# Resilience of international trade to typhoon-related supply disruptions

Kilian Kuhla[a,b], Sven N Willner[a], Christian Otto[a], Anders Levermann[a,b,c]

[a] *Potsdam Institute for Climate Impact Research, Potsdam, Germany*
[b] *Institute of Physics, Potsdam University, Potsdam, Germany*
[c] *Columbia University New York, New York, USA*

**Abstract**

Shipping accidents and environmental disasters pose a challenge to the reliability of maritime supply chains. With international trade intensifying without a significant diversification of the supply routes the risk of perturbations is likely to increase, because higher atmospheric carbon dioxide provides more energy to tropical cyclones which tends to make them more destructive. In this study we analyze the regional and global economic repercussions of short-term transport disruptions of West Pacific trading routes during typhoon seasons. Using a numerical agent-based shock model with myopic local optimization, we compute the response of more than 7,000 regional economic sectors with more than 1.8 million trade- and supply relations. Disturbances due to typhoons observed between 2000–2020 are found to have caused local oversupply and scarcity situations as well as the associated regional price changes. In our model economic agents respond to these price signals and temporary supply bottlenecks by rescheduling and increasing their demand. As a consequence we find annual average export volume to increase in all trade blocs due to a decrease of export prices, but substantial regional differences emerge. Resilience of export to typhoon induced perturbations is increased in China, ASEAN, East Asia, and Europe. We trace this back to an increase of the inter-connectivity of these trade blocs to their foreign trade partners.

*Keywords:* agent-based modeling, trade modeling, transport disruptions, trade resilience

*Preprint submitted to Journal of Economic Dynamics and Control* *January 21, 2022*

## 1. Introduction

Since the end of World War II, international trade has grown immensely [1] and even the COVID-19 pandemic has only shortly interrupted this trend [2]. With the increase of global exports to production, the exposition of the global economy to supply chain risks has increased. To date, up to 90% of the national exposition to insecurities in water, energy, and land resources derive from international trade [3].

Over 80% of the world trade volume is transported on sea [4], rendering disruptions of maritime trade routes a substantial threat to global supply chain security. This was impressively demonstrated by the blockage of the Suez-Canal by the container vessel "Evergreen" in Spring 2021. This resulted in substantial delivery delays and associated production shortfalls, especially in Europe and Asia [5]. Besides straits and canals [6], ports are major bottlenecks of the maritime trade network [7]. In addition to socioeconomic factors such as accidents [8] or congestion during loading and unloading [9, 10], storm surge and strong winds from extreme weather is one of the main source of transport delays through ports [11].

The increase in the concentration of carbon dioxide in the atmosphere is increasing the energy that is accumulating in the ocean [12, 13]. The emergence of tropical cyclones such as hurricanes and typhoons follows a complicated mechanism that is subject to energy constraints and shear wind strength. The amount of energy that is accumulating within a tropical cyclone that has already developed is physically constraint by the amount of energy available in the upper ocean layers. Thus under future warming the number of tropical cyclones as a whole is difficult to predict, but it is clear that the number of strong typhoons and hurricanes will statistically increase under future warming [14, 15, 16]. This combination of intensifying trade volume and increased risk of perturbations by typhoons motivates an investigation of the economic responses of these transportation interruptions.

Linking major Asian exporters such as China and Japan to their European and American trade partners, the West Pacific basin is of predominant importance for international maritime shipping. For instance, the maritime trade of the world's largest (national) exporter [17] — China — relies exclusively on West Pacific shipping routes through the South China and East China Sea. During June and December, maritime transport in the region is put at risk by typhoons. Strong winds, high swells, and poor visibility of these events can cause transport delays due to port closures and re-direction of transport vessels [18, 19].

In this study we extend the agent-based global supply chain model Acclimate[20] by a global network of maritime trade routes. We employ the model to study the economic repercussions of transport disruptions of recurrent typhoons. Immediate responses of trading partners to transportation perturbations caused by typhoons are referred to as direct impacts. Further, we compute and analyze *indirect* or *higher-order* impacts, which arise due to economic ripple propagation along supply chains, e.g, through price fluctuation or demand shifts.

Including the shocks by the typhoons of 2000–2015 in the model, we find average export volumes to increase in all major trade blocs due to a decrease of export prices. However, substantial regional differences occur. In all but one trade blocs the decrease in export prices is overcompensated by the increase in export volume resulting in an increase of the value of exported goods; in China as the most strongly affected trade bloc a moderate increase in export volume is overcompensated by the decline in export prices. We also study how the topography of the underlying trade network affects the resilience of international trade to typhoon strikes. Using exports as a measure for international trade, we find that that its resilience to typhoon strikes has increased over the period 2000–2015 especially in China, ASEAN, East Asia, and Europe. We explain these gains in resilience by an increase of the inter-connectivity of these trade bloks to foreign trade partners within the study period.

This paper is organized as follows. We first review the related literature in Sec. 2, before presenting our modeling approach in Sec. 3. In Sec. 4 we present our modeling and before discussing them in Sec. 5.

## 2. Related literature

### *2.1. Supply chain risks*

The modeling of supply chains is typically carried out on either on the macroeconomic level, i.e. nations and their bilateral trade relations, or on a microeconomic level, i.e. regional firms or the multinational corporations and their networks (cf. Johnson [21] for a comprehensive review). Here, we focus on the macro level, where two modeling frameworks are well established: input-output (I-O) models and computable general equilibrium (CGE) models (see van der Veen [22] and Okuyama et al. [23] for a comprehensive introduction). Both approaches can reflect the economic dependencies in high detail [24]. However, when it comes to describing and temporally resolving the indirect economic effects of disasters due to the cascading of losses along supply chains — the main focus of this paper — both approaches, I-O and CGE, may not be able to realistically describe the economic responses in the period of days to months following a disaster [25, 26, 27]. Whereas the production system in I-O models is fixed, rendering short-term adaptation impossible [28], that of CGEs is highly adaptive and flexible due to price responsiveness and a high degree of substitutability among commodities. CGEs are calibrated such that supply and demand elasticities as well as the elasticities of substitution are suitable to describe an economy in long-term equilibrium. Consequently, in contrast to I-O models that tend to overestimate losses, CGEs are prone to mitigate losses unrealistically well [25].

Attempts to represent a system's complex dynamics from the bottom up are undertaken by use of agent-based models (ABMs), e.g., [29, 30]. Here, the stylized facts of macroeconomic systems emerge from the interplay of individual heterogeneous agents [31, 32]. This may in particular include non-equilibrium dynamics. For instance, micro-economically founded agent-based growth models have been shown to reproduce exponential growth [33, 34] and myopic decision rationals have been shown to induce far-sighted inter-temporal optimization [35]. In recent years, ABMs have been frequently applied to study the implications of specific policies [36]. Further, similar to static methods, a focus has been put on systemic risk by studying bankrupt avalanches and their dependence on network topology [37, 38, 39, 40, 41]. However, ABMs still struggle to gain broader recognition from the mainstream neoclassical economic community [42]. Regarding the analysis of production loss cascades along supply-chains, ABM approaches appear promising. With their help, loss-propagation can be very naturally discussed in a setting where the economy is described by heterogeneous interacting agents yielding a production system with well tuneable flexibilities [43]. For example, Gualdi et al. [44] presented an ABM of an evolutionary network of monopolistically competitive firms, which is able to reproduce important stylized facts of real-world firm networks. They can allocate the scale-free topology of firm networks to the competition among the firms. Further, as in the static theory [45], their model permits to ascribe aggregate volatility to the fat-tailed distribution of firm sizes.

A foray in the description of disaster-induced losses in supply networks was undertaken by Hallegatte [25] with the introduction of an agent-based dynamic model, the ARIO model. A more recent version of the model accounts for inventories acting as buffer-stock, which are essential for the assessment of indirect losses in the disaster aftermath [46]. This model has been successfully employed in several empirical disaster impact studies such as Hallegatte [47], Ranger et al. [48], and Hallegatte et al. [49]. Further, Henriet et al. [50] extended the model to study how the robustness of a firm network to micro-shocks depends on the structure of the network as well as the heterogeneity of direct losses. Moreover, the authors provided an algorithm to disaggregate I-O tables such that a firm network with realistic size distribution is obtained.

In the most recent model generation, Otto et al. [20] implemented endogenous price dynamics between the economic agents. Thereby, the relevance of inventories and idle capacities as adaptation measures to repercussions in the economic network was elaborated. Using the *Acclimate* model, Willner et al. [51] examined direct and higher-order impacts of river floods. The study reveals that China suffer by far the highest direct flood-induced production losses, which increase even further under near-future warming projections. Additionally it highlights that the USA exhibit significantly high indirect losses compared to their direct impact of river floods. Besides effects on regional and global production, Kuhla et al. [52] computed the resulting impact on consumption regarding productivity reduction caused by heat stress. Within the first four decades of the century, the direct production losses are projected to increase by 47% while losses for consumers double. A qualitative analysis on the repercussion of hurricane Sandy revealed that local disaster impact propagates as ripples with three phases through supply chains [53]. Further results of the study suggest that regional higher-order economic impacts increase with higher inter-connectivity to disaster area.

The ABM and explicit non-equilibrium dynamics approach of the model further allowed to assess the economic repercussions of several events and how they interact. Here, Kuhla et al. [54] showed that the interaction of indirect economic effects of heat stress, flooding, and tropical cyclone events can lead to an economic ripple resonance intensifying regional and globel consumption losses . While climate-related direct losses rise, e.g. under global warming, additional consumer losses amplify disproportional, which stresses the importance of in more-depth assessment of consecutive disaster and global adaptation measures.

Risk for supply chains may arise from internal or external factors [55, 56] or from operational disruptions [57, 58]. Furthermore, managing decisions of firms like just-in-time-policy or lean production may increase risk for stable supply chains [59]. On the demand side, uncertainties and unforeseen changes of demand are additional potential supply chain risks [60]. Regarding a firm's bankruptcy and resulting supply chain effects, the analysis of Yang et al. [61] depicted that competitors could be put under higher pressure and affected suppliers could even partly benefit. Also, Giannakis et al. [62] identified and evaluated 30 sustainability-related risks, where greenhouse gases and natural disasters score highest. Next to firm-related supply chain risks, trading effects, like currency fluctuations or restriction of information, can affect demand and supply [63]. In order to mitigate trade disturbances due to (short-term) exchange rate fluctuations Günay et al. [64] developed a stochastic optimization model. With this, they find nation-depending fluctuation range thresholds for product architecture selection. Durowoju et al. [65] used entropy theory to depict that disrupted information flow puts more pressure on managing inventories, which drives cost on producer side and may lead to interruption in the supply chain. Regarding evaluation of manufacturing and supply information, the review work of Ivanov et al. [66] suggests that digitalization and big data analyses pose promising technologies helping to reduce ripple effects along supply chains.

Additional to business and trading supply risks, problems in transport pose substantial risks on the logistics side of supply chains. Here, Morris et al. [67] found that the last part of a transport supply chain — the delivery to the costumer — is often impeded by congestion, theft, and availability of fast parking facilities. Tatikonda et al. [68] found that supply via road comes with risks of truck accidents and that improved working conditions, e.g. team-based drivers, could reduce such risks and improve drivers health. The transition from transport via road to sea and vice versa can further be delayed by port strikes, which lead to additional transport costs and congestions along the whole supply chain [69]. Similar, quitting ship crew members stresses supply chains, which emphasizes the necessity of better working conditions for employees as shown by Jiang et al. [70]. For goods transported via sea, potential pirate attacks can increase transport costs and stress the affected supply chains as Martínez et al. [6] depicted.

### *2.2. Maritime transport at risk due to climatic conditions*

Climatic extremes, like heavy winds or rainfall caused by storms, delay transportation via sea [71]. For ports, and thus overall maritime trade, the most frequent natural threats are posed by tropical storms [72]. Using a dynamic I-O model, Thekdi et al. [73] depicted that a hurricane reduces shipping activities which again cause economic losses in transportation and fossil fuel sectors. Cao et al. [74] estimated that the worst-case economic losses at a port due to a single typhoon can add up to roughly USD0.9 bn. Examining the impact of tropical cyclones further, Zhang et al. [75] found that four major Chinese ports exhibit on average 0.9–2.6 disruption days per year in the most typhoon-prone months. Further, their computations stressed the importance to include disruption time and port throughput within the economic loss assessment.

Being aware of such disruptive maritime events, frameworks for optimally rescheduling liner shipping are developed, e.g. by Brouer et al. [76] or Li et al. [77]. These aim to adapt transportation plans and to reduce resulting costs. Negative impacts on maritime transport will continue and even intensify. This increases the necessity of deep adaptation as Monios et al. [78] elaborated. Likewise, Lam et al. [79] concluded that there are still some research gaps to be filled regarding disruptions in maritime transport and their consequences.

### *2.3. Global trade — risks and resilience*

Global supply chains experience operational, logistic, and physical threats, which puts global trade at a whole at risk. Despite these risks, international trade has grown faster than national GDPs in the last 60 years [80] and up to 80% of this trade is shipped via sea [4]. Inter-connectivity of global trade, measured in different metrics like supply propagation connectivity [81] or link density [82], has increased since the beginning of the century. Next to discussions about benefits and harms of global trade [83, 84, 85], there is an ongoing scientific debate about the adaptation and resilience capacity of the highly-interconnected global trade network toward larger shocks. In general, work from Fyodorov et al. [86] suggests that a coupled system of nonlinear ordinary differential equations increases stability with complexity, which could be applied to trade networks. Further, the information theory-based network flow analyses of Kharrazi et al. depicted that more interconnected global trade has become more resilient towards economic shock despite lowering overall efficiency [87].

Contrary to that, findings of Kummu et al. [88] suggest that resilience towards trade risk has decreased over the last three decades. In particular, they analyzed multiple indicators of international food system resilience and found that regional food import dependency mostly increase while number of trading decreases. Wenz et al. [81] found that higher inter-connectivity of international trade network increase vulnerability towards climate extremes. Similar, Moran et al. [89] evaluated, using random matrix theory, that a complex system of firms decreases its stability with increasing size in term of number of firms or connectivity.

## 3. Modeling approach

### *3.1. Loss-propagation model Acclimate*

In this study, we compute direct and higher-order economic impacts due to typhoon-induced transport delays using the agent-based loss-propagation model Acclimate. This model consists of around $7,000$ economic agents, firms and consumers, who maximize myopically and locally their profit or consumption, respectively. Flows of goods and services — between 27 economic sectors of 268 regions (186 nations as well as 51 US-states and 31 Chinese provinces) — connect these agents, which form a network of around 1.8 million linkages. The sectors and regions used in our simulation are listed in Table S1 and Table S2, respectively. The 26 consumption commodities are not substitutable. The model has endogenous price dynamics and explicitly distinguishes between quantity, price, and value of goods and services. Due to exogenous (direct impacts) and endogenous (indirect impacts) production, trading and transport anomalies, the model computes daily economic repercussions, which are deviations from the baseline state. As an economic baseline we use the static multi-regional input-output data from the Eora database [90] of the year 2015. Further model assumptions and local economic mechanisms are described in detail by Otto et al. [20].

### *3.2. Product transport in Acclimate*

In this section we describe the transport of commodities and products in Acclimate. In the following, we will only to transportation between firms as it is the same for a firm and a consumer. Every firm, or "regional sector", $ir$ is

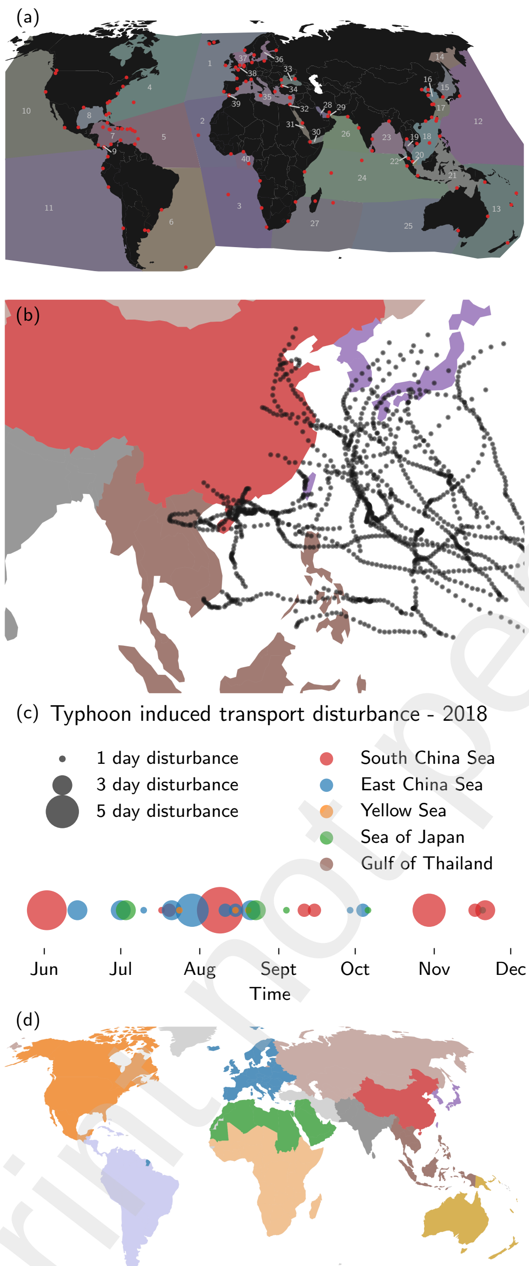


Figure 1: **West Pacific typhoon seasons affects East Asian maritime routes**
(a) Modeled maritime entities (colored areas on water) which form the maritime trading network are connected to land routes via the ports (red dots). Names of maritime trading routes are listed in Table 2.
(b) Zoom into West Pacific regions. Black dotted lines depict trajectory of tropical storms (wind speed $\geq 22$ kn) in the period 2000–2021.
(c) Scheme of typhoon-induced transport disturbances in South China Sea (red), East China Sea (blue), Yellow Sea (orange), Sea of Japan (green), and Gulf of Thailand (brown) for the season 2018. Diameters of circles proportional to the number of days of disturbance.
(d) Blocs used for analyses in this paper: China (red), Europe (blue), NAFTA (orange), ASEAN (brown), Latin America (light purple), SAARC (grey), East Asia (purple), Arab League (green), Post-Soviet states (light brown), Australia & Oceania (ochre), Sub-Saharan Africa (light orange), and Rest of the World (light grey).

described by its economic sector $i$, in which it produces, and by the region $r$ in which it is located. The economic linkage between firm $ir$ (supplier) and firm

$js$ (purchaser) is referred to as business connection. The economic network — the set of all business connections — lies on a geographical transport network, which is described in detail below.

A business connection consists of one or more transport chain links. In every time step $t$ the product flow $Z^{(t)}_{ir\to js}$ between $ir$ and $js$ is transferred from one transport chain link to the next. Thus, the number of transport chain links of a business connection equals the transport time $\tau_{rs}$ between regions $r$ and $s$ measured in time steps. Service or non-service economic sectors (Table S1) transfer their products between supplier $ir$ and purchaser $js$ differently. On the one hand, economic products, which are assigned to the service sector, are not physical commodities and are delivered between firms within the next time step, e.g., Financial Intermediation & Business Activities. On the other hand, non-service products are delivered between supplier $ir$ and purchaser $js$ with a finite transport time along a business connection.

In the former version of Acclimate, the length and transport time of a non-service business connection was defined by the distance $\Delta^c_{rs}$ between the centroids $c_r$ and $c_s$ of region $r$ and $s$, respectively. Using the exogenous delivery velocity $v^c$ and the distance $\Delta^c_{rs}$ between the regions, each business connection had a fixed transport time $\tau_{rs}$ measured in time steps.

Here, we extend Acclimate with the geographical transportation network. Each business connection between non-service supplier $ir$ and purchaser $js$ has a transportation route $\mathcal{T}_{ir\to js}$ , which may include transportation via land, sea, or aviation. Each business connection with its transport chain links lies on a particular transportation route. This means that the length of the transport, and thus the number of transport chain links, is based on the transportation route. With this, an economic linkage is bound to the physical trading route it uses. How a transportation route is set up depends on whether the commodity is an aviation-good or non-aviation-good. In the former, the transport route consists of the centroids of the respective regions $r$ and $s$. Their distance $\Delta^c_{rs}$ is passed by aviation speed $v^a$. The transport by aviation can be compared with the previous transport modeling only at higher speed. Since our sectoral resolution is rather coarse and up to 90% of the merchandise goods are transported by ship, there are no products transported by aviation in this study.

Transportation routes of non-aviation goods are based on a geographical entity network, which consists of land entities, maritime entities, and ports. The former comprise the model regions and are spatially depicted via regions' centroids $c_r$. Each land entity has a connection to their adjacent land entity. Transport between neighboring regions progresses at land velocity $v^l$ and takes transport time $\tau_{rs} = \frac{\Delta^c_{rs}}{v^l}$, where $\Delta^c_{rs}$ is the distance between centroids of $r$ and $s$. If regions $r$ and $w$ are not directly connected but both are adjacent to region $s$, the transportation route is $r \rightarrow s \rightarrow w$. For this, the distance (transport time) between $r$ and $w$ is the sum of the distances (transport times) between $r$ and $s$, and $s$ and $w$: $\Delta^c_{rw} = \Delta^c_{rs} + \Delta^c_{sw}$ $(\tau_{rw} = \tau_{rs} + \tau_{sw})$. As long as there is a contiguous chain of land entities between a region $r$ and $w$, there can be a transportation route via land between those regions (even if there is more than one region between them). The total distance and transport time is calculated from the sum of the distances and transport times of the connected sub chain links, as in the example above. If a set of transport routes $\{\mathcal{T}_{irjs}\}$ is possible between firm $ir$ and $js$ , the one with the shortest distance is used for the transportation route via land. For example, the transportation route between a firm in Denmark and Italy consists of the land entities Denmark, Germany, Austria and Italy and not Denmark, Germany, France and Italy, even if this connection would be possible. Since continents are not connected to each other, there is no transportation route for each pair of regions that uses only land entities. For this we explicitly model sea routes using maritime entities.

For the maritime entities we split the relevant navigable seas into single areas with unique centroids[1] (Fig. 1a). Each maritime entity $\alpha$ is connected to their adjacent maritime entities $\{\beta\}$. The transport between them via sea has a velocity of $v^s$ and takes transport time $\tau_{\alpha\beta} = \frac{\Delta^c_{\alpha\beta}}{v^s}$, where $\Delta^c_{\alpha\beta}$ is the distance between the centroids of $\alpha$ and $\beta$. Analog to land entities, maritime entities

[1]The centroids of the maritime entities are listed in 10.5281/zenodo.5807332

that are not directly connected are connected via neighbor or next-neighbor (or next-next-neighbor and so on). As well as for land entities, distance or transport time between those not-directly connected entities aggregate the distance or transport time of the connected sub chain links between them. Likewise, if there are multiple options, the shortest transportation via sea route is chosen.

Land and maritime entities are not directly connected. Rather, a land entity and a maritime entity can both have a connection to a port $h$ (Fig. 1a). Ports are characteristic geographic points and therefore have a longitude and latitude coordinate. At the port as the common 'interface' between land and sea entity, transport on land (sea) changes to transport by sea (land) and thus the velocity changes to $v^s$ ($v^l$). The turnaround time at a port can be set exogenously and is fixed at one time step in this study ($\tau_h = 1$). If the transportation route $\mathcal{T}_{ir\to js}$ of firms $ir$ and $js$ consist of land and maritime entity, the total distance $\Delta^c_{rs}$ can be calculated by

$$\Delta^c_{rs} = \sum_{\{ww'\}} \Delta^c_{ww'} + \sum_{\{\alpha\alpha'\}} \Delta^c_{\alpha\alpha'} + \sum_{\{wh\}} \Delta^c_{wh} + \sum_{\{\alpha h\}} \Delta^c_{\alpha h}, \tag{1}$$

where $ww'$, $\alpha\alpha'$, $wh$, and $\alpha h$ are the set of connected and used land–land connections, sea–sea connections, land–port connections and sea–port connections, respectively. Analogously, the total transport time adds up to

$$\tau_{rs} = \sum_{\{ww'\}} \frac{\Delta^c_{ww'}}{v^l} + \sum_{\{\alpha\alpha'\}} \frac{\Delta^c_{\alpha\alpha'}}{v^s} + \sum_{\{wh\}} \frac{\Delta^c_{wh}}{v^l} + \sum_{\{\alpha h\}} \frac{\Delta^c_{\alpha h}}{v^s} + \sum_{\{h\}} \tau_h, \tag{2}$$

where $\{h\}$ is the set of used ports of transportation route $\mathcal{T}_{ir\to js}$ .

By using [91] and [92], we state that the price of one ton transported for one mile (a ton mile) on land is 3.7 times more expensive than transporting one ton-mile via sea. So the relative price per ton mile via sea is $p^s = 1$ and via land $p^l = 3.7$. Using this, we can calculate the cost of a transport route. The relative costs $\mathcal{C}_{rs}$ of transportation route $\mathcal{T}_{ir\to js}$ are

$$\mathcal{C}_{rs} = \sum_{\{ww'\}} \Delta^c_{ww'} p^l + \sum_{\{\alpha\alpha'\}} \Delta^c_{\alpha\alpha'} p^s + \sum_{\{wh\}} \Delta^c_{wh} p^l + \sum_{\{\alpha h\}} \Delta^c_{\alpha h} p^s, \tag{3}$$

where the set notation are the same as in eq. (1). If a set of transport routes $\{\mathcal{T}_{irjs}\}$ is possible between firm $ir$ and $js$ , the one with the *lowest* transportation costs is used for the transportation route. Using this decision rationale, there is a unique transportation route that is autonomously chosen by the economic agents and that closely replicates real-world trade routes. Transportation routes using maritime entities can be longer but still are more cost efficient, i.e. cheaper.

For example, a commodity from Germany to Beijing is transported as follows. From Germany (centroid) via land to the Port of Hamburg and shipped via North Sea, English Channel, Northern Atlantic Ocean North East, Strait of Gibraltar, Mediterranean Sea, Suez Canal, Red Sea, Gulf of Aden, Arabian Sea, Bay of Bengal, Strait of Malacca, Strait of Singapore, South China Sea, East China Sea, Yellow Sea to the Port of Tianjin. The final path to Beijing is then covered by road again. In our transport network we implement the 188 most important continental ports and islands (Table S3). Important to note is, the transportation prices on land or sea, and the relative transportation costs have no relevance to the further economic analysis and are only used for the model-internal decision firms for the transportation route.

As we mentioned above, the business connection of firm $ir$ and $js$ is "embedded" in the transportation route of those firms. This means, the number of transport chain links per business connection equals the total transportation time (measured in time steps) of the transportation route. More precisely, the transport chain links are divided among the individual sub-paths. A sub-path, distance between two entities or an entity and a port, or a port turnaround, has as many transport chain links as it takes transport time to complete this sub-path. Newly introduced parameters (compared to Otto et al. [20]) are listed in Table 1.

### *3.3. Transport perturbations*

We assume that the transportation route between two agents is fixed and cannot be changed within the short time scales of the model. Each geographic entity $e$ — land entity, maritime entity or port — has a passage flow $\chi_e(t)$, which determines how much of the baseline flow can pass through this entity per time step. The size of the baseline flow $Z^*_{ir\to js}$ depends on the specific firms

| Name | Symbol | Value | Unit |
|---|---|---|---|
| Time step | $\Delta t$ | 1 | day |
| Land velocity | $v^l$ | 70 | km·h$^{-1}$ |
| Sea velocity | $v^s$ | 40 | km·h$^{-1}$ |
| Port delay | $\tau_h$ | 1 | day |
| Relative sea transport price | $p^s$ | 1 | – |
| Relative land transport price | $p^l$ | 3.7 | – |

Table 1: **Transportation parameter**

A list of the transportation parameter of the Acclimate extension transport module.

$ir$ and $js$ . We assume that without perturbation a theoretically infinite volume of goods can flow through the land entities, maritime entities, or ports. The volume of flow of goods in a certain route segment can be exogenously disturbed. If an entity is disturbed, the flow of goods can be impeded by a factor $[0, 1]$. This means for entity $e$:

$$\chi_e(t) = \begin{cases} \infty & \text{, if no perturbation} \\ [0,1] & \text{, if perturbation} \end{cases} .$$

Each business connection between firms $ir$ and $js$ determines for each time step $t$ the minimum passage flow $m_{ir\to js}(t)$ of all its associated geographic entities $\{e'\}$: $m_{ir\to js}(t) = \min \chi_e(t)|_{e\in\{e'\}}$. If the minimum passage flow is below 1 ($m_{ir\to js}(t) < 1$) it has two consequences for the business connection of firms $ir$ and $js$ .

First, in such a situation the flow of goods $(1-m_{ir\to js}(t))Z^*_{ir\to js}$ $(\equiv \mathcal{B}_e(t))$ is blocked at entity $e$. This blocked flow ($\mathcal{B}_e(t)$ accumulates over time

$$\mathcal{B}_e(t) = (1 - m_{ir\to js}(t_1))Z^*_{ir\to js} + (1 - m_{ir\to js}(t_2))Z^*_{ir\to js} + \cdots ,$$

as long as $m_{ir\to js}(t) < 1$. If the blockage is lifted and $m_{ir\to js}(t) > 1$, the blocked flow is released with $\mathcal{B}_e(t+1) = \mathcal{B}_e(t) - (m_{ir\to js}(t) - 1)Z^*_{ir\to js}$ per time step (until it is zero) and is transported further along the business connections. If $m_{ir\to js}(t) = \infty$, the blocked flow passes entirely through the entity $e$ in one time step.

Second, as long as the minimum passage flow is below 1 ($m_{ir\to js}(t)< 1$), the purchaser $js$ will reduce its demand $D_{ir\to js}(t)$ to $ir$ by

$$D_{ir\to js}(t) = m_{ir\to js}(t) D^*_{ir\to js}, \quad \text{if } m_{ir\to js}(t) < 1. \tag{4}$$

Firm $js$ does not have the foresight how long the disturbance will occur and thus reduces its demand to supplier with a perturbed business connection. On the one hand, supplier $ir$ receives a lower demand if there is no compensating increased demand from other purchasers $\{j's'\}$. It has overproduced goods, which results in lower production and offering prices. On the other hand, to fulfill its demand (in order to produce the inquired products of other firms or consumers), firm $js$ will distribute remaining demand $(1 - m_{ir\to js}(t))D^*_{ir\to js}$ on its other supplier $\{i'r'\}$. Thus some suppliers $\{i'r'\}$ receive increased demand, which causes production and prices to rise. However, depending on their ability to do so, $js$'s demand may not be entirely fulfilled.

Important to note is that the delayed commodities are not destroyed and their delivering continues after the local blockage ceases. Nevertheless, reacting to shifted demand, the economic agents change demand, production, prices, and supply, which causes repercussions within the economic network. Even if there is no (direct) production failures of firms (as it has been studied in [20, 51, 52, 53, 54]) the perturbations propagate through the supply chains.

### *3.4. Typhoon impact on transmissibility of sea routes*

We focus on transport perturbation of the most affected maritime routes: South China Sea, East China Sea, Yellow Sea, Sea of Japan, and Gulf of Thailand. Tropical cyclones during a West Pacific typhoon season may restrict the navigability of these sea routes. Therefore, we assume that for the duration of a storm with more than 22 kn over those shipping routes, the flow of goods is constrained to 25% compared to baseline flow. The results in this study (in Section 4) are robust against these parameter choices as we depict in our sensitivity analysis in Section 4.6. Non-passed goods can be transported further via this sea route once the storm has passed or its wind speed is below the threshold of

| | Sea entity | | Sea entity |
|---|---|---|---|
| 1 | Northern Atlantic North East | 21 | Tiger Cub Sea |
| 2 | Northern Atlantic South East | 22 | Strait of Malacca |
| 3 | Southern Atlantic East | 23 | Bay of Bengal |
| 4 | Northern Atlantic North West | 24 | Indian Ocean North |
| 5 | Northern Atlantic South West | 25 | Indian Ocean South East |
| 6 | Southern Atlantic West | 26 | Arabian Sea |
| 7 | Caribbean Sea | 27 | Indian Ocean South West |
| 8 | Gulf of Mexico | 28 | Persian Gulf |
| 9 | Panama Canal | 29 | Strait of Hormuz |
| 10 | Northern Pacific East | 30 | Gulf of Aden |
| 11 | Southern Pacific East | 31 | Red Sea |
| 12 | Northern Pacific West | 32 | Suez Canal |
| 13 | Southern Pacific West | 33 | Black Sea |
| 14 | Sea of Okhotsk | 34 | Bosporus |
| 15 | Sea of Japan | 35 | Mediterranean Sea |
| 16 | Yellow Sea | 36 | Baltic Sea |
| 17 | East China Sea | 37 | North Sea |
| 18 | South China Sea | 38 | English Channel |
| 19 | Gulf of Thailand | 39 | Strait of Gibraltar |
| 20 | Strait of Singapore | 40 | Gulf of Guinea |

Table 2: **Sea entity**

Maritime trading routes implemented in Loss-propagation model Acclimate. Numbering refers to Fig. 1a.

22 kn. That means

$$\chi_e(t) = \begin{cases} \infty, & \text{if wind speed} < 22 \text{ kn in } \mathcal{P}_e \\ 0.25, & \text{if wind speed} \geq 22 \text{ kn in } \mathcal{P}_e \end{cases}, \tag{5}$$

where $\mathcal{P}_e$ is the polygon that defines the area of maritime routes $e$, here, South China Sea, East China Sea, Yellow Sea, Sea of Japan, and the Gulf of Thailand[2]. From tropical storm trajectories (Fig. 1b), based on IBTrACS [93, 94], we derive time series of commodity passage for the East Asian maritime trade routes for the years 2000–2020. Exemplary time series for the disturbed trade routes are depicted in Fig. 1c.

[2]Definition of polygons are available under 10.5281/zenodo.5807332.

### 3.5. Regional and sectoral aggregation

Based on these time series of short-term transport delays the Acclimate model computes the resulting economic repercussions. We then analyze the direct and indirect impacts. In the following, the regional results are summarized to economic blocs (Fig. 1d): China, Europe, NAFTA[3] (North American Free Trade Agreement), ASEAN (Association of Southeast Asian Nations), Latin America (except Mexico), SAARC (South Asian Association for Regional Cooperation), East Asia (Japan, North Korea, South Korea, Taiwan), Arab League, Post-Soviet states, Australia & Oceania, Sub-Saharan Africa, and Rest of the World. The detailed grouping of the regions is listed in Table S2. We include Mongolia among the Post-Soviet states because of its historical economic close relationship to the Soviet Union, even though this is historically inaccurate. Furthermore, we include Mauritania and Sudan to the bloc Arab League, even if they would fit to the definition of Sub-Sahara Africa as well. The economic blocs are economically quite large, which is why individual sectors and their flows do not exhibit significant different patterns. Therefore, we aggregate all flows and production of the sectors together. We list in Table 3 how many trading links and which economic volume in bn USD per year pass the typhoon-impacted West Pacific trading routes per the economic bloc.

In our further analyses we mainly focus on China, ASEAN, East Asia, Europe and NAFTA. For the first three blocs, several close maritime trade routes are directly affected by West Pacific typhoon season. The last two are the largest global economic blocs next to China. Results for other aggregated blocs are given in the Supplementary Information.

[3] Our computations base on the economic network of 2015, therefore we use the economic bloc NAFTA, despite it was replaced in 2020 by he succession agreement USMCA.

| | South China Sea | | East China Sea | | Yellow Sea | | Sea of Japan | | Gulf of Thailand | |
|---|---|---|---|---|---|---|---|---|---|---|
| | [links] | [bn USD] | [links] | [bn USD] | [links] | [bn USD] | [links] | [bn USD] | [links] | [bn USD] |
| China | 2515 | 856.7 | 2810 | 1030.2 | 1865 | 603.8 | 26 | 89.2 | 80 | 54.5 |
| | (47.1%) | (46.7%) | (52.6%) | (56.2%) | (34.9%) | (32.9%) | (0.5%) | (4.9%) | (1.5%) | (3.0%) |
| Europe | 876 | 797.7 | 378 | 322.8 | 263 | 151.3 | 32 | 99.8 | 41 | 44.5 |
| | (15.5%) | (25.8%) | (6.7%) | (10.5%) | (4.7%) | (4.9%) | (0.6%) | (3.2%) | (0.7%) | (1.4%) |
| NAFTA | 624 | 107.3 | 1106 | 104.3 | 636 | 48.2 | 53 | 54.5 | 75 | 19.0 |
| | (10.2%) | (8.3%) | (18.1%) | (8.1%) | (10.4%) | (3.7%) | (0.9%) | (4.2%) | (1.2%) | (1.5%) |
| ASEAN | 834 | 559.6 | 141 | 152.9 | 103 | 60.5 | 9 | 65.7 | 437 | 272.7 |
| | (53.4%) | (57.6%) | (9.0%) | (15.7%) | (6.6%) | (6.2%) | (0.6%) | (6.8%) | (28.0%) | (28.1%) |
| Latin | 141 | 25.2 | 195 | 18.7 | 110 | 11.3 | 20 | 7.1 | 13 | 1.1 |
| America | (5.6%) | (6.0%) | (7.7%) | (4.4%) | (4.4%) | (2.7%) | (0.8%) | (1.7%) | (0.5%) | (0.3%) |
| SAARC | 169 | 59.8 | 51 | 19.5 | 34 | 7.6 | 5 | 7.5 | 3 | 0.2 |
| | (15.5%) | (17.6%) | (4.7%) | (5.7%) | (3.1%) | (2.2%) | (0.5%) | (2.2%) | (0.3%) | (0.1%) |
| East Asia | 342 | 685.3 | 274 | 572.2 | 81 | 150.9 | 226 | 467.5 | 17 | 81.3 |
| | (42.3%) | (44.4%) | (33.9%) | (37.0%) | (10.0%) | (9.8%) | (28.0%) | (30.3%) | (2.1%) | (5.3%) |
| Arab League | 428 | 150.4 | 178 | 63.1 | 122 | 7.6 | 16 | 52.0 | 17 | 8.0 |
| | (23.0%) | (33.8%) | (9.5%) | (14.2%) | (6.5%) | (1.7%) | (0.9%) | (11.7%) | (0.9%) | (1.8%) |
| Post-Soviet | 54 | 11.8 | 66 | 48.6 | 56 | 48.4 | 4 | 0.2 | 4 | 1.8 |
| states | (7.0%) | (3.0%) | (8.5%) | (12.3%) | (7.2%) | (12.3%) | (0.5%) | (0.1%) | (0.5%) | (0.5%) |
| Australia | 83 | 86.9 | 50 | 42.7 | 38 | 18.4 | 6 | 18.8 | 9 | 6.2 |
| & Oceania | (15.3%) | (28.0%) | (9.2%) | (13.7%) | (7.0%) | (5.9%) | (1.1%) | (6.1%) | (1.7%) | (2.0%) |
| Sub-Saharan | 352 | 31.8 | 171 | 18.6 | 113 | 8.5 | 19 | 6.3 | 21 | 1.0 |
| Africa | (18.4%) | (18.1%) | (8.9%) | (10.6%) | (5.9%) | (4.8%) | (1.0%) | (3.6%) | (1.1%) | (0.6%) |

Table 3: **Economic blocs and their dependency on West Pacific trading routes.** Used aggregated economic bloc used in post-simulation analysis (Fig. 1b) and their number of business connection through a West Pacific trading route as well as the economic size of those business connections in bn USD. The number in brackets depict the share of the trading route compared to the total links or exports of the bloc, respectively.

## 4. Results

In the following results are presented in changes of the economic values with respect to their unperturbed baseline. Unless otherwise stated, the economic network and baseline refer to the year 2015. In our analysis we distinguish between the *quantity* and the *value* of an economic variable. The former refers to the physical amount of traded goods or hours spent on services measured in fixed 2015-USD. The latter refers to the value of traded goods and services, which is composed of the quantity and the *price* of a commodity or service ($value = price \cdot quantity$). Thereby, in the model price is the relative deviation from the (unknown) baseline price (i.e. 1 for the baseline) and quantity as well as value are both measured in USD. The first relies on fixed prices within the baseline MRIO table of 2015. The second accounts for endogenous price changes in our model. The temporal evolution of quantity, price, and thus also of the value for each traded good, is computed by *Acclimate*, after which they are aggregated to annual values in the post-computing analysis. In the following we also distinguish between *internal* and *external* demand. The former refers to demand which comes exclusively from firms and consumers of the economic bloc itself, while the later corresponds to the demand from other economic blocs. Similarly, we refer to internal and external trade as flows of commodities and services where the receivers are inside or outside of the economic bloc, respectively. In this study we use external trade and export as synonyms.

### *4.1. Transport perturbations cause demand-supply mismatch*

In order to clarify the economic dynamics during and after a transport disturbance due to a typhoon, we focus in this section on the typhoon seasons of 2018 and the simulated economic repercussions of the most affected bloc, China, and the biggest profiteer, NAFTA.

Tropical storms cause transport disturbances on West Pacific shipping routes from 1 to 8 days depending on their trajectory (Fig. 1c). Chinese maritime trading routes may be perturbed due to one of these typhoons, which causes

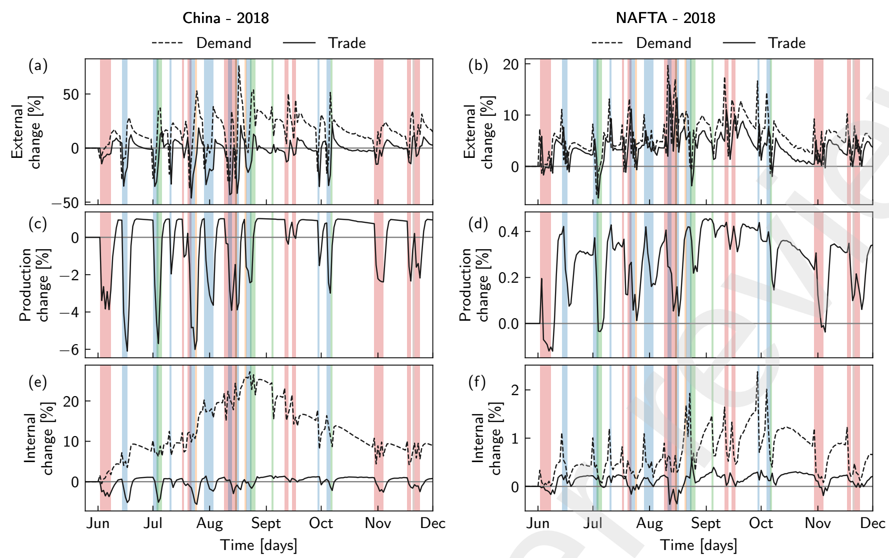


Figure 2: **Typhoon-induced transport disturbance induce demand shifts and furthermore production and trade changes.** The external (upper panels) and internal (middle panels) demand change (dashed line) with corresponding production change (middle pannels) and following trade change (solid line) due to transport disturbance in maritime trade routes for China (a,c,d) and (b,d,f) NAFTA. Changes are relative to baseline. The perturbed trading route is marked via same color scheme, which is used in Fig. 1d. The exemplary typhoon season shown is 2018.

short-term decrease of external demand (Fig. 2a). A decline of external demand yields a lower Chinese production (Fig. 2c) during a typhoon. In the aftermath of a transport disturbance external demand and therewith production in China increases.

In contrast to China, NAFTA maritime trading routes are just partially affected by the West Pacific typhoon season. As a result, they are used as substitute suppliers for other blocs and thus external demand increases at the beginning of the transport perturbation (Fig. 2b). But since production in other blocs decrease, external demand declines after some time steps while West Pacific transport disturbance. Thus, NAFTA's initial rise in external demand, trade, and production abates partly (Fig. 2b,d).

The demand and supply shocks during a typhoon cause Chinese production to decline, which causes that demand of the domestic market cannot be perfectly fulfilled as well. Thus, internal trade decreases during phases of production reduction. Less production causes a decline in inner-Chinese trade (internal trade), despite the fact that internal demand increased. As stated previously, in the disaster aftermath external demand increases. The lack of supply and a rise in production puts more pressure on the Chinese market externally and internally. Thus, internal demand increases even further (Fig. 2e). The same pattern occurs for every transport disturbance. However, previous economic repercussions are reflected in the dynamics (Fig. 2e), e.g. internal demand may rise after one typhoon and before the next. The high frequency of transport perturbations between June and end of August yield increased internal demand. In other words, the frequency of transport shocks is too high compared to the relaxation time of internal demand. For NAFTA, short-term production declines causes short internal supply shortages, but internal trade increases in the aftermath. Supply uncertainties are counteracted as well by increased demand from the domestic market (Fig. 2f).

### *4.2. Exports increase despite typhoon transport perturbations*

In the following, our results are given in median annual changes of 21 West Pacific typhoon seasons (2000–2020) with corresponding likely ranges.

#### *4.2.1. Exports increase in quantity*

Despite imminent typhoon-induced maritime transport restrictions, China is able to increase its annual exports in quantity (Fig. 3a). In contrast to this, China depicts losses in exported value. The other economic blocs are able to increase their exports in quantity and value facing the typhoon-induced transport disruptions. In this regard, NAFTA is the biggest winner. Our results hint that inter-regional trade involving NAFTA might be boosted by typhoon-induced transport disruption (Fig. 3a). So the annual intra-regional trade of the economic blocs depict gains — at least in the amount of exports — even

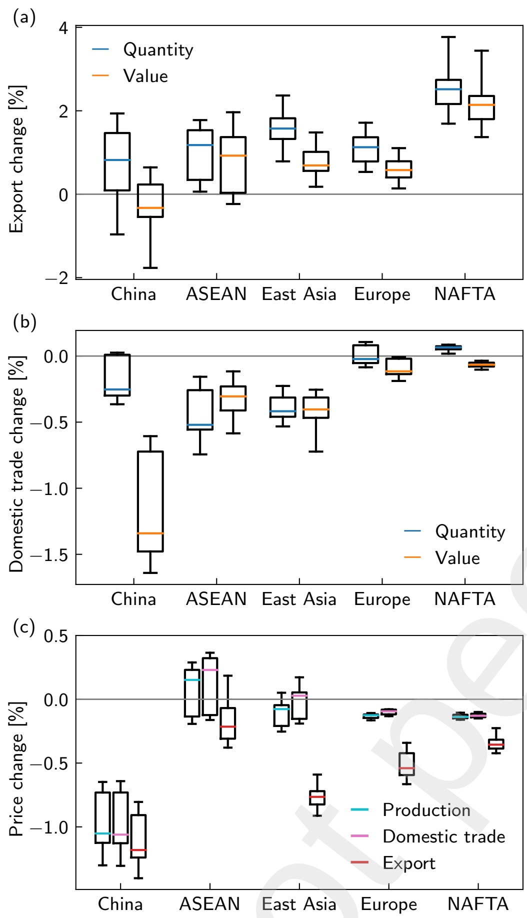


Figure 3: **Perturbed trading routes yield price changes which mostly intensify internal trading losses or decreases export gains in value.** Ensemble includes 21 typhoon seasons (2000–2020). Colored lines, boxes and whiskers indicate median changes for each estimate, the 25–75 and 5–95 percentile ranges, respectively. Changes are depicted for one year and are relative to the economic baseline.
(a) Typhoon disturbed inter-regional trade increases amount of exports (blue) but lower prices decreases gain in value (orange).
(b) Domestic trade decreases in quantity and value in most economic blocs. Raised demand increases production in NAFTA and thus the domestic trade also increases slightly in quantity.
(c) Prices of production (light blue), and goods and services traded internally (pink) or exported (red) decrease in most economic blocs.

if transport is disturbed. In the disaster aftermath, increased demand and trade lead to an rise of exports of every economic bloc. We interpret this positive feedback as resilience towards trade perturbation caused by maritime disturbances.

#### *4.2.2. Internal trade mostly reduces*

Trade inside each economic bloc does not depict such a perturbation resilience; trade within the domestic market decreases in most blocs (Fig. 3b).

Here, China has the largest losses in value and only NAFTA can strengthen its internal trade. However, the internally highly interconnected economic blocs of China and Europe show comparatively small impacts on the volume of internal trade.

#### *4.2.3. Production and trading prices mostly decrease*

In our study setup no good is destroyed by typhoons, nor do firms stop production due to direct impacts of a typhoon. Therefore, there is no direct global scarcity of commodities but rather a dislocation and delay of goods and services. As firms' inventories tend to be fuller and inter-regional buyers are absent, a regional oversupply is created, causing prices to fall (Fig. 3c). This effect occurs mainly in China. Since China is directly affected from typhoon-induced transport disruption, there is a larger oversupply of goods. Thus, production and domestic trade prices drop as well as offering prices for exporting commodities. However, the latter is likely to be beneficial for demand from abroad, allowing China to increase their exports in quantity (Fig. 3a). Lower export prices are common across the economic blocs, even for ASEAN which increases production and internal trade prices. Since the South China Sea is within the trade routes of the ASEAN region, internal trade between ASEAN countries is disrupted, resulting in no intra-regional oversupply and thus no price reductions but price increases instead (Fig. 3c).

### *4.3. Affected trading routes impact Chinese exports*

In this study we focus on the transport obstructions through the South China Sea, East China Sea, Yellow Sea, Sea of Japan, and the Gulf of Thailand. China uses, depending on its trading partner, every single one of these five trading routes. Important trading routes are the first three ones, regarding number of trading connection and traded economic volume (Table 3). China depicts a different export change if only trading routes in East China Sea or South China Sea are disturbed compared to all five West Pacific trading routes (Fig. 4a). Transport blockages in East China Sea cause Chinese export losses in

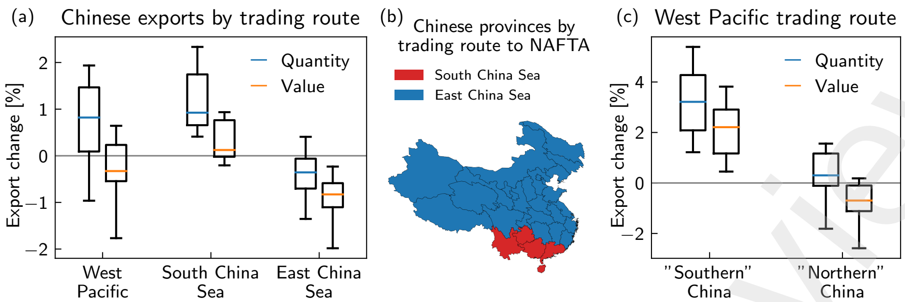


Figure 4: **Chinese export resilience to transport disruption depend on affected trading route.**

For (a) and (c): Ensemble includes 21 typhoon seasons (2000–2020). Colored lines, boxes and whiskers indicate median changes each estimates, the 25–75 and 5–95 percentile ranges, respectively. Changes refer to the economic baseline.

(a) Chinese export changes if typhoon seasons cause transport perturbation on all five West Pacific trading routes, only on South China Sea or only on East China Sea. Disruption of the latter causes export losses in quantity and value.

(b) Regarding maritime trading route to NAFTA, China provinces are divided into those using South China Sea (red) – "Southern" China – or East China Sea (blue) – "Northern" China.

(c) Regarding typhoon-induced transport perturbation on all five West Pacific trading routes, "Southern" China can benefit (more) from typhoon-induced transport perturbation on all five West Pacific trading routes compared to "Northern" China.

quantity and value. In contrast to that, Chinese firms are able to increase their exports from perturbation within the South China Sea. The reason for this is that one important receiving economic bloc from China is NAFTA — 22% of Chinese exports are to NAFTA (Table 4). Chinese provinces can be divided into "Northern" China that uses East China Sea to NAFTA and "Southern" China that uses South China Sea to export commodities to NAFTA (Fig. 4b). The total production of the former is about 5 times higher than the latter(Table 4). Regarding typhoon-induced West Pacific transport route perturbations "Southern" China profits, while "Northern" China exports in value decreases (Fig. 4c). As a result, China as a whole has more difficulties to compensate for export reductions going through East China Sea, which suggest that this maritime entity is crucial to Chinese economic well-being.

| | GDP [tn USD] | China [bn USD] | Europe [bn USD] | NAFTA [bn USD] | ASEAN [bn USD] | Latin America [bn USD] | SAARC [bn USD] | East Asia [bn USD] | Arab League [bn USD] | Post-Soviet states [bn USD] | Australia & Oceania [bn USD] | Sub-Saharan Africa [bn USD] | Rest of World [bn USD] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| China | 24.6 (17.8%) | 22,793 | 445 (24.3%) | 398 (21.7%) | 144 (7.9%) | 49 (2.7%) | 44 (2.4%) | 319 (17.4%) | 47 (2.6%) | 20 (1.1%) | 44 (2.4%) | 18 (1.0%) | 307 (16.7%) |
| Europe | 35.3 (25.5%) | 449 (14.5%) | 32,201 | 780 (25.2%) | 209 (6.8%) | 235 (7.6%) | 127 (4.1%) | 288 (9.3%) | 263 (8.5%) | 215 (6.9%) | 75 (2.4%) | 123 (4.0%) | 325 (10.5%) |
| NAFTA | 34.1 (24.6%) | 124 (9.7%) | 434 (33.7%) | 32,781 | 111 (8.6%) | 195 (15.1%) | 20 (1.6%) | 227 (17.6%) | 37 (2.9%) | 12 (0.9%) | 67 (5.2%) | 12 (1.0%) | 47 (3.7%) |
| ASEAN | 5.0 (3.6%) | 176 (18.2%) | 186 (19.2%) | 164 (16.9%) | 4,016 | 13 (1.3%) | 46 (4.7%) | 238 (24.6%) | 27 (2.7%) | 3 (0.3%) | 50 (5.2%) | 8 (0.9%) | 58 (6.0%) |
| Latin America | 7.8 (5.6%) | 34 (7.9%) | 110 (26.0%) | 210 (49.7%) | 7 (1.7%) | 7,353 | 4 (1.0%) | 31 (7.3%) | 6 (1.4%) | 4 (0.9%) | 4 (0.9%) | 6 (1.5%) | 7 (1.8%) |
| SAARC | 4.1 (3.0%) | 26 (7.7%) | 99 (29.2%) | 65 (19.1%) | 29 (8.7%) | 10 (2.8%) | 3,762 | 21 (6.2%) | 49 (14.5%) | 4 (1.3%) | 4 (1.3%) | 15 (4.5%) | 16 (4.7%) |
| East Asia | 11.8 (8.5%) | 440 (28.5%) | 245 (15.9%) | 321 (20.8%) | 242 (15.7%) | 41 (2.6%) | 37 (2.4%) | 10,284 | 37 (2.4%) | 8 (0.5%) | 48 (3.1%) | 12 (0.8%) | 113 (7.3%) |
| Arabic League | 4.3 (3.1%) | 23 (5.1%) | 146 (32.9%) | 43 (9.6%) | 30 (6.8%) | 9 (1.9%) | 23 (5.2%) | 129 (29.0%) | 3,818 | 5 (1.1%) | 6 (1.3%) | 8 (1.9%) | 23 (5.3%) |
| Post-Soviet states | 4.0 (2.9%) | 54 (13.8%) | 231 (58.6%) | 23 (5.8%) | 6 (1.4%) | 3 (0.8%) | 11 (2.8%) | 35 (9.0%) | 3 (0.9%) | 3,592 | 0 (0.0%) | 1 (0.2%) | 27 (6.8%) |
| Australia & Oceania | 2.7 (2.0%) | 51 (16.5%) | 36 (11.6%) | 34 (10.9%) | 51 (16.5%) | 5 (1.5%) | 13 (4.2%) | 90 (28.9%) | 8 (2.6%) | 2 (0.5%) | 2,389 | 5 (1.5%) | 16 (5.3%) |
| Sub-Saharan Africa | 2.1 (1.5%) | 24 (13.9%) | 72 (41.1%) | 32 (18.2%) | 5 (3.1%) | 6 (3.4%) | 7 (4.0%) | 18 (10.1%) | 3 (1.8%) | 1 (0.4%) | 3 (1.6%) | 1,923 | 4 (2.4%) |
| Rest of World | 2.7 (1.9%) | 95 (21.1%) | 151 (33.5%) | 61 (13.7%) | 41 (9.2%) | 11 (2.3%) | 14 (3.1%) | 30 (6.6%) | 20 (4.5%) | 15 (3.4%) | 4 (1.0%) | 7 (1.6%) | 2,238 |
| "Northern" China | 20.6 (14.9%) | – | 372 (20.3%) | 333 (18.1%) | 121 (6.6%) | 41 (2.2%) | 36 (2.0%) | 267 (14.6%) | 39 (2.1%) | 17 (0.9%) | 37 (2.0%) | 15 (0.8%) | 257 (14.0%) |
| "Southern" China | 4.0 (2.9%) | – | 73 (4.0%) | 65 (3.6%) | 23 (1.3%) | 8 (0.4%) | 7 (0.4%) | 52 (2.8%) | 8 (0.4%) | 3 (0.2%) | 7 (0.4%) | 3 (0.2%) | 50 (2.7%) |

Table 4: **Economic volume of blocs in 2015.** Left side: Annual production in tn USD with share of world production below in brackets per bloc. Right side: Supply volume in bn USD internally and to others of economic blocs. The share of exports of a bloc to another is given below the corresponding supply. Self-supply of each bloc is roughly a magnitude higher than the total exports of a bloc.

### *4.4. Increased inter-connectivity supports short-term export adaptation*

So far, our results and interpretations base on the trade structures of 2015. In this section, we examine export changes for other in order to reveal factors for the identified trade resilience. Using the same impact of 2000–2020 typhoon seasons, we compute the export changes to different economic baselines from 2000 to 2015 (Fig. 5). Overall, the economic blocs' exports increases with later economic baselines. The most directly affected blocs, China, ASEAN, and East Asia experience lower export losses or partly get net-export gains in later years. Especially ASEAN and East Asia turn into net-export winner in quantity and value. Next to them, Europe is able to become a net-export winner as well within later years. The positive export response of NAFTA is robust against different network years.

This increase in resilience to transport perturbations for most blocs cannot be explained by the export share of each economic bloc. While China more than doubles its export between 2000 and 2015, East Asia's and NAFTA's share decreases roughly by a third (Fig. 6a). At the same time ASEAN increases its share by 20% and Europe's share is more or less stable at a high level. Nevertheless, resilience increases collectively in the later economic networks.

We find that the reason that trade resilience increases for some blocs in recent years arises from the changes of number of trade connections. From the beginning of the millennium the number of connections to external purchasers per firm within a economic bloc develops different from the export share (Fig. 6b). We refer to the number of connections to external purchasers as the total number of trading links to the outside of each economic bloc. We normalize this number of outside connections with the economic bloc's number of firms to account for blocs' different economic sizes. From 2000 to 2015 China, Europe, East Asia, and ASEAN increased their number of outside connections per firm, while NAFTA is at a stable high level. A higher number of connections to other firms enables economic agents to shift supply and demand on non-disturbed trading routes. A higher number of outside connections can be interpreted as a more strengthened inter-connectivity of a bloc. Increasing inter-connectivity

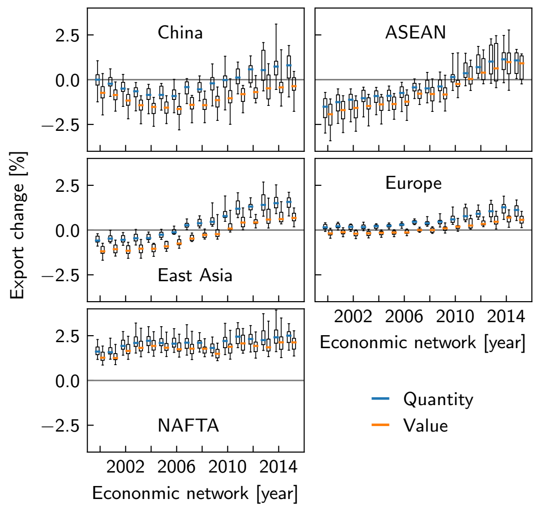


Figure 5: **Most blocs become over time more resilient against perturbations to West Pacific transport.** Annual export change per quantity (blue) and value (orange) for economic network baselines for the years 2000–2015. The trend of results for the most affected economic blocs — China, ASEAN and East Asia — changes with underlying economic network. Export losses due to transport perturbations convert to export quantity gains for these blocs. Europe becomes a net-export value winner for later network years. Results for NAFTA are robust against changes in baseline network. Ensemble includes 21 typhoon seasons (2000–2020). Colored lines, boxes and whiskers indicate median changes each estimates, the 25–75 and 5–95 percentile ranges, respectively. Changes refer to the economic baseline.

supports to buffer export losses and may turn export losses to export gains (Fig. 6c). A diverse variety of links to other blocs supports export adaptation to demand and supply fluctuations. Other economic blocs show an increase in the number of outside connections since the beginning of the century as well (Fig. S3a). Likewise, their trade resilience towards maritime disturbance grow with higher trade-inter-connectivity (Fig. S3b).

### *4.5. Demands and supply shifts between blocs*

After giving an explanation for trade resilience, we want to focus on changes in trade between the five main economic blocs. So in this section, our analysis

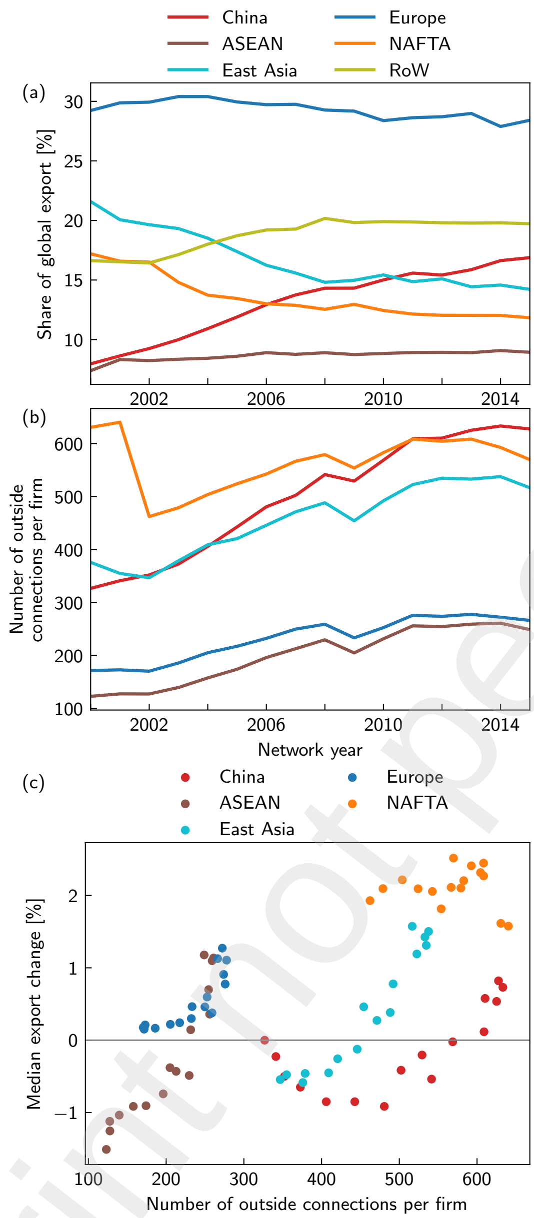


Figure 6: **Inter-connectivity of economic blocs change for different economic baselines.** China, ASEAN, East Asia, Europe, NAFTA, and Rest of the World (RoW) are depicted in red, brown, turkis, blue, orange, and lime, respectively.

(a) Annual export share changes regionally between 2000 and 2015.

(b) Number of foreign connections per firm within the economic bloc for different economic baselines.

(c) Median annual export change in quantity per region over number of foreign connections per firm. Export resilience tends to increase with more foreign connections.

bases again on the economic baseline of 2015. As we present changes in trade only for the five blocs considered so far (Fig. 7), trading results between any two blocs are listed in Table S4 and Table S5. The blocs' exports in the baseline and its corresponding share of exports can be found in Table 4.

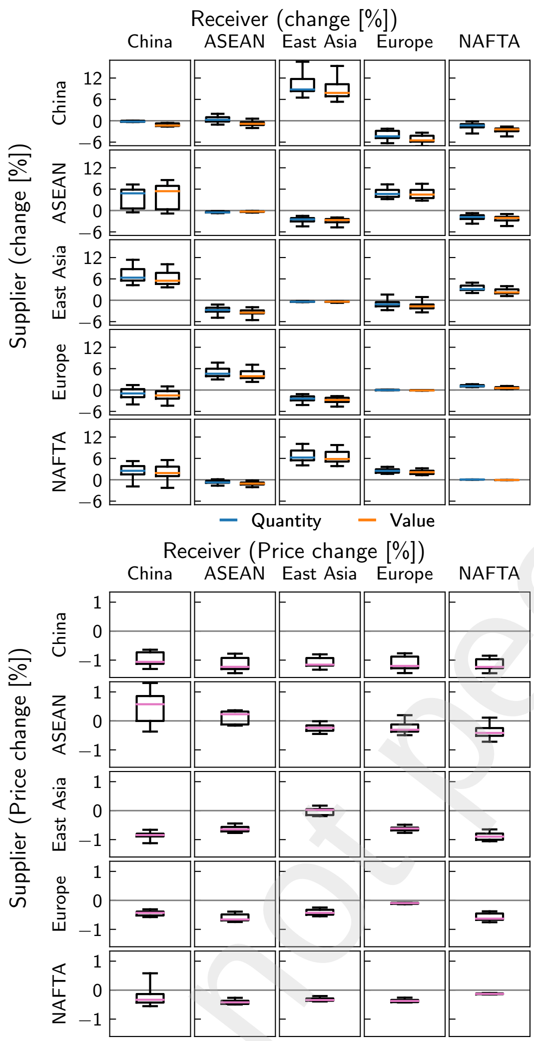


Figure 7: **Inter-connectivity increases except for NAFTA.** Ensemble includes 21 typhoon seasons (2000–2020). Colored lines, boxes and whiskers indicate median changes each estimates, the 25–75 and 5–95 percentile ranges, respectively. Changes refer to the economic baseline.
(a) Annual supply change per supplier (row) and purchaser (column) due to West Pacific typhoon season. Export between blocs increases (decreases) by quantity (value). Bloc-internal trade change is shown on the diagonal graphs.
(b) Annual price change of traded goods and services per supplier (row) and purchaser (column) due to West Pacific typhoon season. Bloc-internal (domestic) trade price change is shown on the diagonal graphs. China depicts the highest export price drop to any other economic bloc.

#### *4.5.1. China's export losses and adaptation mechanism*

China decreases its exports in quantity to almost any other economic bloc (Fig. 7a). Export losses are particularly severe for the largest customer (24%) of Chinese goods: Europe. However, the Chinese export reduction to other blocs is probably buffered by lower trading prices compared to other export prices of other blocs (Fig. 7b). Lower supply prices make Chinese goods more attractive for firms and consumers from outside of China. In particular, there are strong

Chinese export gains towards East Asia. East Asia is already a big purchaser of Chinese exports (about 17%) and can substitute for lack in supply and demand, especially when the trading route through South China Sea is perturbed.

#### *4.5.2. East Asia intensifies its trade with China and NAFTA*

Going the other way around, China has an even bigger share of East Asian exports (29%). By disturbing the trading route through South China Sea, East Asia trade relations with ASEAN and Europe are flagging. The East Asia's export share of these blocs add up to 32%. Demand and supply deficits are compensated for by China and NAFTA. The latter increases its trade as well when trading routes between East Asia and China is partly perturbed.

#### *4.5.3. ASEAN's trade relocates to the west*

During typhoons the ASEAN states are challenged by trade interruptions to East Asia and NAFTA. Both are significant buyers of ASEAN goods (25% and 17%, respectively). In order to sell their commodities ASEAN increases its exports to Europe and SAARC (Table S4). Exports to China are increasing as well, but ensemble results fluctuate widely. This may arise from the different connections to China. Some ASEAN states, like Vietnam or Thailand, have some trading route on land, which (in this study) are not affected by typhoon-induced transport disruption. Other states, like Philippines or Indonesia, are very much cut off from China regarding transport during a typhoon. Nevertheless, regarding ASEAN as a whole, export gains to China prevail.

#### *4.5.4. Europe substitutes eastern Asian purchaser*

During the West Pacific typhoon seasons, the globally largest exporting bloc, Europe, increases its exports to any other bloc (Table S4), except for China and East Asia. However, the losses in exports to China are marginal and do not occur for all seasons. Especially seasons with a low impact on the South China Sea may exert less pressure on the export problems between China and Europe.

#### 4.5.5. NAFTA is net-export winner

NAFTA faces the biggest export gains in quantity and in value. It increases its export to any bloc except for ASEAN and Rest of the World (Table S4). The diversified export rise comes from the geographic benefit of the NAFTA countries. NAFTA can satisfy mostly increased demand from the west, east, and south without depending on interruptions in the Western Pacific trading routes, except for ASEAN states and some provinces of China. But even the partly limited trade to China is compensated for. Therefore, NAFTA can increase exports to China. As NAFTA has a negative trade balance with most other blocs, the export rise is even more favorable for it.

### 4.6. Sensitivity analysis

In this study we use a novel approach model for maritime transport disturbances due to typhoons. A typhoon that passes through a sea area reduces the ability to ship goods through this area. To implement this we assume, on the one hand, a passage limit (25%) on the amount of goods passing a route during a disturbance. On the other hand, we set a wind speed threshold (22 kn) when a sea route is perturbed by a tropical storm. Sensitivity analyses of those parameters depict that our results do not significantly change under these parameters (Fig. 8a). If the passage limit during a storm is attenuated (limit closer to 100%) more goods can be transported through the trading route. This causes that export changes decline slightly. A higher transport throughput yields to less economic repercussion, which changes the quantity of the results but not their general trend. When increasing the disturbance threshold, the export changes decrease as well, but do not show a trend shift (Fig. 8b). A higher wind speed threshold causes fewer days of transport perturbation, especially for South China Sea (Fig. S2). But even with fewer transport disturbances and thus less economic repercussion, the trend of export changes is preserved.

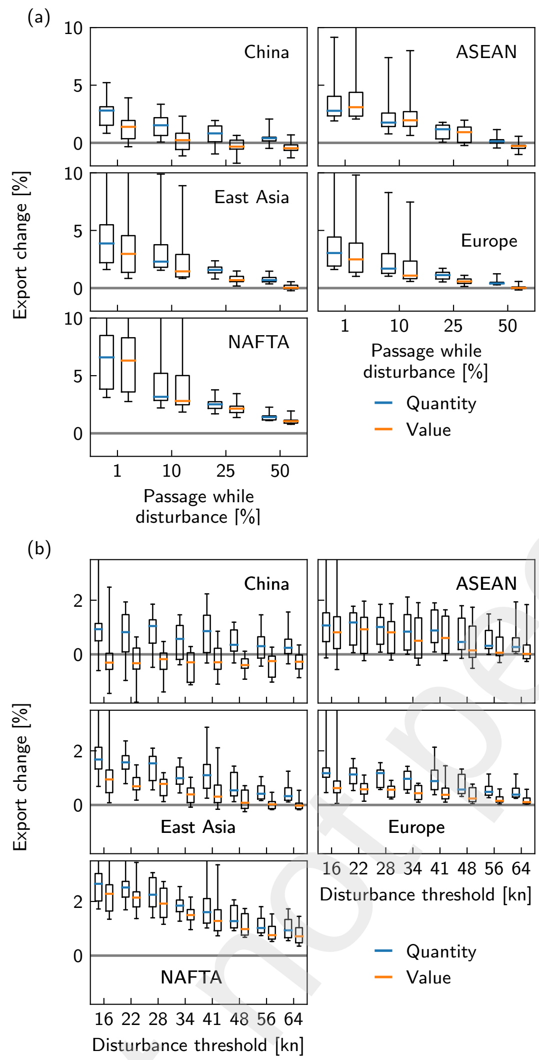


Figure 8: **Trends in result are robust against changes of disturbance modeling.**
Annual export change per quantity (blue) and value (orange) for different (a) passages – possible commodity flows through maritime trading route – and (b) wind speed thresholds while typhoon-induced disturbances. Ensemble includes 21 typhoon seasons (2000–2020). Colored lines, boxes and whiskers indicate median changes each estimates, the 25–75 and 5–95 percentile ranges, respectively. Results with full percentile ranges is depicted in Fig. S4. Changes refer to the economic baseline.
(a) Attenuate the passage limit yield that more commodities can go through sea route while disruption time. Note, that the x-axis is not true to scale. Since perturbations of trade becomes smaller for softer limits, export increase of each economic bloc is weakened but the trend persists.
(b) Higher thresholds of wind speed result in fewer days of transport perturbation. Since perturbations of trade becomes smaller for higher thresholds, export changes decline as well but trend of the response of economic blocs remains the same.

## 5. Discussion

In this study, we focus on transport perturbations induced by typhoons in the West Pacific. We find that during the perturbation directly affected trade blocs such as China or East Asia become less attractive for the their trade partners, who partially reschedule their demand to other non-affected trade partners, e.g., Europe or NAFTA. This results in a decline of production in the directly affected blocs, which can translate into production declines in non-directly affected blocs due to reduced demand received from outside of the region. These production anomalies result in reductions in trade within the respective trade blocs as well. The resulting price drops lead to a temporal increase in demand, production, as well as internal and external trade above their pre-disaster levels once the perturbation has ceased.

Accounting for the last 21 West Pacific typhoon seasons, we find that, in absolute terms, annual average export volumes increase all trade blocs. This suggests that inter-regional trade is partially resilient against typhoon-induced transport disruptions. In relative terms, trade between Europe and East Asia, China, and East Asia, decreases, while trading between Europe and South Asia — SAARC and ASEAN — increases. Due to regional proximity, trade between China and East Asia is being strengthened, although the latter is increasingly relying on trade on the other side of the Pacific (NAFTA and Latin America). NAFTA is the overall net-export winner, which can be explained by its geographic advantage to reach most economic actors without transport disruption.

Further, we find that the resilience of the exports of the trade blocs are correlated with the number of outside connections per sector. Export gains increase with the number of connections to external trade partners of the firms within the block. Since the connectivity of firms in China, ASEAN and East Asia to external trade partners has substantially increased between 2000–2015, they shifted from net-export losers in the early 2000s to net-export winners in 2015.

By its very nature, economic modeling must always be understood in the context of its limitations due to the complexity of human behavior. Nevertheless, for reasonable assumptions, conclusions can be made within the limits drawn. In this study, we focus on short-term transport disruptions (a few days) due to typhoons and the resulting economic repercussions. For this, our assumption of myopic economic agents with no long-term investment strategy is justifiable. Adaptation measures, such as the formation of new transport routes or trade links, are, however, not in the scope of our study.

The modeled maritime transport network consists of ocean sub-regions (e.g. Northern Atlantic North East or Southern Pacific East), seas (e.g. Red Sea), coastal bodies of water (e.g. Gulf of Mexico or Bay of Bengal), and artificial or natural sea straits (e.g. Suez Canal or Strait of Malacca). Thereby, the selection of the trade routes is a trade-off between computational effort and required resolution for this study. We include only possible and plausible routes that are also navigable throughout the year. For example, maritime routes across the partially ice-free Arctic Ocean are not taken into account. Furthermore, we assume that theoretically an infinite amount of commodities can pass through a land entity, maritime entity or port. This assumption is perhaps practical but rather less realistic, especially for ports. In our model, ships pass through the midpoints of the associated sea entities along a transport route and ships cannot adjust their maritime routes due to preceding transport obstructions. This is a constraint on the adaptation measures of the transportation planners, however, reasonable for the length of our simulated shocks. The Suez canal obstruction in early 2021 depicted that the most ships did not change transport routes for a short-term (daily scale) transport blockage.

Additionally, we have to make simplifying assumptions for the transport perturbation in the West Pacific sea routes. Here, the transport disruption over a wind speed threshold is based on studies referring to storm-induced delays for ports [11] or to container network analysis [95]. Next to this, our sensitivity analyses reveal, that the choice of disturbance threshold and intensity does not change the trend of our results. To tackle the problem with climate variability, our results base on an ensemble of 21 typhoon seasons (which included measured storm tracks).

At a first glance, our findings that exports increase in the disaster aftermath contrast with estimated export losses of previous studies [96, 97]. However, our analysis focuses on short-term transport delays and does not include the destruction of production goods or the long-term destruction of infrastructure. Because tropical storms can cause both impacts — short-term transportation disruption and destruction of physical capital — further research should consider both effects in a joint setup.

While the underlying economic network evolves, the number of outside connections per firm of the economic blocs changes(Fig. 6). However, although the blocs exhibit divergent rates of change, the signs of change are uniform across the blocs (except in the early 2000s). That means that the trading density of the economic network increases or decreases homogeneously. In the literature, the debate [98] whether more dense and complex networks are more stable [99, 86] or less stable [99, 89] is still open. Assuming trade resilience to maritime disruptions as a measure of stability of a global trade network, our results suggest that more complex networks (more inter-connections) are more likely to be stable (more trade resilience). Nevertheless, this likely differs depending on location and size of the perturbation.

The transportation extension of Acclimate presented in this study can be used to examine economic repercussions of further short-term supply chain constraints. Tropical storms impede shipping even in other locations, and other extreme events can disrupt supply chains for short periods of time. For those regions, our analysis could be easily extended. The storm tracks used here vary widely between seasons and our results depict clear results in trends, which hints that we there is a more in-depth mechanism. The diversification of trading partners enables economies to counteract transport disruptions with increased export in the aftermath. In a world where extreme events are likely to increase, this trade resilience can mitigate local economic perturbations.

**Data and materials availability**

The implementation of the *Acclimate* model is available as open source on `https://github.com/acclimate/acclimate` with identifier 10.5281/zenodo.needed. The used data for categorization of the maritime entities and the geographic network are available at 10.5281/zenodo.5807332).

#### Acknowledgments

This research has received funding from the German Academic Scholarship Foundation and the German Federal Ministry of Education and Research (BMBF) under the research projects CLIC (FKZ: 01LA1817C), QUIDIC (01LP1907A), and SLICE (FKZ: 01LA1829A), from the Horizon 2020 Framework Program of the European Union (grant agreement 820712), and by the Defense Advanced Research Project Agency under the World Modelers program (grant W911NF1910013).

#### References

[1] G. Federico, A. Tena-Junguito, A tale of two globalizations: gains from trade and openness 1800–2010, Review of World economics 153 (3) (2017) 601–626.

[2] WTO, Global trade rebound beats expectations but marked by regional divergences, accessed: 2021-11-05 (Oct 2021).
URL https://www.wto.org/english/news_e/pres21_e/pr889_e.html

[3] O. Taherzadeh, M. Bithell, K. Richards, Water, energy and land insecurity in global supply chains, Global Environmental Change 67 (2021) 102158. doi:https://doi.org/10.1016/j.gloenvcha.2020.102158.
URL https://www.sciencedirect.com/science/article/pii/S095937802030741X

[4] S. N. Sirimanne, J. Hoffman, W. Juan, R. Asariotis, M. Assaf, G. Ayala, H. Benamara, D. Chantrel, J. Hoffmann, A. Premti, et al., Review of maritime transport 2019, Tech. rep., tech. rep (2019).

[5] Ship still stuck in suez canal as backlog grows to 150 other ships — cbc news, accessed: 2021-11-05 (Mar 2021).

URL https://www.cbc.ca/news/business/suez-canal-egypt-ever-given-1.5963207

[6] I. Martínez-Zarzoso, S. Bensassi, The price of modern maritime piracy, Defence and Peace Economics 24 (5) (2013) 397–418.

[7] V. Wendler-Bosco, C. Nicholson, Port disruption impact on the maritime supply chain: a literature review, Sustainable and Resilient Infrastructure 5 (6) (2020) 378–394.

[8] M. Hassanzadeh, Port safety; requirements & economic outcomes, Marine Navigation and Safety of Sea Transportation: Maritime Transport & Shipping (2013) 117–121.

[9] H. S. Loh, Q. Zhou, V. V. Thai, Y. D. Wong, K. F. Yuen, Fuzzy comprehensive evaluation of port-centric supply chain disruption threats, Ocean & Coastal Management 148 (2017) 53–62.

[10] U. Gidado, Consequences of port congestion on logistics and supply chain in african ports, Developing Country Studies 5 (6) (2015) 160–167.

[11] J. Verschuur, E. Koks, J. Hall, Port disruptions due to natural disasters: Insights into port and logistics resilience, Transportation research part D: transport and environment 85 (2020) 102393.

[12] J. A. Church, N. J. White, L. F. Konikow, C. M. Domingues, J. G. Cogley, E. Rignot, J. M. Gregory, M. R. van den Broeke, A. J. Monaghan, I. Velicogna, Revisiting the earth's sea-level and energy budgets from 1961 to 2008, Geophysical Research Letters 38 (18).

[13] L. Cheng, K. E. Trenberth, J. Fasullo, T. Boyer, J. Abraham, J. Zhu, Improved estimates of ocean heat content from 1960 to 2015, Science Advances 3 (3) (2017) e1601545.

[14] K. Emanuel, Increasing destructiveness of tropical cyclones over the past 30 years, Nature 436 (7051) (2005) 686–688.

[15] K. A. Emanuel, Downscaling cmip5 climate models shows increased tropical cyclone activity over the 21st century, Proceedings of the National Academy of Sciences 110 (30) (2013) 12219–12224.

[16] K. Balaguru, G. R. Foltz, L. R. Leung, K. A. Emanuel, Global warming-induced upper-ocean freshening and the intensification of super typhoons, Nature communications 7 (1) (2016) 1–8.

[17] Exports of goods and services (current usd), accessed: 2021-11-05 (2020). URL https://data.worldbank.org/indicator/NE.EXP.GNFS.CD?view=map

[18] B. D. Brouer, J. Dirksen, D. Pisinger, C. E. Plum, B. Vaaben, The vessel schedule recovery problem (vsrp)–a mip model for handling disruptions in liner shipping, European Journal of Operational Research 224 (2) (2013) 362–374.

[19] J. Wang, M. Li, Y. Liu, H. Zhang, W. Zou, L. Cheng, Safety assessment of shipping routes in the south china sea based on the fuzzy analytic hierarchy process, Safety Science 62 (2014) 46–57. doi:10.1016/j.ssci.2013.08.002.

[20] C. Otto, S. Willner, L. Wenz, K. Frieler, A. Levermann, Modeling loss-propagation in the global supply network: The dynamic agent-based model acclimate, Journal of Economic Dynamics and Control 83 (2017) 232–269. doi:10.1016/j.jedc.2017.08.001.
URL https://doi.org/10.1016/j.jedc.2017.08.001

[21] R. C. Johnson, Measuring global value chains, Annual Review of Economics 10 (2018) 207–236.

[22] A. van der Veen, Disasters and economic damage: macro, meso and micro approaches, Disaster Prevention and Management: An International Journal 13 (4) (2004) 274–279. doi:10.1108/09653560410556483.

[23] Y. Okuyama, J. R. Santos, Disaster Impact and Input–Output Analysis, Economic Systems Research 26 (1) (2014) 1–12. doi:10.1080/09535314.2013.871505.

[24] A. Rose, Economic Principles, Issues, and Research Priorities in Hazard Loss Estimation, in: Y. Okuyama, S. Chang (Eds.), Modeling Spatial and Economic Impacts of Disasters, Advances in Spatial Science, Springer Berlin Heidelberg, 2004, pp. 13–36. doi:10.1007/978-3-540-24787-6_2. URL http://dx.doi.org/10.1007/978-3-540-24787-6{_}2

[25] S. Hallegatte, An adaptive regional input-output model and its application to the assessment of the economic cost of Katrina, Risk Analysis 28 (3) (2008) 779–799. doi:10.1111/j.1539-6924.2008.01046.x.

[26] J. D. Farmer, D. Foley, The economy needs agent-based modelling, Nature 460 (7256) (2009) 685–686. doi:10.1038/460685a.

[27] J. D. Farmer, C. Hepburn, P. Mealy, A. Teytelboym, A Third Wave in the Economics of Climate Change, Environmental and Resource Economics 62 (2) (2015) 329–357. doi:10.1007/s10640-015-9965-2.

[28] J. M. Albala-Bertrand, Disasters and the networked economy, routledge Edition, Routledge, 2013.

[29] M. Gallegati, M. G. Richiardi, Agent Based Models in Economics, Complex Systems in Finance and Econometrics (2011) 30–53.

[30] R. L. Axtell, What economic agents do: How cognition and interaction lead to emergence and complexity, Review of Austrian Economics 20 (2-3) (2007) 105–122. doi:10.1007/s11138-007-0021-5.

[31] A. Caiani, A. Godin, E. Caverzasi, M. Gallegati, S. Kinsella, J. E. Stiglitz, Agent based-stock flow consistent macroeconomics: Towards a benchmark model, Journal of Economic Dynamics and Control 69 (2016) 375–408. doi:10.1016/j.jedc.2016.06.001.

[32] D. Delli Gatti, C. Di Guilmi, E. Gaffeo, G. Giulioni, M. Gallegati, A. Palestrini, A new approach to business fluctuations: heterogeneous interacting agents, scaling laws and financial fragility, Journal of Economic Behavior & Organization 56 (2005) 489–512. doi:10.1016/j.jebo.2003.10.012.

[33] D. Delli Gatti, E. Gaffeo, M. Gallegati, G. Giulioni, A. Kirman, A. Palestrini, A. Russo, Complex dynamics and empirical evidence, Information Sciences 177 (5) (2007) 1204–1221. doi:10.1016/j.ins.2006.08.003.

[34] A. Mandel, Agent-based dynamics in the general equilibrium model, Complexity Economics 1 (2012) 105–121. doi:10.7564/12-COEC6.

[35] Y. M. Asano, J. J. Kolb, J. Heitzig, J. D. Farmer, Emergent inequality and business cycles in a simple behavioral macroeconomic model, Proceedings of the National Academy of Sciences 118 (27).

[36] G. Dosi, G. Fagiolo, A. Roventini, Schumpeter meeting Keynes: A policy-friendly model of endogenous growth and business cycles, Journal of Economic Dynamics and Control 34 (9) (2010) 1748–1767. doi:10.1016/j.jedc.2010.06.018.

[37] G. Weisbuch, S. Battiston, From production networks to geographical economics, Journal of Economic Behavior and Organization 64 (3-4 SPEC. ISS.) (2007) 448–469. doi:10.1016/j.jebo.2006.06.018.

[38] D. Delli Gatti, M. Gallegati, B. Greenwald, A. Russo, J. E. Stiglitz, The financial accelerator in an evolving credit network, Journal of Economic Dynamics and Control 34 (9) (2010) 1627–1650. doi:10.1016/j.jedc.2010.06.019.

[39] L. Ricetti, A. Russo, G. Mauro, Leveraged network-based financial accelerator, Journal of Economic Dynamics and Control 37 (2) (2013) 404–421. doi:10.1016/j.jedc.2012.10.004.

[40] S. Vitali, S. Battiston, M. Gallegatti, Financial fragility and distress propagation in a network of regions, Journal of Economic Dynamics and Control 72 (March 2005) (2016) 141–154. doi:10.1016/j.jedc.2016.03.010.

[41] M. Wolski, M. van der Leur, Interbanks loans, collateral and modern monetary policy, Journal of Economic Dynamics and Control 72 (March 2005) (2016) 141–154. doi:10.1016/j.jedc.2016.03.010.

[42] R. Leombruni, M. Richiardi, Why are economists sceptical about agent-based simulations?, Physica A: Statistical Mechanics and its Applications 355 (1) (2005) 103–109. doi:10.1016/j.physa.2005.02.072.

[43] J. E. Stiglitz, M. Gallegati, Heterogeneous Interacting Agent Models for Understanding Monetary Economies, Eastern Economic Journal 37 (1) (2011) 6–12. doi:10.1057/eej.2010.33.

[44] S. Gualdi, A. Mandel, On the emergence of scale-free production networks, Journal of Economic Dynamics and Control 73 (2016) 61–77. arXiv:1509.01483, doi:10.1016/j.jedc.2016.09.012.

[45] D. Acemoglu, V. M. Carvalho, A. Ozdaglar, A. Tahbaz-Selehi, The Network Origins of Aggregate Fluctuations, Econometrica 80 (5) (2012) 1977–2016. doi:10.3982/ECTA9623.

[46] S. Hallegatte, Modeling the Role of Inventories and Heterogeneity in the Assessment of the Economic Costs of Natural Disasters., Risk analysis 34 (1) (2013) 152–167. doi:10.1111/risa.12090.

[47] S. Hallegatte, Strategies to adapt to an uncertain climate change, Global Environmental Change 19 (2) (2009) 240–247. doi:10.1016/j.gloenvcha.2008.12.003.

[48] N. Ranger, S. Hallegatte, S. Bhattacharya, M. Bachu, S. Priya, K. Dhore, F. Rafique, P. Mathur, N. Naville, F. Henriet, C. Herweijer, S. Pohit, J. Corfee-Morlot, An assessment of the potential impact of climate

change on flood risk in Mumbai, Climatic Change 104 (1) (2011) 139–167. doi:10.1007/s10584-010-9979-2.

[49] S. Hallegatte, N. Ranger, O. Mestre, P. Dumas, J. Corfee-Morlot, C. Herweijer, R. M. Wood, Assessing climate change impacts, sea level rise and storm surge risk in port cities: A case study on Copenhagen, Climatic Change 104 (1) (2011) 113–137. doi:10.1007/s10584-010-9978-3.

[50] F. Henriet, S. Hallegatte, L. Tabourier, Firm-network characteristics and economic robustness to natural disasters, Journal of Economic Dynamics & Control 36 (2012) 150 –167. doi:10.1016/j.jedc.2011.10.001.

[51] S. N. Willner, C. Otto, A. Levermann, Global economic response to river floods, Nature Climate Change 8 (7) (2018) 594–598.

[52] K. Kuhla, S. N. Willner, C. Otto, L. Wenz, A. Levermann, Future heat stress to reduce people's purchasing power, PloS one 16 (6) (2021) e0251210.

[53] R. Middelanis, S. N. Willner, C. Otto, K. Kuhla, L. Quante, A. Levermann, Wave-like global economic ripple response to hurricane sandy, Environmental Research Letters.

[54] K. Kuhla, S. N. Willner, C. Otto, T. Geiger, A. Levermann, Ripple resonance amplifies economic welfare loss from weather extremes, Environmental Research Letters 16 (11) (2021) 114010.

[55] P. Trkman, K. McCormack, Supply chain risk in turbulent environments—a conceptual model for managing supply chain network risk, International Journal of Production Economics 119 (2) (2009) 247–258.

[56] T. Wu, J. Blackhurst, V. Chidambaram, A model for inbound supply risk analysis, Computers in industry 57 (4) (2006) 350–365.

[57] A. R. Ravindran, R. Ufuk Bilsel, V. Wadhwa, T. Yang, Risk adjusted multicriteria supplier selection models with applications, International Journal of Production Research 48 (2) (2010) 405–424.

[58] C. S. Tang, Perspectives in supply chain risk management, International journal of production economics 103 (2) (2006) 451–488.

[59] S. M. Wagner, V. Silveira-Camargos, Managing risks in just-in-sequence supply networks: Exploratory evidence from automakers, IEEE Transactions on Engineering Management 59 (1) (2010) 52–64.

[60] A. Baghalian, S. Rezapour, R. Z. Farahani, Robust supply chain network design with service level against disruptions and demand uncertainties: A real-life case, European journal of operational research 227 (1) (2013) 199–215.

[61] S. A. Yang, J. R. Birge, R. P. Parker, The supply chain effects of bankruptcy, Management Science 61 (10) (2015) 2320–2338.

[62] M. Giannakis, T. Papadopoulos, Supply chain sustainability: A risk management approach, International Journal of Production Economics 171 (2016) 455–470.

[63] W. Ho, T. Zheng, H. Yildiz, S. Talluri, Supply chain risk management: a literature review, International Journal of Production Research 53 (16) (2015) 5031–5069.

[64] E. E. Günay, K. Park, G. E. O. Kremer, Integration of product architecture and supply chain under currency exchange rate fluctuation, Research in Engineering Design (2021) 1–18.

[65] O. A. Durowoju, H. K. Chan, X. Wang, Entropy assessment of supply chain disruption, Journal of Manufacturing Technology Management.

[66] D. Ivanov, A. Dolgui, B. Sokolov, The impact of digital technology and industry 4.0 on the ripple effect and supply chain risk analytics, International Journal of Production Research 57 (3) (2019) 829–846.

[67] A. G. Morris, A. L. Kornhauser, M. J. Kay, Getting the goods delivered in dense urban areas: a snapshot of the last link of the supply chain, Transportation Research Record 1653 (1) (1999) 34–41.

[68] M. V. Tatikonda, M. Frohlich, Human operators and supply chain disruptions: A longitudinal study of truck driver accidents, in: Academy of Management Proceedings, Academy of Management Briarcliff Manor, NY 10510, 2013, p. 17133.

[69] H. S. Loh, V. Van Thai, Cost consequences of a port-related supply chain disruption, The Asian Journal of Shipping and Logistics 31 (3) (2015) 319–340.

[70] B. Jiang, R. C. Baker, G. V. Frazier, An analysis of job dissatisfaction and turnover to reduce global supply chain risk: Evidence from china, Journal of operations management 27 (2) (2009) 169–184.

[71] J. Vilko, P. Ritala, J. Hallikas, Risk management abilities in multimodal maritime supply chains: Visibility and control perspectives, Accident Analysis & Prevention 123 (2019) 469–481.

[72] S. Re, Natural catastrophes and man-made disasters in 2015: Asia suffers substantial losses, Tech. rep., Swiss Re (2016).

[73] S. A. Thekdi, J. R. Santos, Supply chain vulnerability analysis using scenario-based input-output modeling: Application to port operations, Risk Analysis 36 (5) (2016) 1025–1039.

[74] X. Cao, J. S. L. Lam, Simulation-based catastrophe-induced port loss estimation, Reliability Engineering & System Safety 175 (2018) 1–12.

[75] Y. Zhang, K. Wei, Z. Shen, X. Bai, X. Lu, C. G. Soares, Economic impact of typhoon-induced wind disasters on port operations: A case study of ports in china, International Journal of Disaster Risk Reduction 50 (2020) 101719.

[76] B. D. Brouer, J. Dirksen, D. Pisinger, C. E. Plum, B. Vaaben, The vessel schedule recovery problem (vsrp)–a mip model for handling disruptions in liner shipping, European Journal of Operational Research 224 (2) (2013) 362–374.

[77] C. Li, X. Qi, D. Song, Real-time schedule recovery in liner shipping service with regular uncertainties and disruption events, Transportation Research Part B: Methodological 93 (2016) 762–788.

[78] J. Monios, G. Wilmsmeier, Deep adaptation to climate change in the maritime transport sector–a new paradigm for maritime economics?, Maritime Policy & Management 47 (7) (2020) 853–872.

[79] J. S. L. Lam, J. A. Lassa, Risk assessment framework for exposure of cargo and ports to natural hazards and climate extremes, Maritime Policy & Management 44 (1) (2017) 1–15.

[80] OWD, Trade as share of GDP – 1960 to 2020, accessed: 2021-12-19 (2021). URL https://ourworldindata.org/grapher/trade-as-share-of-gdp?tab=chart

[81] L. Wenz, A. Levermann, Enhanced economic connectivity to foster heat-stress-related losses, Science Advances 2 (6) (2016) e1501026. doi:10.1126/sciadv.1501026.

[82] J. Maluck, R. V. Donner, A network of networks perspective on global trade, PloS one 10 (7) (2015) e0133310.

[83] A. Costinot, A. Rodríguez-Clare, Trade theory with numbers: Quantifying the consequences of globalization, in: Handbook of international economics, Vol. 4, Elsevier, 2014, pp. 197–261.

[84] E. Ortiz-Ospina, D. Beltekian, Trade and globalization, accessed: 2021-11-05 (Nov 2018).
URL https://ourworldindata.org/trade-and-globalization

[85] N. Pavcnik, The impact of trade on inequality in developing countries, Tech. rep., National Bureau of Economic Research (2017).

[86] Y. V. Fyodorov, B. A. Khoruzhenko, Nonlinear analogue of the may- wigner instability transition, Proceedings of the National Academy of Sciences 113 (25) (2016) 6827–6832.

[87] A. Kharrazi, E. Rovenskaya, B. D. Fath, Network structure impacts global commodity trade growth and resilience, PloS one 12 (2) (2017) e0171184.

[88] M. Kummu, P. Kinnunen, E. Lehikoinen, M. Porkka, C. Queiroz, E. Röös, M. Troell, C. Weil, Interplay of trade and food system resilience: Gains on supply diversity over time at the cost of trade independency, Global Food Security 24 (2020) 100360.

[89] J. Moran, J.-P. Bouchaud, May's instability in large economies, Physical Review E 100 (3) (2019) 032307.

[90] M. Lenzen, K. Kanemoto, D. Moran, A. Geschke, Mapping the structure of the world economy, Environmental science & technology 46 (15) (2012) 8374–8381.

[91] T. E. Zabelsky, 2002 economic census: Transportation 2002 commodity flow survey, Tech. rep., U.S. Department of Commerce and U.S. Department of Transportation (2002).

[92] M. Research, Technology, Logistics costs and u.s. gross domestic product, accessed: 2019-02-02.
URL https://ops.fhwa.dot.gov/freight/freight_analysis/econ_methods/lcdp_rep/index.htm#Toc112735358

[93] K. R. Knapp, M. C. Kruk, D. H. Levinson, H. J. Diamond, C. J. Neumann, The international best track archive for climate stewardship (ibtracs) unifying tropical cyclone data, Bulletin of the American Meteorological Society 91 (3) (2010) 363–376.

[94] K. R. Knapp, H. J. Diamond, J. P. Kossin, M. C. Kruk, C. J. I. Schreck, International best track archive for climate stewardship (ibtracs) project, version 4.wp, https://doi.org/10.25921/82ty-9e16, accessed: 2020-03-03.

[95] J. Wu, D. Zhang, C. Wan, Resilience assessment of maritime container shipping networks–a case of the maritime silk road, in: 2019 5th Inter-

national Conference on Transportation Information and Safety (ICTIS), IEEE, 2019, pp. 252–259.

[96] Y. Okuyama, How shaky was the regional economy after the 1995 kobe earthquake? a multiplicative decomposition analysis of disaster impact, The Annals of Regional Science 55 (2) (2015) 289–312.

[97] S. E. Chang, Disasters and transport systems: loss, recovery and competition at the port of kobe after the 1995 earthquake, Journal of transport geography 8 (1) (2000) 53–65.

[98] P. Landi, H. O. Minoarivelo, Å. Brännström, C. Hui, U. Dieckmann, Complexity and stability of adaptive ecological networks: a survey of the theory in community ecology, Systems analysis approach for complex global challenges (2018) 209–248.

[99] C. van Altena, L. Hemerik, P. C. de Ruiter, Food web stability and weighted connectance: the complexity-stability debate revisited, Theoretical Ecology 9 (1) (2016) 49–58.

## Supplementary information

*Table of contents*

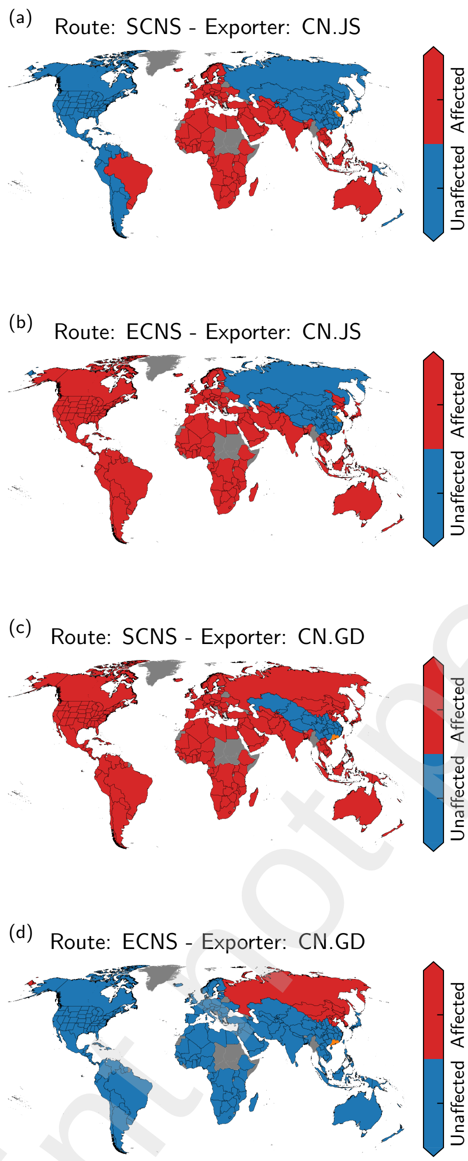


Figure S1: **Chinese exports to NAFTA are split into two spheres: Depending on South China Sea or Depending on East China Sea**

(a) Affected exports for Jiangsu – CN.JS ("Northern" China) if South China Sea – SCNS is perturbed.

(b) Affected exports for Jiangsu – CN.JS ("Northern" China) if East China Sea – ECNS is perturbed.

(c) Affected exports for Guandong – CN.GD ("Southern" China) if South China Sea – SCNS is perturbed.

(d) Affected exports for Guandong – CN.GD ("Southern" China) if East China Sea – ECNS is perturbed.

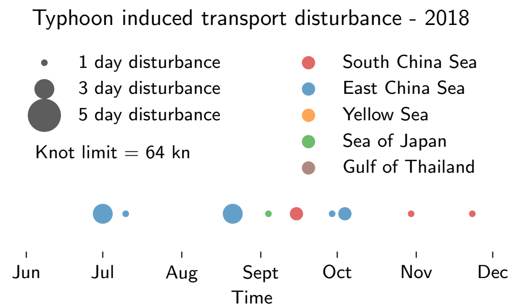


Figure S2: **Larger disturbance threshold causes less disruption days.**

Same as Fig. 1d with an disturbance threshold of 64 kn.

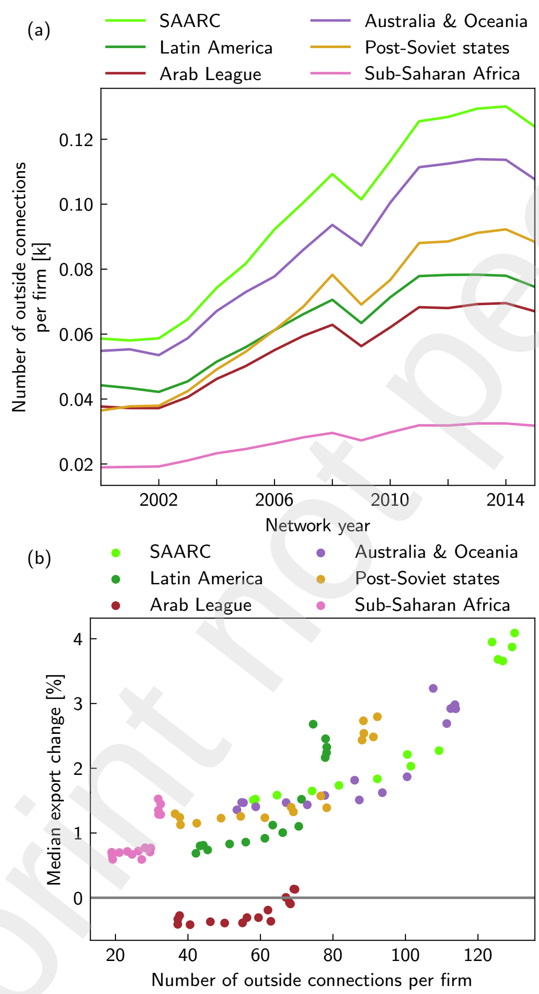


Figure S3: **Trade-inter-connectivity increases except for economic blocs and builds resilience towards transport disruptions.**

(a) Number of foreign connections per firm within the economic bloc connections.

(b) Median annual export change in quantity per region over number of foreign connections per firm. Export resilience tends to increase with more foreign connections.

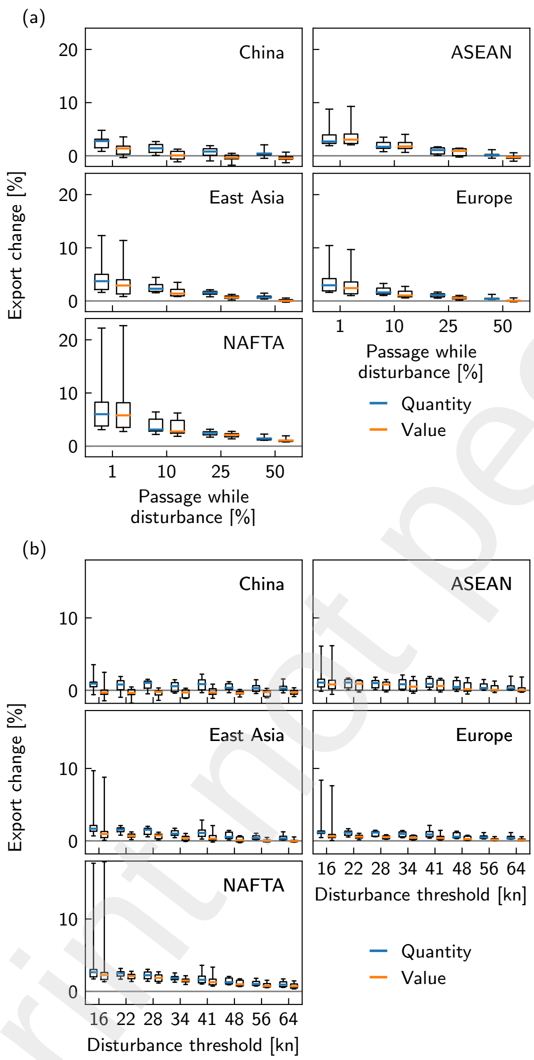


Figure S4: **Trends in result are robust against changes of disturbance modeling.**
Same results and description as 8 but entire 5–95 percentile ranges is shown.

Table S1: **Sectors used in the simulations.** Non-service sectors are affected by typhoon-induced transport perturbation, whereas service sectors are not.

| Code | Name | Affected by typhoon-induced transport perturbation |
|---|---|---|
| AGRI | Agriculture | × |
| FISH | Fishing | × |
| MINQ | Mining and quarrying | × |
| GAST | Hotels and restaurants | × |
| WHOT | Wholesale trade | × |
| OTHE | Others | × |
| REPA | Maintenance and Repair | × |
| RETT | Retail Trade | × |
| FOOD | Food and Beverages | × |
| TEXL | Textiles and Wearing Apparel | × |
| TRAN | Transport | × |
| WOOD | Wood and Paper | × |
| OILC | Petroleum, Chemical & Non-Metallic Mineral Products | × |
| METL | Metal Products | × |
| MACH | Electrical and Machinery | × |
| TREQ | Transport Equipment | × |
| MANU | Other Manufacturing | × |
| REXI | Re-export and Re-import | × |
| CONS | Construction | × |
| RECY | Recycling | × |
| ELWA | Electricity, Gas & Water | × |
| ADMI | Public Administration | |
| EDHE | Education, Health & Other Services | |
| HOUS | Private Households | |
| COMM | Post and Telecommunications | |
| FINC | Financial Intermediation & Business Activities | |
| FCON | Final consumption | |

Table S2: **Regions used in the simulations.**
ISO3 code and corresponding economic bloc of used simulations.

| ISO3 code | Name of region | Economic bloc |
|---|---|---|
| AFG | Afghanistan | SAARC |
| ALB | Albania | Europe |
| DZA | Algeria | Arab League |
| AND | Andorra | Europe |
| AGO | Angola | Sub-Saharan Africa |
| ATG | Antigua and Barbuda | Latin America |
| ARG | Argentina | Latin America |
| ARM | Armenia | Post-Soviet states |
| ABW | Aruba | Latin America |
| AUS | Australia | Australia & Oceania |
| AUT | Austria | Europe |
| AZE | Azerbaijan | Post-Soviet states |
| BHS | Bahamas | Latin America |
| BHR | Bahrain | Arab League |
| BGD | Bangladesh | SAARC |
| BRB | Barbados | Latin America |
| BLR | Belarus | Europe |
| BEL | Belgium | Europe |
| BLZ | Belize | Latin America |
| BEN | Benin | Sub-Saharan Africa |
| BMU | Bermuda | Rest of World |
| BTN | Bhutan | SAARC |
| BOL | Bolivia | Latin America |
| BIH | Bosnia and Herzegovina | Europe |
| BWA | Botswana | Sub-Saharan Africa |
| BRA | Brazil | Latin America |
| VGB | British Virgin Islands | Latin America |
| BRN | Brunei Darussalam | ASEAN |
| BGR | Bulgaria | Europe |
| BFA | Burkina Faso | Sub-Saharan Africa |
| BDI | Burundi | Sub-Saharan Africa |
| KHM | Cambodia | ASEAN |

| ISO3 code | Name of region | Economic bloc |
|---|---|---|
| CMR | Cameroon | Sub-Saharan Africa |
| CAN | Canada | NAFTA |
| CPV | Cabo Verde | Sub-Saharan Africa |
| CYM | Cayman Islands | Latin America |
| CAF | Central African Republic | Sub-Saharan Africa |
| TCD | Chad | Sub-Saharan Africa |
| CHL | Chile | Latin America |
| CN.AH | Anhui | China |
| CN.BJ | Beijing | China |
| CN.CQ | Chongqing | China |
| CN.FJ | Fujian | China |
| CN.GS | Gansu | China |
| CN.GD | Guangdong | China |
| CN.GX | Guangxi | China |
| CN.GZ | Guizhou | China |
| CN.HA | Hainan | China |
| CN.HB | Hebei | China |
| CN.HL | Heilongjiang | China |
| CN.HE | Henan | China |
| CN.HU | Hubei | China |
| CN.HN | Hunan | China |
| CN.JS | Jiangsu | China |
| CN.JX | Jiangxi | China |
| CN.JL | Jilin | China |
| CN.LN | Liaoning | China |
| CN.NM | Nei Mongol | China |
| CN.NX | Ningxia Hui | China |
| CN.QH | Qinghai | China |
| CN.SA | Shaanxi | China |
| CN.SD | Shandong | China |
| CN.SH | Shanghai | China |
| CN.SX | Shanxi | China |
| CN.SC | Sichuan | China |
| CN.TJ | Tianjin | China |
| CN.XJ | Xinjiang Uygur | China |

| ISO3 code | Name of region | Economic bloc |
|---|---|---|
| CN.XZ | Xizang | China |
| CN.YN | Yunnan | China |
| CN.ZJ | Zhejiang | China |
| COL | Colombia | Latin America |
| COG | Republic Congo | Sub-Saharan Africa |
| CRI | Costa Rica | Latin America |
| HRV | Croatia | Europe |
| CUB | Cuba | Latin America |
| CYP | Cyprus | Europe |
| CZE | Czech Republic | Europe |
| CIV | Côte d'Ivoire | Sub-Saharan Africa |
| PRK | North Korea | East Asia |
| COD | Democratic Republic Congo | Sub-Saharan Africa |
| DNK | Denmark | Europe |
| DJI | Djibouti | Sub-Saharan Africa |
| DOM | Dominican Republic | Latin America |
| ECU | Ecuador | Latin America |
| EGY | Egypt | Arab League |
| SLV | El Salvador | Latin America |
| ERI | Eritrea | Sub-Saharan Africa |
| EST | Estonia | Europe |
| ETH | Ethiopia | Sub-Saharan Africa |
| FJI | Fiji | Australia & Oceania |
| FIN | Finland | Europe |
| FRA | France | Europe |
| PYF | French Polynesia | Australia & Oceania |
| GAB | Gabon | Sub-Saharan Africa |
| GMB | Gambia | Sub-Saharan Africa |
| GEO | Georgia | Post-Soviet states |
| DEU | Germany | Europe |
| GHA | Ghana | Sub-Saharan Africa |
| GRC | Greece | Europe |
| GRL | Greenland | Rest of World |
| GTM | Guatemala | Latin America |
| GIN | Guinea | Sub-Saharan Africa |

| ISO3 code | Name of region | Economic bloc |
|---|---|---|
| GUY | Guyana | Latin America |
| HTI | Haiti | Latin America |
| HND | Honduras | Latin America |
| HKG | Hong Kong | Rest of World |
| HUN | Hungary | Europe |
| ISL | Iceland | Europe |
| IND | India | SAARC |
| IDN | Indonesia | ASEAN |
| IRN | Iran | Rest of World |
| IRQ | Iraq | Arab League |
| IRL | Ireland | Europe |
| ISR | Israel | Rest of World |
| ITA | Italy | Europe |
| JAM | Jamaica | Latin America |
| JPN | Japan | East Asia |
| JOR | Jordan | Arab League |
| KAZ | Kazakhstan | Post-Soviet states |
| KEN | Kenya | Sub-Saharan Africa |
| KWT | Kuwait | Arab League |
| KGZ | Kyrgyz Republic | Post-Soviet states |
| LAO | Lao PDR | ASEAN |
| LVA | Latvia | Europe |
| LBN | Lebanon | Arab League |
| LSO | Lesotho | Sub-Saharan Africa |
| LBR | Liberia | Sub-Saharan Africa |
| LBY | Libya | Arab League |
| LIE | Liechtenstein | Europe |
| LTU | Lithuania | Europe |
| LUX | Luxembourg | Europe |
| MAC | Macao | Rest of World |
| MDG | Madagascar | Sub-Saharan Africa |
| MWI | Malawi | Sub-Saharan Africa |
| MYS | Malaysia | ASEAN |
| MDV | Maldives | SAARC |
| MLI | Mali | Sub-Saharan Africa |

| ISO3 code | Name of region | Economic bloc |
|---|---|---|
| MLT | Malta | Europe |
| MRT | Mauritania | Arab League |
| MUS | Mauritius | Sub-Saharan Africa |
| MEX | Mexico | NAFTA |
| MCO | Monaco | Europe |
| MNG | Mongolia | Post-Soviet states |
| MNE | Montenegro | Europe |
| MAR | Morocco | Arab League |
| MOZ | Mozambique | Sub-Saharan Africa |
| MMR | Myanmar | ASEAN |
| NAM | Namibia | Sub-Saharan Africa |
| NPL | Nepal | SAARC |
| NLD | Netherlands | Europe |
| ANT | Netherlands Antilles | Europe |
| NCL | New Caledonia | Australia & Oceania |
| NZL | New Zealand | Australia & Oceania |
| NIC | Nicaragua | Latin America |
| NER | Niger | Sub-Saharan Africa |
| NGA | Nigeria | Sub-Saharan Africa |
| NOR | Norway | Europe |
| PSE | West Bank and Gaza | Rest of World |
| OMN | Oman | Arab League |
| PAK | Pakistan | SAARC |
| PAN | Panama | Latin America |
| PNG | Papua New Guinea | Australia & Oceania |
| PRY | Paraguay | Latin America |
| PER | Peru | Latin America |
| PHL | Philippines | ASEAN |
| POL | Poland | Europe |
| PRT | Portugal | Europe |
| QAT | Qatar | Arab League |
| KOR | South Korea | East Asia |
| MDA | Moldova | Europe |
| ROU | Romania | Europe |
| RUS | Russian Federation | Post-Soviet states |

| ISO3 code | Name of region | Economic bloc |
|---|---|---|
| RWA | Rwanda | Sub-Saharan Africa |
| WSM | Samoa | Australia & Oceania |
| SMR | San Marino | Europe |
| STP | São Tomé and Principe | Sub-Saharan Africa |
| SAU | Saudi Arabia | Arab League |
| SEN | Senegal | Sub-Saharan Africa |
| SRB | Serbia | Europe |
| SYC | Seychelles | Sub-Saharan Africa |
| SLE | Sierra Leone | Sub-Saharan Africa |
| SGP | Singapore | ASEAN |
| SVK | Slovak Republic | Europe |
| SVN | Slovenia | Europe |
| SOM | Somalia | Sub-Saharan Africa |
| ZAF | South Africa | Sub-Saharan Africa |
| SSD | South Sudan | Sub-Saharan Africa |
| ESP | Spain | Europe |
| LKA | Sri Lanka | SAARC |
| SDN | Sudan | Arab League |
| SUR | Suriname | Latin America |
| SWZ | Swaziland | Sub-Saharan Africa |
| SWE | Sweden | Europe |
| CHE | Switzerland | Europe |
| SYR | Syrian Arab Republic | Arab League |
| TWN | Taiwan | East Asia |
| TJK | Tajikistan | Post-Soviet states |
| THA | Thailand | ASEAN |
| MKD | Macedonia | Europe |
| TGO | Togo | Sub-Saharan Africa |
| TTO | Trinidad and Tobago | Latin America |
| TUN | Tunisia | Arab League |
| TUR | Turkey | Rest of World |
| TKM | Turkmenistan | Post-Soviet states |
| UGA | Uganda | Sub-Saharan Africa |
| UKR | Ukraine | Europe |
| ARE | United Arab Emirates | Arab League |

| ISO3 code | Name of region | Economic bloc |
|---|---|---|
| GBR | United Kingdom | Europe |
| TZA | Tanzania | Sub-Saharan Africa |
| US.AL | Alabama | NAFTA |
| US.AK | Alaska | NAFTA |
| US.AZ | Arizona | NAFTA |
| US.AR | Arkansas | NAFTA |
| US.CA | California | NAFTA |
| US.CO | Colorado | NAFTA |
| US.CT | Connecticut | NAFTA |
| US.DE | Delaware | NAFTA |
| US.DC | District of Columbia | NAFTA |
| US.FL | Florida | NAFTA |
| US.GA | Georgia | NAFTA |
| US.HI | Hawaii | NAFTA |
| US.ID | Idaho | NAFTA |
| US.IL | Illinois | NAFTA |
| US.IN | Indiana | NAFTA |
| US.IA | Iowa | NAFTA |
| US.KS | Kansas | NAFTA |
| US.KY | Kentucky | NAFTA |
| US.LA | Louisiana | NAFTA |
| US.ME | Maine | NAFTA |
| US.MD | Maryland | NAFTA |
| US.MA | Massachusetts | NAFTA |
| US.MI | Michigan | NAFTA |
| US.MN | Minnesota | NAFTA |
| US.MS | Mississippi | NAFTA |
| US.MO | Missouri | NAFTA |
| US.MT | Montana | NAFTA |
| US.NE | Nebraska | NAFTA |
| US.NV | Nevada | NAFTA |
| US.NH | New Hampshire | NAFTA |
| US.NJ | New Jersey | NAFTA |
| US.NM | New Mexico | NAFTA |
| US.NY | New York | NAFTA |

| ISO3 code | Name of region | Economic bloc |
|---|---|---|
| US.NC | North Carolina | NAFTA |
| US.ND | North Dakota | NAFTA |
| US.OH | Ohio | NAFTA |
| US.OK | Oklahoma | NAFTA |
| US.OR | Oregon | NAFTA |
| US.PA | Pennsylvania | NAFTA |
| US.RI | Rhode Island | NAFTA |
| US.SC | South Carolina | NAFTA |
| US.SD | South Dakota | NAFTA |
| US.TN | Tennessee | NAFTA |
| US.TX | Texas | NAFTA |
| US.UT | Utah | NAFTA |
| US.VT | Vermont | NAFTA |
| US.VA | Virginia | NAFTA |
| US.WA | Washington | NAFTA |
| US.WV | West Virginia | NAFTA |
| US.WI | Wisconsin | NAFTA |
| US.WY | Wyoming | NAFTA |
| URY | Uruguay | Latin America |
| UZB | Uzbekistan | Post-Soviet states |
| VUT | Vanuatu | Australia & Oceania |
| VEN | Venezuela | Latin America |
| VNM | Vietnam | ASEAN |
| YEM | Yemen | Arab League |
| ZMB | Zambia | Sub-Saharan Africa |
| ZWE | Zimbabwe | Sub-Saharan Africa |

Table S3: **Ports implemented in loss-propagation model Acclimate.**
Name and code corresponding latitude and longitude coordinates of implemented ports. The usage of ports depend on economic baseline and spatial resolution.

| Name | code | Latitude [°] | Longitude [°] |
|---|---|---|---|
| Abidjan | CIABJ | 5.299 | -4.026 |
| Adelaide | AUADL | -34.802 | 138.498 |
| Algeciras | ESALG | 36.137 | -5.437 |

| Name | code | Latitude [°] | Longitude [°] |
|---:|:---:|---:|---:|
| Ambarli | TRAMR | 40.967 | 28.690 |
| Antwerp | BEANR | 51.298 | 4.307 |
| Auckland | NZAKL | -36.837 | 174.772 |
| Balboa | PABLB | 8.980 | -79.581 |
| Bandar Abbas | IRBND | 27.102 | 56.077 |
| Beira | MZBEW | -19.813 | 34.832 |
| Bergen | NOBGO | 60.386 | 5.237 |
| Bordeaux | FRBOD | 44.899 | -0.538 |
| Bremerhaven | DEBRV | 53.551 | 8.562 |
| Brisbane | AUBNE | -27.374 | 153.172 |
| Buenaventura | COBUN | 3.892 | -77.072 |
| Buenos Aires | ARBUE | -34.613 | -58.362 |
| Busan | KRPUS | 35.105 | 129.071 |
| Callao | PECLL | -12.045 | -77.148 |
| Cartagena | COCTG | 10.351 | -75.516 |
| Caucdeo | DOCAU | 18.434 | -69.628 |
| Charleston | USCHS | 32.809 | -79.891 |
| Chennai | INMAA | 13.099 | 80.302 |
| Chittagong | BDCGP | 22.448 | 91.725 |
| Colombo | LKCMB | 6.951 | 79.850 |
| Colon | PAONX | 9.357 | -79.909 |
| Constanta | ROCND | 44.152 | 28.662 |
| Cork | IEORK | 51.900 | -8.440 |
| Dalian | CNDLC | 38.967 | 121.751 |
| Darwin | AUDRW | -12.519 | 130.861 |
| Djibouti | DJJIB | 11.601 | 43.117 |
| Durban | ZADUR | -29.890 | 31.030 |
| Felixstowe | GBFXT | 51.960 | 1.345 |
| Freeport | BSFPO | 26.529 | -78.763 |
| Gdansk | PLGDN | 54.382 | 18.695 |
| Genova | ITGOA | 44.408 | 8.857 |
| Gioia Tauro | ITGIT | 38.457 | 15.907 |
| Gothenburg | SEGOT | 57.698 | 11.895 |
| Guayaquil | ECGYE | -2.262 | -79.926 |
| Hamburg | DEHAM | 53.519 | 9.939 |

| Name | code | Latitude [°] | Longitude [°] |
|---|---|---|---|
| Havanna | CUHAV | 23.130 | -82.340 |
| Ho Chi Minh | VNSGN | 10.713 | 106.769 |
| Hobart | AUHBA | -42.880 | 147.336 |
| Honolulu | USHNL | 21.317 | -157.893 |
| Houston | USHOU | 29.636 | -95.071 |
| Jebel Ali | AEJEA | 25.018 | 55.010 |
| Jeddah | SAJED | 21.488 | 39.157 |
| Kaohsiung | TWKHH | 22.574 | 120.307 |
| Karachi | PKKHI | 24.826 | 66.980 |
| Kingston | JMKIN | 17.967 | -76.797 |
| Laem Chabang | THLCH | 13.111 | 100.900 |
| Lagos | NGLOS | 6.445 | 3.358 |
| Lazaro Cardenas | MXLZC | 17.959 | -102.211 |
| Le Havre | FRLEH | 49.450 | 0.318 |
| Limassol | CYLMS | 34.680 | 33.040 |
| Limon-Moin | CRMOB | 10.007 | -83.077 |
| Long Beach | USLGB | 33.755 | -118.214 |
| Los Angeles | USLAX | 33.745 | -118.198 |
| Luanda | AOLAD | -8.789 | 13.265 |
| Manila | PHMNL | 14.606 | 120.965 |
| Manzanillo | MXZLO | 19.069 | -104.303 |
| Marseille | FRMRS | 43.332 | 5.340 |
| Miami | USMIA | 25.770 | -80.204 |
| Mombasa | KEMBA | -4.059 | 39.644 |
| Montevideo | UYMVD | -34.892 | -56.224 |
| Montreal | CAMTR | 45.426 | -73.769 |
| Moresby | PGPOM | -9.447 | 147.119 |
| New York & New Jersey | USNYC | 40.664 | -74.090 |
| Nhava Sheva | INNSA | 18.953 | 72.945 |
| Norfolk | USORF | 36.895 | -76.216 |
| Novorossiysk | RUNVS | 44.721 | 37.810 |
| Oakland | USOAK | 37.798 | -122.286 |
| Osaka | JPOSA | 34.582 | 135.427 |
| Paranagua | BRPNG | -25.502 | -48.469 |
| Perth | AUFRE | -32.056 | 115.744 |

| Name | code | Latitude [°] | Longitude [°] |
|---|---|---|---|
| Piraeus | GRPIR | 37.937 | 23.654 |
| Port Klang | MYPKG | 2.978 | 101.337 |
| Port Said | EGPSD | 31.233 | 32.335 |
| Primorsk | RUPRI | 60.346 | 28.665 |
| Qingdao | CNTAO | 36.053 | 120.273 |
| Reykjavik | ISREY | 64.150 | -21.870 |
| Richards Bay | ZARCB | -28.812 | 32.062 |
| Rotterdam | NLRTM | 51.888 | 4.386 |
| Saldanha | ZASDB | -33.018 | 17.980 |
| San Antonio | CLSAI | -33.589 | -71.619 |
| San Juan | PRSJU | 18.444 | -66.093 |
| Santos | BRSSZ | -23.925 | -46.337 |
| Savannah | USSAV | 31.997 | -80.959 |
| Seattle | USSEA | 47.670 | -122.567 |
| Shangai | CNSHA | 31.321 | 121.434 |
| Shenzhen | CNSZX | 22.494 | 113.936 |
| Sines | PTSIE | 37.938 | -8.847 |
| Sinpapore | SGSIN | 1.310 | 103.710 |
| Southampton | GBSOU | 50.898 | -1.424 |
| Suzhou | CNSZH | 31.225 | 120.468 |
| Sydney | AUSYD | -33.912 | 151.183 |
| Tanger-Med | MAPTM | 35.894 | -5.496 |
| Tanjung Priok | IDJKT | -6.099 | 106.895 |
| Teluk Bayur | IDPDG | -1.001 | 100.375 |
| Tianjin | CNTXG | 38.991 | 117.715 |
| Tokyo | JPTYO | 35.618 | 139.916 |
| Valencia | ESVLC | 39.440 | -0.318 |
| Valparaiso | CLVAP | -33.035 | -71.618 |
| Vancouver | CAVAN | 49.194 | -122.982 |
| Veracruz | MXVER | 19.207 | -96.137 |
| Walvis Bay | NAWVB | -22.970 | 14.487 |
| Wellington | NZWLG | -41.277 | 174.786 |
| Xiamen | CNXMN | 24.486 | 118.030 |
| Åland | ALA | 60.221 | 19.974 |
| American Samoa | ASM | -14.300 | -170.718 |

| Name | code | Latitude [°] | Longitude [°] |
|---|---|---|---|
| Anguilla | AIA | 18.215 | -63.054 |
| Antarctica | ATA | -80.562 | 20.814 |
| Antigua & Barbuda | ATG | 17.077 | -61.798 |
| Aruba | ABW | 12.509 | -69.970 |
| Barbados | BRB | 13.172 | -59.556 |
| Bermuda | BMU | 32.298 | -64.782 |
| Bonaire | BES | 12.185 | -68.290 |
| Bouvet Island | BVT | -54.428 | 3.382 |
| British Indian Ocean Territory | IOT | -7.340 | 72.434 |
| British Virgin Islands | VGB | 18.424 | -64.620 |
| Cape Verde | CPV | 15.084 | -23.625 |
| Cayman Islands | CYM | 19.318 | -81.244 |
| Christmas Island | CXR | -10.485 | 105.637 |
| Clipperton Island | XCL | 10.303 | -109.217 |
| Cocos Islands | CCK | -12.168 | 96.909 |
| Comoros | COM | -11.663 | 43.354 |
| Cook Islands | COK | -21.235 | -159.778 |
| Cuba | CUB | 21.617 | -78.936 |
| Curaçao | CUW | 12.194 | -68.973 |
| Cyprus | CYP | 34.850 | 32.700 |
| Dominica | DMA | 15.435 | -61.350 |
| Dominican Republic | DOM | 18.490 | -69.940 |
| Falkland Islands | FLK | -51.740 | -58.753 |
| Faroe Islands | FRO | 62.169 | -6.953 |
| Fiji | FJI | -17.836 | 177.965 |
| French Polynesia | PYF | -17.730 | -149.410 |
| French Southern Territories | ATF | -49.315 | 69.487 |
| Grenada | GRD | 12.114 | -61.684 |
| Guadeloupe | GLP | 16.228 | -61.576 |
| Guam | GUM | 13.444 | 144.777 |
| Guernsey | GGY | 49.456 | -2.579 |
| Haiti | HTI | 18.570 | -72.310 |
| Heard Island & McDonald Islands | HMD | -53.093 | 73.517 |
| Iceland | ISL | 64.983 | -18.579 |
| Isle of Man | IMN | 54.228 | -4.538 |

| Name | code | Latitude [°] | Longitude [°] |
|---|---|---|---|
| Jamaica | JAM | 18.157 | -77.310 |
| Jersey | JEY | 49.214 | -2.133 |
| Madagascar | MDG | -19.382 | 46.697 |
| Maldives | MDV | 1.906 | 73.538 |
| Malta | MLT | 35.888 | 14.440 |
| Marshall Islands | MHL | 7.096 | 171.222 |
| Martinique | MTQ | 14.653 | -61.018 |
| Mauritius | MUS | -20.284 | 57.572 |
| Mayotte | MYT | -12.824 | 45.144 |
| Micronesia | FSM | 6.880 | 158.227 |
| Montserrat | MSR | 16.739 | -62.190 |
| Nauru | NRU | -0.528 | 166.934 |
| Netherlands Antilles | ANT | 17.640 | -63.230 |
| New Caledonia | NCL | -21.326 | 165.489 |
| Niue | NIU | -19.052 | -169.859 |
| Norfolk Island | NFK | -29.033 | 167.952 |
| Northern Mariana Islands | MNP | 15.189 | 145.754 |
| Palau | PLW | 7.499 | 134.565 |
| Paracel Islands | PIS | 16.067 | 112.545 |
| Pitcairn Islands | PCN | -24.377 | -128.323 |
| Puerto Rico | PRI | 18.224 | -66.480 |
| Reunion | REU | -21.133 | 55.533 |
| Saint-Barthélemy | BLM | 17.902 | -62.830 |
| Saint Helena | SHN | -15.965 | -5.707 |
| Saint Kitts & Nevis | KNA | 17.339 | -62.765 |
| Saint Lucia | LCA | 13.898 | -60.967 |
| Saint Pierre & Miquelon | SPM | 46.951 | -56.322 |
| Saint Vincent & the Grenadines | VCT | 13.251 | -61.189 |
| Samoa | WSM | -13.621 | -172.447 |
| Sao Tome & Principe | STP | 0.239 | 6.602 |
| Seychelles | SYC | -4.677 | 55.468 |
| Solomon Islands | SLB | -9.623 | 160.160 |
| South Georgia & the South Sandwich Islands | SGS | -54.375 | -36.688 |
| Spratly islands | SP- | 11.053 | 114.284 |
| Svalbard & Jan Mayen | SJM | 78.608 | 15.828 |

| Name | code | Latitude [°] | Longitude [°] |
|---|---|---|---|
| Taiwan | TWN | 23.751 | 120.974 |
| Tokelau | TKL | -9.178 | -171.779 |
| Tonga | TON | -21.174 | -175.192 |
| Trinidad & Tobago | TTO | 10.424 | -61.296 |
| Turks & Caicos Islands | TCA | 21.775 | -71.758 |
| Tuvalu | TUV | -7.480 | 178.680 |
| United States Minor Outlying Islands | UMI | 19.289 | 166.636 |
| Vanuatu | VUT | -15.241 | 166.873 |
| Virgin Islands | VIR | 17.733 | -64.768 |
| Wallis and Futuna | WLF | -13.285 | -176.205 |

| | China | Europe | NAFTA | ASEAN | Latin America | SAARC | East Asia | Arab League | Post-Soviet states | Australia & Oceania | Sub-Saharan Africa | Rest of World |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| China | -0.25 | -4.37 | -1.32 | 0.26 | -5.31 | -1.84 | 8.78 | -7.14 | -2.82 | 1.77 | -7.6 | 4.48 |
| | (-0.3,0.01) | (-4.85,-2.83) | (-1.86,-0.94) | (-0.22,1.0) | (-5.83,-4.23) | (-2.12,-0.2) | (8.33,11.73) | (-7.46,-5.58) | (-3.24,-1.18) | (-2.38,3.18) | (-8.14,-5.91) | (4.06,6.3) |
| Europe | -0.96 | -0.02 | 1.09 | 4.57 | 1.47 | 3.17 | -2.42 | 2.26 | 2.72 | 6.54 | 2.1 | 0.05 |
| | (-2.01,0.26) | (-0.05,0.08) | (0.98,1.38) | (3.9,5.98) | (1.27,1.6) | (2.83,3.87) | (-2.9,-1.78) | (1.95,2.71) | (2.33,3.45) | (3.72,7.71) | (1.6,2.56) | (-0.11,0.17) |
| NAFTA | 2.52 | 2.51 | 0.07 | -0.75 | 1.16 | 0.71 | 6.24 | 0.68 | 0.57 | 4.23 | 2.71 | -2.43 |
| | (1.51,3.84) | (1.98,2.95) | (0.05,0.07) | (-0.85,-0.29) | (1.06,1.27) | (0.56,1.15) | (5.46,8.22) | (0.57,0.75) | (0.28,1.33) | (1.79,5.15) | (1.93,2.96) | (-3.05,-1.74) |
| ASEAN | 4.83 | 4.65 | -1.83 | -0.52 | 0.63 | 7.19 | -2.47 | 2.77 | -9.65 | 3.03 | 2.32 | -3.24 |
| | (0.58,5.86) | (3.84,5.79) | (-2.38,-1.32) | (-0.56,-0.26) | (0.39,1.09) | (5.89,8.04) | (-3.07,-2.12) | (2.49,3.31) | (-11.24,-7.49) | (2.39,3.55) | (1.78,2.82) | (-4.77,-2.59) |
| Latin America | 8.02 | 3.51 | 0.93 | 3.67 | -0.09 | 3.91 | 4.89 | 2.66 | 4.05 | 23.19 | 3.68 | -0.05 |
| | (-0.35,10.02) | (2.98,4.32) | (0.87,1.06) | (3.28,4.66) | (-0.11,0.0) | (3.01,4.67) | (4.28,5.9) | (2.31,3.35) | (3.46,5.3) | (5.47,31.47) | (2.66,4.19) | (-0.55,0.55) |
| SAARC | 10.77 | 4.43 | 0.17 | 12.71 | 2.18 | -0.22 | -3.34 | 2.33 | 4.58 | 15.25 | 1.87 | 0.03 |
| | (2.04,16.76) | (3.99,5.71) | (-0.05,0.42) | (10.07,14.18) | (1.95,2.5) | (-0.32,-0.1) | (-3.63,-2.48) | (2.14,2.79) | (3.04,6.94) | (5.77,21.62) | (1.52,2.21) | (-0.01,0.4) |
| East Asia | 6.34 | -1.12 | 3.14 | -2.74 | 3.6 | -4.95 | -0.42 | -4.57 | 5.14 | 1.76 | 1.5 | -5.73 |
| | (5.53,8.75) | (-1.69,-0.52) | (2.88,4.11) | (-3.19,-2.1) | (2.96,4.07) | (-5.64,-4.42) | (-0.46,-0.31) | (-5.21,-3.53) | (4.23,5.79) | (1.32,2.53) | (1.0,1.95) | (-6.54,-4.48) |
| Arab League | 4.42 | 1.58 | 2.46 | 3.0 | 3.76 | 3.88 | -6.26 | -0.12 | 1.55 | 8.76 | 2.73 | 1.81 |
| | (0.51,6.39) | (1.41,1.91) | (1.89,2.97) | (2.58,3.71) | (3.37,4.36) | (3.32,4.6) | (-7.0,-5.39) | (-0.15,-0.07) | (1.39,1.82) | (7.02,10.88) | (2.25,3.25) | (1.7,2.15) |
| Post-Soviet states | 9.77 | 1.34 | 0.49 | -4.98 | 2.13 | 2.82 | 4.86 | 3.25 | -0.16 | 0.07 | 3.2 | 0.0 |
| | (5.73,16.92) | (1.12,1.53) | (0.34,0.6) | (-5.72,-3.76) | (1.71,2.6) | (2.43,3.58) | (4.48,6.01) | (2.71,3.53) | (-0.27,-0.05) | (-3.94,28.36) | (1.19,3.55) | (-0.1,0.06) |
| Australia & Oceania | 2.67 | 6.89 | 3.29 | 4.35 | 3.44 | 6.85 | 1.94 | 4.77 | -5.65 | -0.68 | 7.18 | -3.96 |
| | (-0.03,4.01) | (5.2,8.15) | (2.57,3.86) | (3.24,4.91) | (2.77,4.2) | (5.54,7.79) | (1.34,2.36) | (3.79,6.07) | (-7.49,-3.85) | (-0.76,-0.2) | (5.24,8.59) | (-4.34,-2.98) |
| Sub-Saharan Africa | -1.98 | 1.99 | 1.57 | 3.82 | 3.5 | 5.26 | -0.87 | 2.9 | -3.58 | 7.39 | -0.21 | -0.61 |
| | (-4.68,-0.39) | (1.78,2.45) | (1.36,2.19) | (3.34,4.04) | (3.02,3.99) | (4.38,5.99) | (-1.03,-0.68) | (2.26,3.43) | (-4.12,-2.84) | (4.9,8.22) | (-0.24,-0.05) | (-1.08,-0.29) |
| Rest of World | 6.23 | 1.53 | -2.69 | -0.35 | -3.06 | 0.6 | -2.29 | 1.13 | 1.96 | 9.17 | -0.17 | -0.39 |
| | (3.49,7.83) | (0.78,1.72) | (-3.01,-1.87) | (-0.94,0.21) | (-4.02,-1.93) | (0.31,1.19) | (-2.98,-1.8) | (0.9,1.26) | (1.65,2.27) | (0.62,14.76) | (-1.12,0.79) | (-0.47,-0.16) |

Table S4: **Annual trade change in quantity.** Annual median quantity supply change per supplier (row) and purchaser (column). Digits in parentheses represent the 25-75 percentile.

| | China | Europe | NAFTA | ASEAN | Latin America | SAARC | East Asia | Arab League | Post-Soviet states | Australia & Oceania | Sub-Saharan Africa | Rest of World |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| China | -1.34 (-1.48,-0.72) | -5.5 (-5.87,-4.21) | -2.41 (-2.94,-2.16) | -0.85 (-1.2,-0.39) | -6.5 (-6.78,-5.58) | -2.9 (-3.35,-1.63) | 7.83 (6.89,10.27) | -7.98 (-8.66,-6.89) | -3.92 (-4.17,-2.33) | 0.5 (-3.13,1.84) | -8.66 (-9.25,-6.67) | 3.6 (3.17,5.12) |
| Europe | -1.53 (-2.42,-0.32) | -0.12 (-0.14,-0.02) | 0.54 (0.4,0.81) | 3.88 (3.36,5.28) | 0.89 (0.66,1.0) | 2.72 (2.38,3.38) | -2.8 (-3.35,-2.18) | 1.78 (1.44,2.04) | 2.23 (1.96,2.94) | 6.2 (3.36,7.35) | 1.55 (1.14,1.89) | -0.38 (-0.54,-0.3) |
| NAFTA | 1.89 (1.03,3.69) | 2.13 (1.62,2.54) | -0.07 (-0.08,-0.05) | -1.08 (-1.34,-0.77) | 0.7 (0.58,0.92) | 0.27 (0.0,0.66) | 5.83 (5.11,7.83) | 0.21 (0.16,0.32) | 0.13 (-0.15,0.79) | 4.09 (1.57,4.97) | 2.25 (1.46,2.51) | -2.78 (-3.57,-2.23) |
| ASEAN | 5.43 (0.34,6.92) | 4.48 (3.5,5.79) | -2.1 (-2.79,-1.78) | -0.31 (-0.41,-0.23) | -0.06 (-0.16,0.34) | 6.53 (5.4,7.39) | -2.68 (-3.3,-2.39) | 2.13 (1.71,2.88) | -9.95 (-11.61,-7.74) | 2.65 (2.06,3.19) | 1.62 (1.25,2.17) | -3.69 (-5.28,-3.05) |
| Latin America | 10.48 (-0.61,12.66) | 3.23 (2.69,4.14) | 0.74 (0.63,0.83) | 3.13 (2.8,4.05) | -0.01 (-0.02,0.01) | 3.42 (2.51,4.27) | 4.54 (3.98,5.64) | 2.03 (1.9,2.7) | 3.71 (3.12,4.91) | 25.23 (5.12,36.48) | 3.19 (2.3,3.73) | -0.43 (-0.86,0.01) |
| SAARC | 11.68 (1.63,18.87) | 4.14 (3.62,5.34) | -0.27 (-0.57,-0.13) | 12.3 (9.5,13.61) | 1.59 (1.42,1.85) | -0.08 (-0.12,0.01) | -3.67 (-3.96,-2.7) | 2.02 (1.7,2.37) | 3.86 (2.64,6.36) | 15.25 (5.38,23.8) | 1.4 (1.13,1.72) | -0.33 (-0.56,-0.07) |
| East Asia | 5.48 (4.59,7.69) | -1.7 (-2.27,-1.18) | 2.23 (1.95,3.07) | -3.47 (-3.7,-2.84) | 2.68 (1.89,3.12) | -5.43 (-6.41,-5.13) | -0.4 (-0.47,-0.31) | -5.15 (-5.78,-4.45) | 4.08 (3.31,4.58) | 1.1 (0.75,1.78) | 0.56 (0.2,0.9) | -6.18 (-7.12,-4.89) |
| ARAB | 3.93 (0.19,5.89) | 1.32 (1.22,1.64) | 1.92 (1.39,2.54) | 2.49 (2.03,3.09) | 3.38 (3.04,3.95) | 3.15 (2.85,3.85) | -6.44 (-7.23,-5.43) | -0.2 (-0.24,-0.18) | 1.03 (0.9,1.24) | 8.26 (6.33,10.31) | 2.12 (1.7,2.52) | 1.35 (1.22,1.62) |
| Post-Soviet states | 9.73 (5.23,18.04) | 1.12 (0.94,1.3) | -0.24 (-0.43,0.05) | -5.69 (-6.47,-4.5) | 1.36 (1.06,1.94) | 2.38 (2.08,3.05) | 4.68 (4.32,5.72) | 2.48 (2.13,2.85) | -0.07 (-0.09,-0.05) | -0.63 (-4.45,28.29) | 2.39 (0.6,2.73) | -0.2 (-0.31,-0.16) |
| Australia & Oceania | 1.87 (-0.43,3.12) | 6.55 (4.92,7.4) | 2.54 (1.88,3.06) | 3.57 (2.73,4.1) | 3.12 (2.33,3.48) | 6.23 (5.02,6.83) | 1.36 (1.01,1.92) | 3.91 (3.07,5.15) | -6.17 (-7.77,-4.62) | -0.91 (-1.0,-0.3) | 6.25 (4.65,7.49) | -4.31 (-4.86,-3.39) |
| Sub-Saharan Africa | -1.7 (-5.14,0.55) | 1.76 (1.47,1.98) | 1.11 (0.83,1.53) | 3.06 (2.73,3.54) | 3.12 (2.4,3.56) | 4.74 (3.9,5.33) | -1.22 (-1.38,-1.02) | 2.13 (1.57,2.56) | -3.87 (-4.59,-3.31) | 6.58 (4.58,7.26) | -0.23 (-0.28,-0.15) | -1.01 (-1.76,-0.75) |
| Rest of World | 5.35 (2.69,7.41) | 1.16 (0.46,1.34) | -3.12 (-3.66,-2.42) | -0.98 (-1.56,-0.22) | -3.65 (-4.5,-2.54) | 0.05 (-0.32,0.71) | -2.7 (-3.5,-2.06) | 0.56 (0.4,0.65) | 1.54 (1.18,1.85) | 9.57 (0.09,15.72) | -0.85 (-1.53,0.23) | -0.24 (-0.29,-0.2) |

Table S5: **Annual trade change in value.** Annual median value supply change per supplier (row) and purchaser (column). Digits in parentheses represent the 25-75 percentile.