It was the fourth-costliest hurricane in history and caused an estimated total damage of $65bn [35] (in 2012 US Dollar), predominantly by driving a storm surge into the coastlines of NY and NJ [36]. Given the magnitude of this local economic shock and the importance of the economically strong regions of NY and NJ in the global trade network, Hurricane Sandy most likely also entailed indirect effect in regions not directly affected. To understand how these repercussions may have spread in the global supply and trade network, we here simulate global consumption expenditure across the global economy in the direct aftermath of the strong economic shock in NY and NJ after Sandy.

We thereby add to the discussion on the welfare impacts of extreme weather events in two major points. First, by taking a modeling approach, we can go beyond a local case study and simulate consumption impacts globally as a result of production shortages and price effects propagating in the global supply network. This allows us to investigate effects that are otherwise hidden in coarse and noisy data. We find that although directly affected regions show the strongest effects, we observe an overall impact on consumption on the global level. Regions with strong trade relations to the US are affected most. Second, our approach allows us to analyze the underlying propagation effects inside our model that lead to the observed global consumption anomalies. The propagation follows a three-phase ripple of prices. An initial upstream effect results in price decreases and associated consumption increases. The following downstream effect leads to price increases and reduced consumption, followed by a normalization phase.

2. Method overview

Our simulations are carried out using the dynamic agent-based model *Acclimate* [37] which models loss-propagation on the global supply network, assuming a demand-driven economy. In this model, economic sectors (in case of the United States and China on a state and province level respectively, otherwise on a national level) are modeled as agents that are interlinked through trade flows, with each agent maximizing its own profit. The economy of each region is divided into 27 sectors, including the final consumer. With a total of 268 modeled regions, this results in over 7000 agents. By applying an external shock in the form of a reduction in the production capacity of one or more agents, the initial baseline state of equilibrium can be disturbed. We model this production shock to represent the direct losses due to Hurricane Sandy in the affected areas of New York and New Jersey. We use a disaggregated [38] version of the EORA MRIO dataset for the year 2012 [39] as economic baseline. *Acclimate* then simulates anomalies around this baseline state that result from the production capacity reduction by profit-maximization of each individual agent on a daily time scale. Prices in the model are endogenous variables which account for local scarcities and transport costs. They always reflect price changes relative to baseline prices and do not represent absolute prices of traded goods (which are unknown since they are not contained in the EORA dataset).

The conceptual approach of this study is summarized in figure 1. We model the direct economic impact from Hurricane Sandy for NY and NJ only (orange and blue, respectively), although another ten

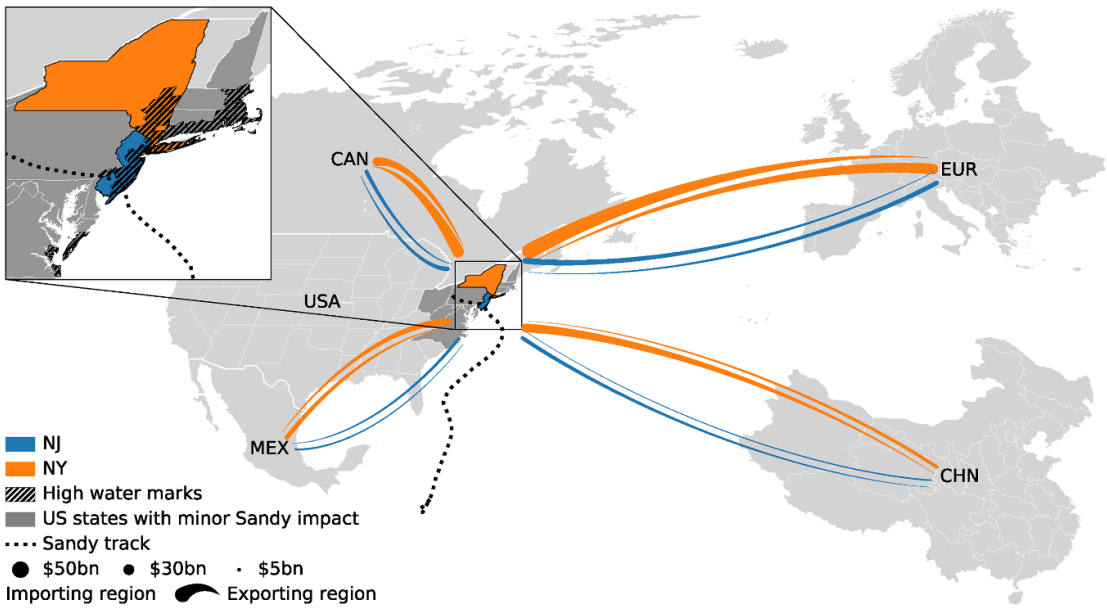

Figure 1. Conceptual design of the study. Hurricane Sandy (track shown as dotted line) resulted in physical damages in multiple US states. New York (orange) and New Jersey (blue) received the largest damages. Dark gray shaded states were affected in a comparatively minor way (see main text) and production shocks in these states therefore are not considered. We derive a disaster-driven reduction of production capacity for New York and New Jersey based on the GRP of counties with reported high water marks (hatched areas) and estimated recovery duration from business interruptions. We simulate the resulting impacts on global consumption through loss propagation in the global trade network. As an example, we here show import and export volumes of New York and New Jersey with Europe, China, Canada, and Mexico, aggregated over all sectors. Trade flows are directed from the sharp end to the large end of a wedge. The width of the large end shows the trade flow magnitude. Note that in the actual model, there are potentially trade flows between any two of the over 7000 economic agents, consisting of 27 sectors in 268 simulated regions. All region shape files retrieved from GADM [41], storm track from IBTrACS [42].

states and the District of Columbia (DC) were also affected (hatched areas). However, NY and NJ were most affected, receiving more than 96% of Congress' Disaster Relief Appropriations Act funds from January 2013 ($50.5bn in total) [40]. And according to estimates of the National Oceanic and Atmospheric Administration [1], the damage share for all other areas is less than 5% of the total damage. We derive production shocks for NY and NJ (supplementary figure 1, supplementary table 1 (available online at stacks.iop.org/ERL/16/124049/mmedia)) based on estimated business interruption (BI) due to the disaster. In this, we assume all sectors to be affected in the same way. While this is generally a strong assumption, we find it reasonable for the short time in the immediate aftermath of the hurricane. We then analyze the resulting global levels of final consumption and related prices as well as production levels, production prices, and demands communicated in the network to assess the higher-order repercussions of Hurricane Sandy. These result from the inter-linkages of NY and NJ within the global trade network (exemplary trade flows in figure 1). For a detailed description of the approach, see appendix A.

3. Three-phase consumption ripple

We compute the relative consumption change in the first 100 d after the disaster for all regions globally (figure 2, supplementary table 2). A region's consumption change is computed as the ratio between the absolute aggregated difference from baseline consumption and the consumption that these regions would exhibit in the unperturbed baseline scenario during this time (equation (5) in appendix A).

A normalisation of consumption and consumption prices in the United States of America occurs about 100 d after the event (figure 3). On a national level, the US show the strongest consumption decrease of all regions within our study. However, on a US state level we find both consumption increases as well as losses (figure 2(b)) in our simulations. Within the US, there is a strong correlation between the gross regional production (GRP) of a state and its consumption change. Economically strong states like California, Texas, or Florida exhibit strong consumption decreases whereas consumption increases in states with a lower GRP like Vermont, Wyoming, or Montana.

Both increases and reductions in consumption are a result of consumption price changes. The consumption level depends directly on the consumption price with sector and region specific consumption price elasticities (see appendix A, supplementary tables 2–4). The latter reflect the sensitivity of consumption (quantity) to price changes. Of course, post-disaster price elasticities might deviate from those during normal times. However, this is

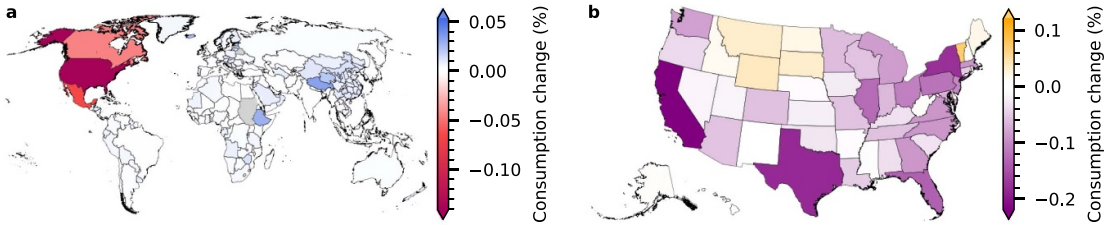

Figure 2. Consumption changes in the direct aftermath of Hurricane Sandy. Changes relative to baseline values during the first 100 d after the disaster (equation (5)) are shown (a) globally and (b) for the US only. Red and purple shading indicate a consumption decrease compared to baseline consumption, blue and yellow shading indicate a consumption increase. Grey areas are excluded from the calculation due to low data quality.

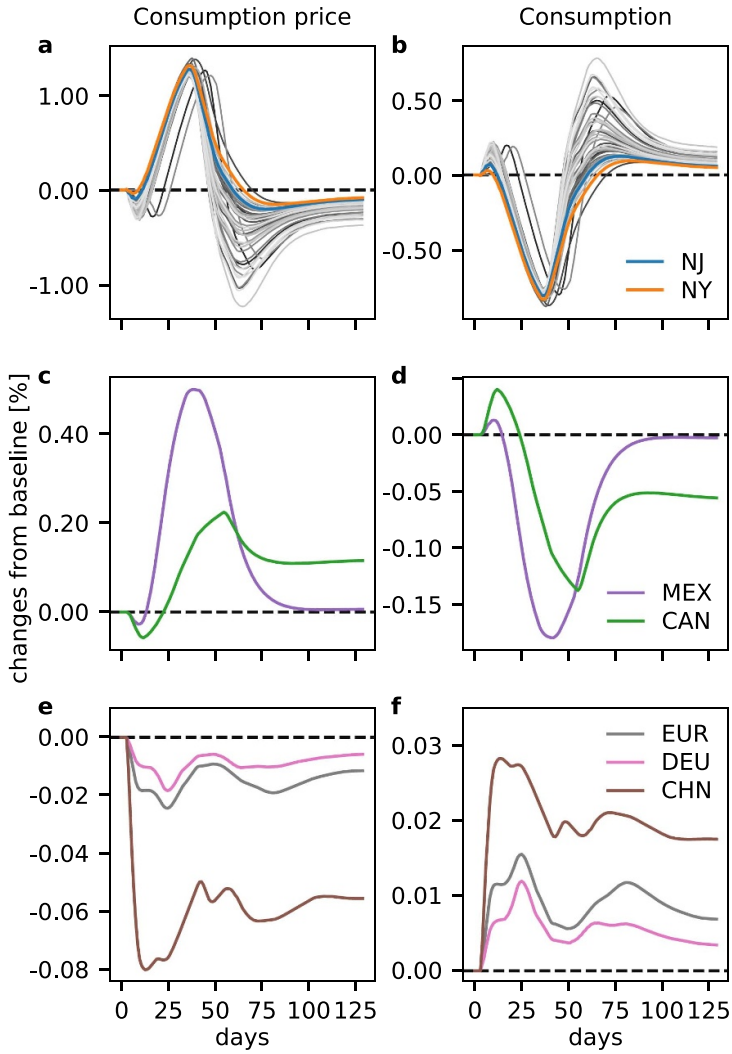

Figure 3. Changes of consumption and consumption prices relative to baseline values. All values are in percent compared to baseline levels (dashed lines). (Left column) Relative consumption price change. (Right column) Relative consumption change. (Upper panels) Results for the directly affected US states NY and NJ and all remaining US states and DC (in grey shades). (Middle panels) Results for Mexico and Canada. (Lower panels) Results for Europe, Germany and China.

difficult to estimate and only relevant for the final consumption in the directly affected states NY and NJ. Consumption in all other regions can be assumed to follow normal elasticities. Previous sensitivity analysis [43] on model-internal price elasticities showed that this parameter choice has no significant impact on results derived via *Acclimate*.

In all regions, we observe an initial consumption price drop directly after the disaster, resulting in a consumption level above baseline. This initial price drop results from a reduction in the (production) demand of the directly affected states of NY and NJ and its quick upstream propagation along the global supply chains. Therefore, reducing demand

instantaneously results in a situation of surplus supply, which causes prices to decline and consumption to rise. However, direct production losses in NY and NJ simultaneously propagate downstream through the global supply network and result in scarcity situations also in other regions that are not directly affected. As a result, shortly after the initial small consumption increase, consumption prices rise again with prices in US states reaching values above baseline level only few days after the hurricane and a maximum peak at over +1.3% about 30 d after the disaster. In case of the United States, the initial price drop associated with increased consumption is therefore quickly reversed by a scarcity driven price inflation resulting in a reduction in consumption. While the upstream effect happens without time delay, the downstream propagation of scarcities is initially buffered by the agents' inventories but also by transport chains through which goods are delivered. Therefore, in contrast to demand shortages propagating upstream, the downstream propagation of scarcities only shows effects with some lag time. The persisting shortage of supply leads to price inflation of intermediate goods that are passed on to the final consumers. As a consequence, the latter have to decrease their consumption. A normalization of US prices and consumption occurs about 100 d after the event. While the US are most impacted by the event, changes from the baseline economic state due to the hurricane event occur globally. A similar development with an initial small consumption increase followed by a stronger counter effect of decreasing consumption can be observed — yet with smaller magnitude — in Mexico and Canada, which have strong trade relations with the United States.

Generally, consumption shows a three-phase wave pattern of an initial price drop due to upstream effects, followed by a price increase attributable to downstream effects and finally a normalization phase where prices develop back towards baseline values. Depending on how strong the upstream and downstream effects are with regards to a particular region, average prices range above or below baseline. For example, the upstream effect for Canada and Mexico is small compared to the downstream effect, leading to higher average prices. In Europe and its strongest economy Germany as well as China, the initial price drop due to the fast upstream effect is large enough to permanently keep prices below baseline (figure 3(e)).

4. Regions' trade with the US

In the simulated disaster aftermath, the magnitude of the effect on a region's consumption depends on the trade relations of that region with the US (i.e. the sum of all imports and exports, figure 4(a)), following a power law relationship. Both high import and export trade flows result in a strong consumption changes (supplementary figure 2). Linear regression in the log-log space indicates an exponent that is below 1, i.e. the absolute consumption difference increases less than linearly with growing trade volume with the US. Regions with strong trade relations experience a stronger price effect. However, due to the prescribed negative price elasticities, this price effect affects consumption less than linearly.

Whether or not a region experiences total gains or losses in consumption depends on the country-specific shape of the three-phase ripple, i.e. whether the upstream or downstream effects is dominant. To show this, we analyze additional simulations with longer recovery times (80, 100, 120 d, figure 4), which mainly intensifies the slower propagating downstream effect (supplementary figure 3). Initially, most regions (with the exception of Mexico, Canada and the Philippines) show consumption gains. With longer duration, the latter decrease and consumption losses increase. With a recovery time extension of 20 d (figure 4(b)), additional regions transitions from gains to losses (e.g. Australia, Venezuela, Ireland, Singapore, Hong Kong). The initially small consumption loss increases with further recovery time extension (panels (c) and (d)). Likewise, regions like Canada, Mexico and the Philippines that show losses already with the original recovery time further increase their losses. In the case of Mexico and Canada, this can supposedly be explained by the geographic and economic proximity of the regions to the US, resulting in a faster downstream propagation to these countries. This suggests that each region has an individual threshold where the direct impact in NY and NJ becomes too strong and a dominating downstream effect results in overall consumption losses. This threshold is already crossed for the Philippines as well as Mexico and Canada with the original recovery time of 60 d.

Generally, the consumption reaction of all regions to the shock duration in NY and NJ appears to follow an inverted U-shape. Without a shock, all regions consume at their baseline level. Short shocks result in consumption gains that increase with the shock duration at first. At some point—depending on the trade relations with the US—consumption gains decrease and eventually transition into losses. Regions with a large trade volume tend to transition sooner than those with smaller trade to the US.

5. Price dynamics

So far we analyzed the consumption price and resulting consumption levels on a regional level and found a three-phased ripple that can result in both overall gains and losses of consumption. In the following, we investigate the underlying price dynamics that lead this ripple which originates in the directly affected regions NY and NJ. For this, we look at changes of

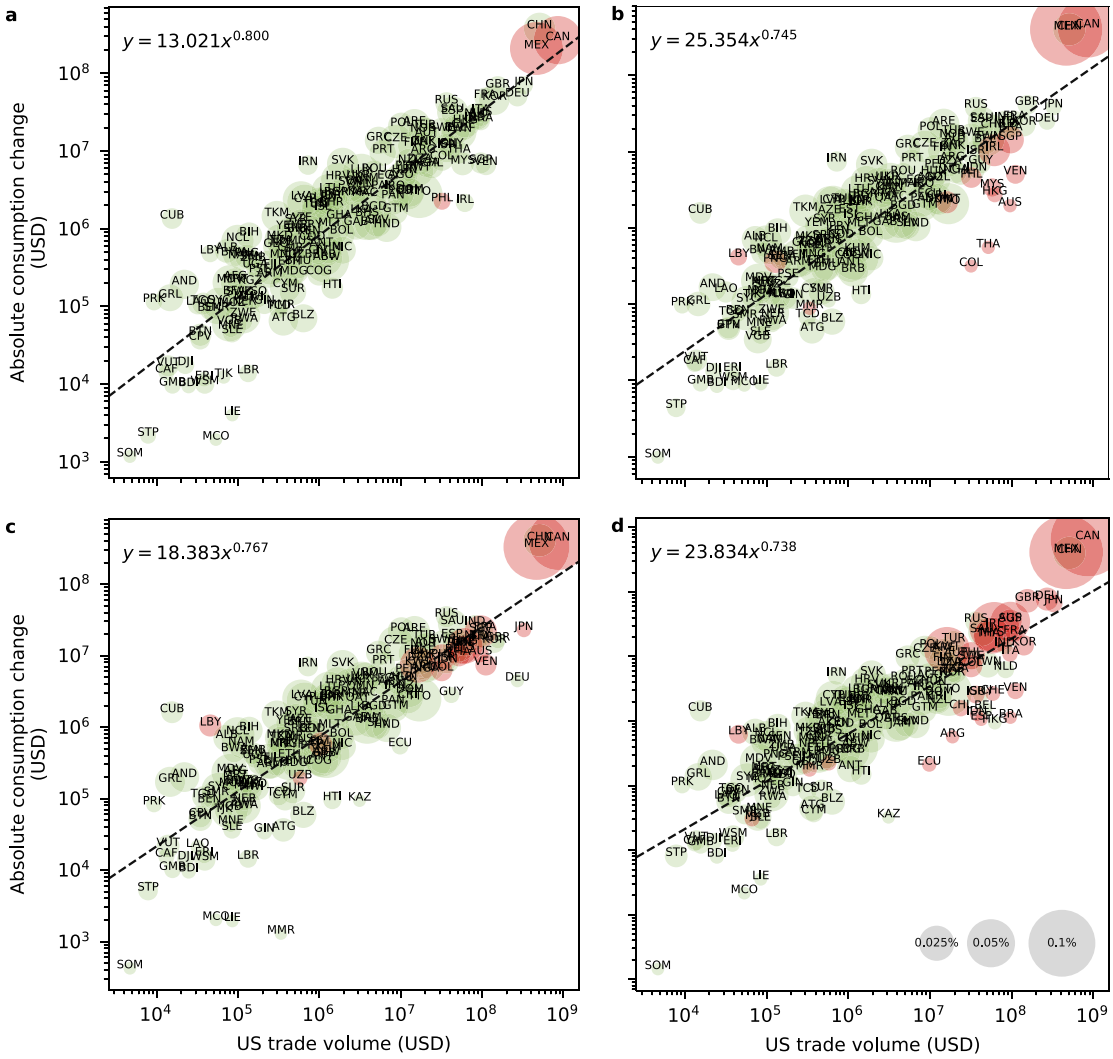

Figure 4. Consumption change over total trade volume with the US with varied recovery times. Consumption changes are cumulated for the first 100 d after the hurricane. US trade volume is the sum of a region's total exports and imports with the United States. Size of the scatters indicates the consumption change relative to what regions would consume under baseline conditions during this time. Green and red colors indicate consumption gains and losses, respectively. The dashed line is the linear fit in the log-log space. Recovery time is set to (a) 60 (default recovery), (b) 80, (c) 100 and (d) 120 d.

production prices and levels of incoming demand as well as changes of the capacity utilization in NY and NJ as well as the rest of the US. We use the economic notion of capacity utilization [44] that is defined as the ratio of actual output to the output that would minimize production costs. This measure quantifies if and by how much a region is in a state of overproduction, relative to the actual production capacity. For the directly affected regions, we need to first adjust production capacity for the applied production shock. We also calculate the similarly adjusted demand exceedance which indicates if fulfilling the entire incoming demand at a given time step would drive the agent into overproduction, i.e. by how much current incoming demand exceeds the production capacity (for both adjusted capacity utilization and demand exceedance see appendix A). Time series for production prices, demand exceedance and capacity utilization in our simulations are shown in figure 5 for the directly affected US states NJ and NY as well as an aggregate over all other US states and DC. We refer to the latter in the following as USA-OTH.

In the *Acclimate* model, production prices and ultimately consumption prices are driven by the demand that agents receive. In the immediate aftermath of the disaster, NY and NJ cannot satisfy their incoming demand due to the applied external reduction of production capacity. This is reflected by a high demand exceedance. As a result, the directly affected states switch to overproduction directly after the disaster, similarly indicated by an increased capacity utilization. At the same time, NY and NJ reduce their demand towards other regions. Due to the resulting initial upstream propagation, the remainder of the US does not fully use the available production capacity and production prices decrease at first (note that the apparent contradiction for the pooled region USA-OTH of positive demand exceedance

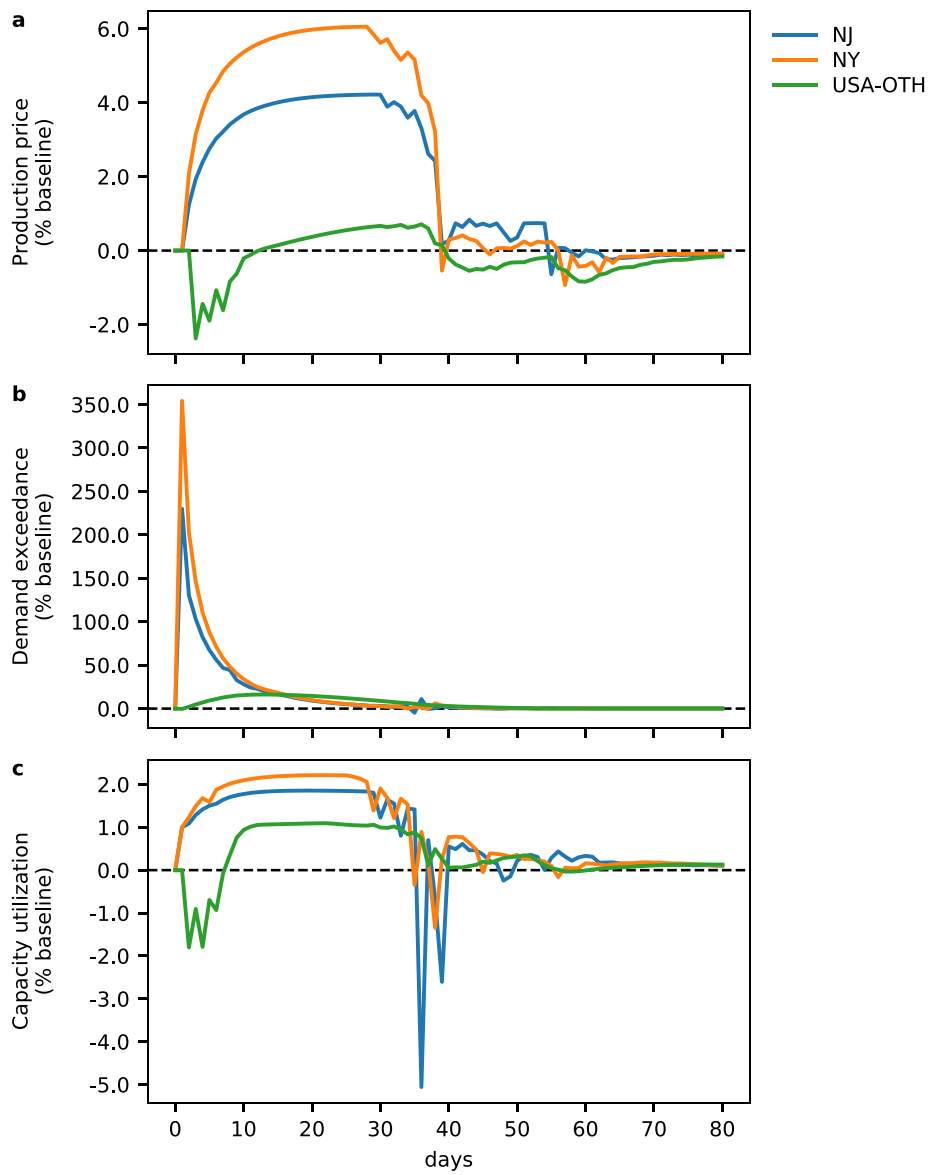

Figure 5. Production price, demand exceedance and capacity utilization for the United States. Directly affected states NJ and NY are shown individually, remaining 48 states and DC are aggregated as USA-OTH. Dashed lines represent baseline values. (a) Changes of the production price from baseline values. (b) Demand exceedance relative to baseline values. (c) Relative change in capacity utilization from baseline values.

and simultaneous low capacity utilization during the first days after the disaster is simply a result of the aggregation that we perform over the US regions and their individual sectors, see appendix A). However, the longer the disruption prevails, the more of the lost production in NY and NJ propagates downstream in the economic network, resulting in scarcity of goods. This scarcity is compensated by other US states and also the latter eventually switch to overproduction. Yet, overproduction comes at the cost of production prices increasing super-linearly with the production level and average prices rise above baseline levels during this upstream phase. In the situation of scarcity in the disaster aftermath, agents in the network are willing to pay these higher-than-usual prices and producing agents keep their increased production level.

We observe this behavior of rising production prices until about 45 d after the disaster, when production prices rapidly drop again. This drop marks the beginning of the normalization phase. Note that it coincides with a change of the capacity utilization change from positive to negative values, causing agents to switch from an overproduction state to a normal production regime. The sudden price drop results from the fact that now production prices no longer depend super-linearly on the produced quantity. Two factors lead to the end of the overproduction regime: (1) many purchasing firms decide simultaneously to reduce their demand due to the high level of prices, and (2) the reduction of production capacity in the directly affected states is released enough so that the new, reduced incoming demand can be satisfied without overproduction.

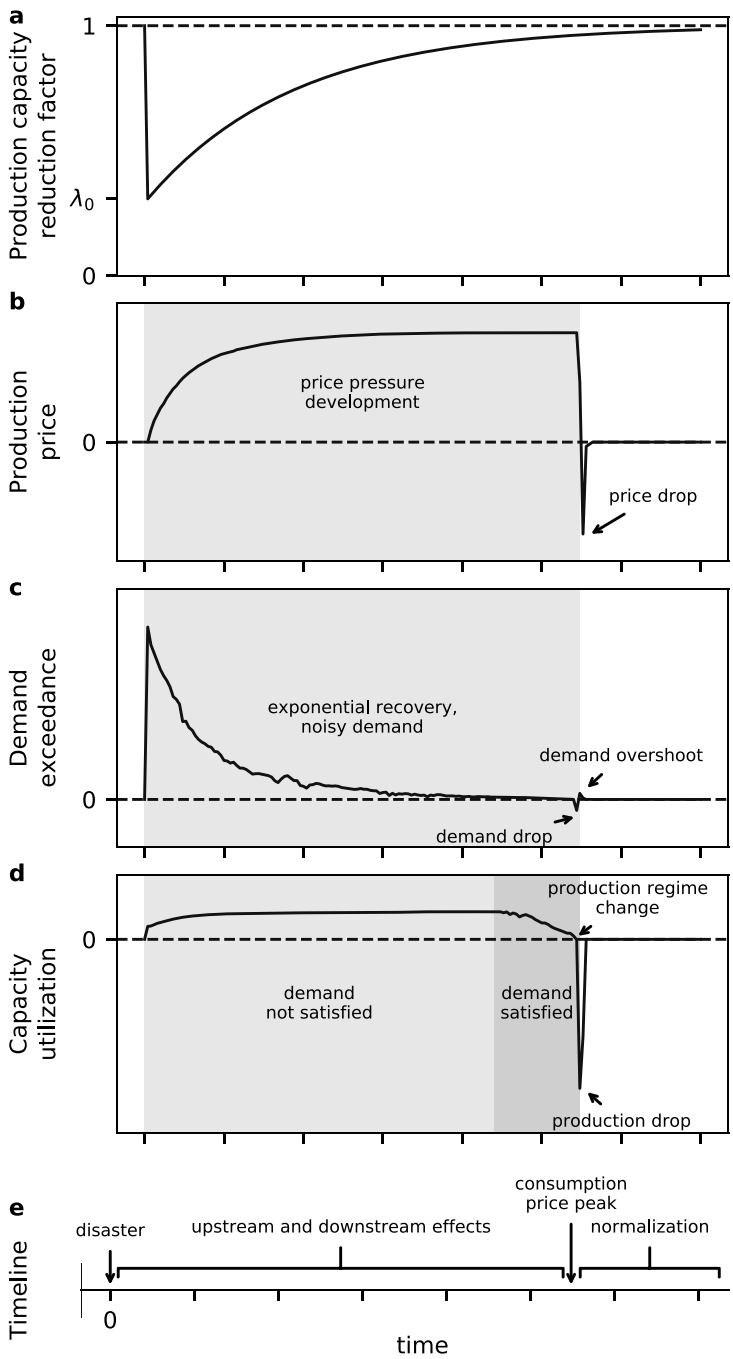

Figure 6. Schematic time evolution of a directly affected agent. Dashed lines represent baseline values. Explicit values and durations are not given because magnitudes and time scales differ between disasters. (a) Production capacity reduction factor with initial production shock λ_0. (b) Relative production price change. Grey shaded area denotes the price pressure development time until the price drop. (c) Demand exceedance. Grey shaded area denotes the time during which the economic shock has not decayed enough for demand variations to end the overproduction regime. Noise is due to demand fluctuation from the profit maximization and associated demand shifts of all agents. When the production capacity has recovered enough, this noise can be strong enough to make an agent switch from an overproduction to a normal production regime (production regime change). (d) Relative change in capacity utilization. Light grey area denotes the time during which the agent does not fulfill the incoming demand while in a state of overproduction. The dark grey shaded area is the time during which the entire demand can be satisfied with overproduction. (e) Timeline with the initial disaster impact, the consumption price peak and upstream, downstream and normalization phases.

As can be seen in figure 5, the demand exceedance for NY and NJ decreases exponentially after the disaster, which is simply due to the defined exponential economic recovery. About 45 d after the event, when we observe the production price drop, the production capacity reduction has released enough for smaller demand variations to cause the demand exceedance to drop below 0. Such variations are a result of the complex dynamics of the model. Since each agent may redistribute its demand in each time step and will do so in order to maximize its profit, the incoming demand (and hence, the demand exceedance) is

subject to some fluctuation. The price tension that previously built up in the network releases and prices drop back towards baseline levels.

A schematic time evolution for the analyzed quantities of a directly affected agent is shown in figure 6 (panels (a)–(d)) with coincident events and phases in the aftermath of the hurricane (panel (d)). While we expect the general behavior of directly affected agents to may be similar for other natural disasters that show an exponential BI recovery, time scales and magnitudes may well be different and are therefore omitted in the figure.

6. Discussion

In this study, we modeled the impact that a severe disaster like Hurricane Sandy (2012) can have on global consumption, resulting from economic forward and backward loss propagation in the global supply network. We find a three-phase economic ripple in the supply chain network. This ripple is characterized by an initial upstream effect and resulting consumption increase, followed by an opposing and slower downstream effect and associated reduced consumption. The last phase is a price normalization.

The magnitude of consumption effects on a region depends on its trade volume with the US. Whether a region experiences overall gains or losses depends on which of the upstream or downstream effect during the ripple is dominating. In our simulations, most regions experience slight consumption gains. With longer duration of the direct impact, these regions show a tendency of decreasing consumption gains and eventually a transition to consumption losses. Many regions experience these losses already with an additional recovery time of only 20 d. This is important for two reasons. First, direct losses of hurricanes must be expected to increase in the future due to climate change [8, 45], resulting in potentially longer recovery durations. Second, the recovery from BI was particularly quick after Hurricane Sandy and it can take much longer for other economies subjected to different natural disasters to recover. In the case of Hurricane Katrina in 2005, the economic activity recovered to pre-disaster levels only about one year later [46].

Of course, results from socioeconomic models like the one used in this study are subject to uncertainties due to the necessary assumptions on which the model builds. In particular, these uncertainties concern the absolute magnitudes of the reported results which may appear small at first sight. We emphasize that these values result from only one local, isolated extreme weather event and are therefore still considerable. Previous research [47] has also shown that economic ripples from disasters can amplify each other. More importantly however, we stress the *qualitative* nature and importance of our findings regarding the economic ripple. Our finding of a three-phase ripple and related consumption changes is qualitatively robust against variations of the local production disruption (supplementary figures 3–5).

While we focused on the specific regions of New York and New Jersey in the United States for this study, similar ripple waves can be expected for major shocks in other regions of the world. Besides hurricanes, we also expect other categories of extreme weather events to have similar economic impacts on consumption. Consecutive and compound events (e.g. the 2020 flood in China and the concurrent heat wave in Europe as recent examples) will likely further increase the magnitudes of the observed indirect effects. Since all these extremes are projected to intensify—at least on a local level—under global warming [48], we believe that modeling approaches like the one we conducted here can contribute valuable insights for necessary mitigation by allowing to simulate and better understand higher-order effects that otherwise cannot be studied.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon request. GADM region shape files can be found at www.gadm.org. Storm track retrieved from IBTrACS database at http://ibtracs.unca.edu/.

The data that support the findings of this study will be openly available following an embargo at the DOI: 10.5281/zenodo.5682128. Data will be available from 01 December 2021.

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 code for data processing and analysis scripts is available from the corresponding author upon request.

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Author contributions

R M, S W, and C O designed the method. S W and C O developed the Acclimate model. K K provided the price elasticities. R M conducted the analysis. R M, S W, C O, and A L analysed and interpreted the results. R M, S W, C O, K K, L Q, and A L discussed the results and wrote the manuscript.

Conflict of interest

The authors declare that they have no competing interests.

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