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Resilience of international trade to typhoon-related supply disruptions

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ABSTRACT

Shipping accidents and environmental disasters pose a challenge to the reliability of maritime supply chains. Since international trade intensifies without a significant diversification of the supply routes the risk of transportation perturbations caused by extreme events like tropical cyclones may increase conceivably. In this study we model the regional and global economic repercussions of typhoon-induced short-term transport disruptions of West Pacific trading routes. 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. We compute that transportation perturbations, due to West Pacific typhoons between 2000–2020, may cause 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 from our numerical analysis, we find annual median export volume to increase in all trade blocs due to a decrease of export prices, but substantial regional differences emerge. Further we show that resilience of export to typhoon-induced perturbations increase in China, ASEAN, East Asia, and Europe within the first 16 years of this century. We trace this back to a rise of the inter-connectivity of these trade blocs to their foreign trade partners.

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1. Introduction

Since the end of World War II, international trade has grown immensely (Federico and Tena-Junguito, 2017) and even the COVID-19 pandemic has only shortly interrupted this trend (WTO, 2021). With the increase of global exports, 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 (Taherzadeh et al., 2021).

Over 80% of the world trade volume is transported on sea (Sirimanne et al., 2019), 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 (cbc, 2021). Besides straits and canals (Martínez-Zarzoso and Bensassi, 2013), ports are major bottlenecks of the maritime trade network (Wendler-Bosco and Nicholson, 2020). In addition

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to socioeconomic factors such as accidents (Hassanzadeh, 2013) or congestion during loading and unloading (Gidado, 2015; Loh et al., 2017), storm surges and strong winds from extreme weather are a major source of transport delays in ports (Verschuur et al., 2020).

The increase in the concentration of carbon dioxide in the atmosphere yields in energy accumulating in the oceans (Cheng et al., 2017; Church et al., 2011). 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, though the number of tropical cyclones as a whole is difficult to predict, it is clear that the number of strong typhoons and hurricanes will statistically increase under future warming (Balaguru et al., 2016; Emanuel, 2005; 2013). Intensifying international trade volume, which is at risk due to transport 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 (wor, 2020) – 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 (Brouer et al., 2013a; Wang et al., 2014).

In this study we extend the agent-based global supply chain model *Acclimate* (Otto et al., 2017) by a geographic 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 2000–2020 in the model, we compute that average export volumes increase in all major trade blocs due to a decrease of export prices. However, substantial regional differences occur. In all but one trade bloc 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 its resilience to typhoon-induced transportation perturbation 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 blocs 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 results and before discussing them in Sec. 5.

2. Related literature

2.1. Supply chain risks

The modeling of supply chains is typically carried out 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 (Johnson, 2018) 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 (van der Veen, 2004) and Okuyama and Santos (2014) for a comprehensive introduction). Both approaches can reflect the economic dependencies in high detail (Rose, 2004). However, when it comes to describing and temporally resolving the indirect economic effects of disasters due to 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 (Farmer and Foley, 2009; Farmer et al., 2015; Hallegatte, 2008). Whereas the production system in I-O models is fixed, rendering short-term adaptation impossible (Albala-Bertrand, 2013), 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 Hallegatte (2008).

Attempts to represent a system's complex dynamics from the bottom up are undertaken by the use of agent-based models (ABMs) (Axtell, 2007; Gallegati and Richiardi, 2011). Here, the stylized facts of macroeconomic systems emerge from the interplay of individual heterogeneous agents (Caiani et al., 2016; Delli Gatti et al., 2005; Dosi and Roventini, 2019). Thereby, ABM models allow to avoid controversial rationality assumptions; stylized facts emerge from the interplay of heterogeneous expectations and action rules of the agents (Asano et al., 2021). Indeed, myopic expectations may be preferable as behavioral rules for agents in complex environments characterized by deep uncertainty compared to more complicated foresight strategies including rational expectations (Dosi et al., 2020).

With regard to climate change impacts, agent-based approaches allow to obtain valuable insights with regard to coalition formation (e.g., climate clubs) and the negotiation of climate policy goals (Gerst et al., 2013) as well as macroeconomic impacts of climate variability and change on the economy including integrated assessment weighing the costs of climate change impacts with the costs of mitigation and adaptation measures (Lamperti et al., 2018); a recent study using an agentbased integrated assessment model with a detailed representation of the global banking networks shows that accounting for financial instabilities induced by climate shocks substantially increases the burden climate change poses on public finances (Lamperti et al., 2019). Further, the ability to account for behavioral heterogeneities and to explicitly model learning processes and the spread of information renders agent-based models well suited for climate policy assessments (Lee et al., 2014) and the modeling of the diffusion of climate-friendly technologies (Vona and Patriarca, 2011) (see Balint et al. (2017) for a recent review on agent-based approaches to model the socioeconomic impacts of climate change).

Further, agent-based approaches have been successfully employed to assess systemic risk by studying bankrupcy avalanches in financial network and to explain their dependence upon the network topology (Delli Gatti et al., 2010; Ricetti et al., 2013; Vitali et al., 2016; Weisbuch and Battiston, 2007; Wolski and van der Leur, 2016). However, ABMs still struggle to gain broader recognition from the mainstream neoclassical economic community (Leombruni and Richiardi, 2005).

Also 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 (Stiglitz and Gallegati, 2011). For example, Gualdi and Mandel (2016) 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 (Acemoglu et al., 2012), 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 (Hallegatte, 2008) with the introduction of the adaptive regional input-output (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 (Hallegatte, 2013). This model has been successfully employed in several empirical disaster impact studies such as Hallegatte (Hallegatte, 2009; Ranger et al., 2011), and Hallegatte et al. (2011). Further, Henriet et al. (2012) 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.

Otto et al. (2017) presented the agent-based network model *Acclimate* that allows to describe the spreading of disasterinduced supply failures in the global economic network and associated price effects such as scarcity-driven price inflation. The model allows to asses the role of inventories and idle capacities to mitigate scarcities in the disaster aftermath. Using the *Acclimate* model, Willner et al. (2018) 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. (2021b) 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 (Middelanis et al., 2021). Further results of the study suggest that regional higher-order economic impacts increase with higher inter-connectivity to disaster area. Using projections of Hurricane Harvey's local economic impact from 2017 to future levels of global warming, Middelanis et al. (2022) show that lost production in Texas due to the disaster can no longer be offset by the US alone under unabated climate change.

The ABM and explicit non-equilibrium dynamics approach of the model further allows to assess the economic repercussions of several events and how they interact. Here, Kuhla et al. (2021a) 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 global consumption losses. While climate-related direct losses rise, e.g. under global warming, additional consumer losses amplify disproportionally, 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 (Trkman and McCormack, 2009; Wu et al., 2006) or from operational disruptions (Ravindran et al., 2010; Tang, 2006). Furthermore, managing decisions of firms like just-intime-policy or lean production may increase risk for stable supply chains (Wagner and Silveira-Camargos, 2010). On the demand side, uncertainties and unforeseen changes of demand are additional potential supply chain risks (Baghalian et al., 2013). Regarding a firm's bankruptcy and resulting supply chain effects, the analysis of Yang et al. (2015) depicted that competitors could be put under higher pressure and affected suppliers could even partly benefit. Also, Giannakis and Papadopoulos (2016) 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 (Ho et al., 2015). In order to mitigate trade disturbances due to (short-term) exchange rate fluctuations Günay et al. (2021) developed a stochastic optimization model. With this, they find nation-depending fluctuation range thresholds for product architecture selection. Durowoju et al. (2012) 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. (2019)

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. (1999) 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 and Frohlich (2013) found that supply via road comes with risks of truck accidents. Here, improved working conditions, e.g. team-based driver groups, 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 congestion along the whole supply chain (Loh and Van Thai, 2015). Similarly, quitting ship crew members stresses supply chains, which emphasizes the necessity of better working conditions for employees as shown by Jiang et al. (2009). For goods transported via sea, potential pirate attacks can increase transport costs and stress the affected supply chains as Martínez-Zarzoso and Bensassi (2013) 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 (Vilko et al., 2019). For ports, and thus overall maritime trade, the most frequent natural threats are posed by tropical storms (Re, 2016). Using a dynamic I-O model, Thekdi and Santos (2016) depicted that a hurricane reduces shipping activities which again cause economic losses in transportation and fossil fuel sectors. Cao and Lam (2018) 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. (2020) 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 have been developed, e.g. by Brouer et al. (2013b) or Li et al. (2016). 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 and Wilmsmeier (2020) elaborated. Likewise, Lam and Lassa (2017) 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 (Levermann, 2013). Despite these risks, international trade has grown faster than national GDPs in the last 60 years (OWD, 2021) and up to 80% of this trade is shipped via sea (Sirimanne et al., 2019). Inter-connectivity of global trade, measured in different metrics like supply propagation connectivity (Wenz and Levermann, 2016) or link density (Maluck and Donner, 2015), has increased since the beginning of the century. Next to discussions about benefits and harms of global trade (Costinot and Rodríguez-Clare, 2014; Ortiz-Ospina and Beltekian, 2018; Pavcnik, 2017), 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 and Khoruzhenko (2016) 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 (Kharrazi et al., 2017).

Contrary to that, findings of Kummu et al. (2020) 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 partners decreases. Wenz and Levermann (2016) found that higher inter-connectivity of international trade network increase vulnerability towards climate extremes. Similarly, Moran and Bouchaud (2019) 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

In this study, we extend and use the agent-based loss-propagation model *Acclimate* to simulate changes in international trade caused *directly* and *indirectly* by typhoons in the Northern West Pacific. In Sec. 3.1, we give a brief overview of the basic mechanism of *Acclimate*. After that, in Sec. 3.2, we review how the transportation of goods has been modeled so far and describe in detail the new modeling steps of the transport network within the model extension. Based on this, we explain in Sec. 3.3 how the disruption of the transport of goods is modeled. In Sec. 3.4 we then specify our modeling approach how a typhoon functions as a driver for maritime transportation perturbations and describe in Sec. 3.5 which maritime trading routes are in the focus of this study and how storm trajectories are derived. In the last segment of our methods, Sec. 3.6, we explain why and how we aggregate our sectoral and regional results to economic blocs. Fig. 1 depicts a schematic scheme of our modeling steps.



Fig. 1. Schematic scheme of modeling steps. In this study, we extend the agent-based trade model *Acclimate* (Otto et al., 2017) (Sec. 3.1) by a geographic transport network. This network relies on geographic links of land and maritime entities as well as ports (Sec. 3.2). By using a transportation cost minimizing algorithm, *Acclimate* autonomously determines the geographic transportation network. The commodity flow via maritime entities can be reduced in the short run due to less navigability during strong tropical storm-induced winds (Secs. 3.3 and 3.4). By using tropical cyclones trajectories from IBTrACS (Knapp et al., 2018), transportation perturbation time series for the geographic transport network is calculated (Sec. 3.5). Disturbed transportation routes cause a delay in good delivery and firms with affected business connections adjust demand decisions.

3.1. Loss-propagation model Acclimate

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 Tbls. S1 and 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 (Lenzen et al., 2012) of the year 2015. Further model assumptions, local economic mechanisms, and model description charts are given in detail by Otto et al. (2017). In Sec. 4.6, we additionally undertake sensitivity analyses to some of the most important model parameters.

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 focus on transportation between firms as it is the same for a firm and a consumer. Every firm, or "regional sector", *ir* is 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 a 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 $Z_{ir \rightarrow js}^{(t)}$ 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 τ_{rs} between regions *r* and *s* measured in time steps. Service or non-service economic sectors (Tbl. 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 Δ_{rs}^c between the centroids c_r and c_s of region r and s, respectively. Using the exogenous delivery velocity v^c and the distance Δ_{rs}^c between the regions, each business connection had a fixed transport time τ_{rs} measured in time steps.



Fig. 2. Modeled maritime entities and ports. The 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 1.

Here, we extend *Acclimate* with the geographical transportation network. Each business connection between non-service supplier *ir* and purchaser *js* has a transportation route $T_{ir \rightarrow js}$, 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 Δ_{rs}^c 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, and a cost-minimizing algorithm (cf. Fig. 1 upper panel), which will be explained in detail in the following paragraphs. Land entities 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 $\tau_{rs} = \frac{\Delta c_s}{v^l}$, where Δ_{rs}^c is the distance between the 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 $r \to s \to w$. 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: $\Delta_{rw}^c = \Delta_{rs}^c + \Delta_{sw}^c$ ($\tau_{rw} = \tau_{rs} + \tau_{sw}$). 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 one in 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 some continents and countries are not connected to each other via land, 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 centroids¹ (Fig. 2). Each maritime entity α is connected to their adjacent maritime entities { β }. The transport between them via sea has a velocity of v^s and takes transport time $\tau_{\alpha\beta} = \frac{\Delta_{\alpha\beta}^c}{v^s}$, where $\Delta_{\alpha\beta}^c$ is the distance between the centroids of α and β . Analog to land entities, maritime entities that are not directly connected are connected via one of their neighbors 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.

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

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. 2). 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 ($\tau_h = 1$). In our transport network we implement the 188 most important continental ports and islands (Tbl. S3 and Fig. 2). If the transportation route $\mathcal{T}_{ir \rightarrow js}$ of firms *ir* and *js* consists of land and maritime entities, the total distance Δ_{rs}^c can be calculated by

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

where ww', $\alpha \alpha'$, wh, and αh 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

$$\tau_{rs} = \sum_{\{ww'\}} \frac{\Delta_{ww'}^c}{\nu^l} + \sum_{\{\alpha\alpha'\}} \frac{\Delta_{\alpha\alpha'}^c}{\nu^s} + \sum_{\{wh\}} \frac{\Delta_{wh}^c}{\nu^l} + \sum_{\{\alphah\}} \frac{\Delta_{\alpha h}^c}{\nu^s} + \sum_{\{h\}} \tau_h,$$
(2)

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

By using (Zabelsky, 2002) and Research and Technology (2019), 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 C_{rs} of transportation route $\mathcal{T}_{ir \to is}$ 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. The influence of the parameter choice of p^s and p^l on the study results is discussed in Sec. 4.6.

For example, the transportation route of a commodity from Germany to Beijing is computed using the implemented cost-minimizing algorithm 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. This modeled maritime route choice is consistent with the realistic ship routes (ShipTraffic.net, 2022; for Your China Imports, 2022). Important to note is, that the transportation costs on land or sea have no relation to the further economic dynamics of the model and are only used for the model-internal decision firms for the (static) transportation routes.

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. (2017)) are listed in Table 2.

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 region, maritime route 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 $Z_{ir \rightarrow js}^*$ depends on the specific firms *ir* and *js*. We assume that without perturbation an unlimited volume of goods can flow through the land entities, maritime entities, or ports. *Acclimate* is an anomaly model (cf. Otto et al. (2017)) and economic deviations only close to the baseline are meaningful, making a possible unlimited passage flow (even if it is not needed) a practical model assumption. 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*:

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

It should be pointed out that an entity can be a part of several transportation routes of different firms. That means that the perturbation of an entity affects every firm that has a business connection which relies on a transportation route which includes this perturbed geographic entity (Fig. 3). Also, the transportation routes between firms are fixed and cannot be changed dynamically during the simulation. This assumption is reasonable as long as the transportation disruptions are



Fig. 3. Exemplary sketch of the connection of a geographic and a economic network. The firms 1–5 are connected physically via a geographic network (upper panel, orange background) which consist of geographic entities A–J (e.g. ports, seas, roads), between which there may or may not be a link. Likewise, two firms might or might not have a business connection. The set of all existing business connections of all firms composes the economic network (lower panel, blue background). Two firms use for their trade a fixed geographic transportation route consisting of geographic entities. If a geographic entity is perturbed every business connection, that have a geographic transportation route that uses this entity, is affected. That means in this example, that if entity H is perturbed, the business connection between firms 1 & 4 and 2 & 4 is affected.

short-term and not long-term or even permanent, and in the absence of structural changes. Since we focus in this study on short-term (a few days) and unpredictable transport perturbations, the re-routing of ships is negligible. Considering the ship congestion caused by the six-day blockade of the Suez Canal in March 2021, this assumption seems reasonable.

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 $(m_{ir \to js}(t) < 1)$ this has two consequences for the business connection of firms *ir* and *js*.

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

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

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. The assumption that an unlimited amount of goods can flow through an entity is only justifiable for short-term transport perturbation. If the accumulated blocked flow $\mathcal{B}_e(t)$ becomes too large, higher-order congestion (e.g. at ports) cannot be captured².

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

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

$$\tag{4}$$

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 $(1 - m_{ir \rightarrow js}(t))D_{ir \rightarrow js}^*$ 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 Kuhla et al. (2021a,b); Middelanis et al. (2021, 2022); Otto et al. (2017); Willner et al. (2018)) the perturbations propagate through the supply chains.

3.4. Storms' impact on transmissibility of sea routes

As mentioned in Sec. 1, tropical storms may restrict the navigability of sea shipping routes. To reflect the degradation of navigability and therefore the transmissibility of goods influenced by a tropical storm, 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 wind speed threshold of 22 kn is based on what has been used in several maritime analyses (e.g. Wang et al. (2014)). Although several studies have addressed the risk of shipping delays due to storms Brouer et al. (2013a); Vilko et al. (2019); Wang et al. (2014), an estimation of a passage disruption is still missing; here we assume a transportation constraint of 25%. However, the results in this study (in Sec. 4) are robust against the parameter choices of wind speed threshold and

² Such higher-order congestion can be constructed if after the perturbation the $\chi_e(t)$ is not set directly to unlimited but to a finite number *x*, thus only *x*-times of the baseline flow can pass through the entity.

Table 1

Sea entity Maritime trading routes implemented in agent-based losspropagation model *Acclimate*. Numbering refers to Fig. 2.

	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

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

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

transportation constraint as we depict in our sensitivity analysis in Sec. 4.6. Delayed goods can be transported further via the affected sea route once the storm has passed or its wind speed is below the threshold of 22 kn. That means

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

where \mathcal{P}_e is the polygon that defines the area of maritime routes e (Fig. a) and the maximum wind speed depicts the highest wind speed in the polygon at time t. That means, in each time step a gridded wind field is overlaid with the gridded (time independent) polygon of a maritime entity. When a coordinate point exceeds the wind speed of 22 kn, the possible passage flow of that maritime entity is set to 25% relative to the baseline. As soon as there is no grid cell where the wind speed exceeds 22 kn, the possible passage flow is unlimited again. This model approach can be used for any maritime entity; however, we focus in this study on the West Pacific maritime trading routes.

3.5. West Pacific maritime entities and typhoon trajectories

The West Pacific maritime shipping routes are predominantly important for international maritime trade, as China, the world's largest national exporter, exclusively relies on those sea routes. This area is periodically affected by typhoons between June and December each year. In this study we focus on the following maritime routes: South China Sea, East China Sea, Yellow Sea, Sea of Japan, and Gulf of Thailand (Fig. 4a). Each routes depict one maritime entity in the described *Acclimate* extension (cf. Table 1). The polygons of each entity, as it is needed in Eq. 5, are available under 10.5281/zenodo.5807332.

The trajectories of tropical storms in the West Pacific and thus the relevant wind fields are derived from International Best Track Archive for Climate Stewardship (IBTrACS) (Knapp et al., 2018; 2010). These data base on satellite observations and have a temporal resolution of 3 hours. In our analysis we use the tropical storm trajectory for every observed storm for the West Pacific typhoon season for the years 2000–2020³.

³ The usage of projected typhoon trajectories concerning climate change are unlikely to significantly alter the results of this study as the transportation perturbations occur at wind speeds over 22 kn, which is well below very intense tropical cyclones (>112kn), for which there are high confident climate change projection trends (Balaguru et al., 2016; Emanuel, 2005; 2013).



Fig. 4. West Pacific typhoons affect East Asian maritime transportation routes (a) West Pacific maritime entities for which we assume that tropical storms perturb transportation of goods: South China Sea (red), East China Sea (blue), Yellow Sea (orange), Sea of Japan (purple), and Gulf of Thailand (brown). (b) West Pacific maritime entities with overlayed trajectories (black dots) of tropical storms (wind speed ≥ 22 kn) between May 2018 until April 2019 derived from IBTrACS (Knapp et al., 2018; 2010). Circles' sizes do not correspond to widths of storms. (c) Visualized example of how a transportation perturbation is calculated for a maritime entity. The sea route area (white) is overlaid by a storm trajectory (black & red) and each day where a storm is within the sea route at least once with more than 22 kn wind speed is determined as a perturbation time point (marked in red). In this example, a transportation disturbance for the East China Sea is calculated for the 10th and 11th of July. (d) Scheme of typhoon-induced transport perturbations for the season of 2018. Each row and color (identical to (a)) belongs to a respective maritime entity. Bars depict the time point and duration of a computed transportation perturbation.



Fig. 5. Map of the economic blocs used for the analyses in this study. The composition of the economic blocs – China (red), Europe (blue), NAFTA (orange), ASEAN (brown), Latin America (light purple), SAARC (grey), East Asia (purple), Arab League (purple), Post-Soviet states (light brown), Australia & Oceania (ochre), Sub-Saharan Africa (light orange), and Rest of the World (light grey) – arise from their economic and cultural affiliation.

For each tropical storm, we overlay the wind field at each time step with the area of the polygon of the corresponding maritime entity. The overlaying of all storm trajectories of season 2018 and the maritime entities is visualized in Fig. 4b-c. Since the simulation of *Acclimate* run on a daily temporal resolution, the following algorithm is used to adjust the temporal resolution of each storm trajectory. If one grid cell of the wind field, which lies within the polygon of one maritime entity, has a wind speed above 22 kn at any time point during the day, the possible passage flow of this maritime entity is set to 25% (cf. Eq. 5). Thereby it is irrelevant how many grid cells have a wind speed above 22 kn and how many time points within this day it occurs (Fig. 4c). Following this procedure for each trajectory of every West Pacific tropical storm between 2000–2020 for every day in each year, we derive time series of commodity passage for the East Asian maritime entities for this time period. That means, that we have an ensemble of 21 time series of typhoon-induced transportation perturbation of the West Pacific maritime trading routes. In Fig. 4d, we show exemplary for the 2018 season, when and for how long the different maritime trading routes are affected by tropical storms.

The transportation perturbation time series start at the 1st of May, thus they can account for some early tropical storm of the West Pacific typhoon season, and cover 365 days. We use each of these 21 transportation perturbation time series as input to drive the *Acclimate* model. Thus, for a fixed model setting, i.e. same economic network, fixed impact parameters (wind speed threshold and capped passage flow while disturbance), and constant macroeconomic parameters (e.g. ratio of transport cost via land and via sea), we obtain via *Acclimate* a simulation ensemble of 21 time series. For our main results our computations are based on the global economic structure of 2015 (except for Sec. 4.4). Using a constant economic network, we are able to account for climate uncertainties, such as years with many or few tropical storms. That means that we use the 21 time series of the typhoon-induced transportation perturbation as an input ensemble to obtain a more robust structural economic response (in terms of the climate impact as the shock source). The result of each simulation consists of economic values, e.g. production of firms, local prices, and commodity flows between each agent, for each day of the one year time period.

3.6. Regional and sectoral aggregation

Based on the mentioned economic repercussions computed by *Acclimate*, we analyze the direct and indirect economic impacts of typhoon-induced short-term transport delays. In order to be able to draw comprehensible and clear conclusions from the large amounts of data and to average over fast fluctuations and noise, we aggregate our results regionally, sectorally, and partly temporally. In the following, the regional results are summarized to economic blocs (Fig. 5): China, Europe, NAFTA⁴ (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 count China as an economic bloc itself, since it is one of the biggest economies and it is most prominent directly affected by the transportation disruption caused by West Pacific typhoons (also, in the model it is represented by each province as a separate region). 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.

⁴ 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.

Table 3

Economic blocs and their dependency on West Pacific trading routes. Aggregated economic bloc used in post-simulation analysis (Fig. 5) 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.

	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%)

The re-aggregation of model agents into the blocs averages their individual fluctuations and improves the robustness of our results. Additionally, most individual countries have a tight economic linkage to their surrounding countries or are even affiliated in a multilateral economic area, which is why an individual-state assessment is not particularly meaningful. These grouping causes that 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. In our results, we will explain the short-term economic repercussions, i.e. on a daily level, in section Sec. 4.1. In the further results (Secs. 4.2 to 4.6) we discuss median annual results, for which we aggregate the analyzed economic variables to annual values. 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.

3.7. Analysis metrics

In Sec. 4 we present our results which are given 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* · *quantity*). Thereby, in our analyses the price is given as 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.

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 synonymously.

4. Results

The findings we present in this section are based on computations of the agent-based shock model *Acclimate* and should be regarded as model projections and not as historical observations. Our results are structured as followed, first we explain the short-term economic repercussions caused by transportation perturbations due to tropical storms. Second, we show how internal and external trade as well as production and prices of economic blocs change on an annual level; thereby



Fig. 6. Typhoon-induced transport disturbance induce demand shifts and furthermore production and trade changes. The external (upper panels) and internal (lower panels) demand change (dashed line) with corresponding production change (middle panels) and following trade change (solid line) due to transport disturbance in maritime trade routes for China (a,c,d) and NAFTA (b,d,f). Changes are relative to baseline. The perturbed trading route is marked via same color scheme, which is used in Fig. 2d. The exemplary economic repercussions are computed via *Acclimate* and arise from estimated transportation perturbations during the typhoon season of 2018.

we identify the phenomenon of trade resilience. Third, we take a closer look at economic changes in China and evaluate the Chinese economic relevance of the maritime trading routes. Fourth, we show how and why potential trade resilience changes under different economic networks. Fifth, we explain the bilateral trade changes between different blocs. And, sixth, we finalize our numerical analysis with a comprehensible sensitivity analysis of different model parameter.

4.1. Transport perturbations cause demand-supply mismatch

In order to clarify the modeled economic dynamics during and after a transport delay due to a typhoon, we focus in this section on the simulated economic repercussions caused by storms from the typhoon seasons of 2018. For this we examine the computed short-term economic changes of the most affected bloc, China, and the biggest profiteer, NAFTA. In this section, we examine modeled results on a time scale of days.

Tropical storms cause transport disturbances on West Pacific shipping routes from 1 to 8 days depending on their trajectory and wind speed (cf. Secs. 3.4 and 3.5 and Fig. 2b-d). In our numerical analysis, we find that Chinese maritime trading routes may be perturbed due to one of these typhoons, which causes short-term decrease of external demand (Fig. 6a). A decline of external demand yields a lower Chinese production (Fig. 6c) 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 transportation perturbation (Fig. 6b). But since production in other blocs decrease, external demand declines after some time steps while West Pacific transport is disturbed. Thus, NAFTA's initial rise in external demand, trade, and production abates partly (Fig. 6b,d).

Our model results depict that the demand and supply shocks during a typhoon yield reductions in Chinese production, which implies 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. 6e). The same pattern occurs for every transport disturbance. However, previous economic repercussions

are reflected in the dynamics (Fig. 6e), 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 decline 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. 6f).

4.2. Exports increase despite typhoon-induced transportation perturbations

Using the 21 transportation perturbation times series computed from the West Pacific typhoon seasons 2000–2020 as input driver for *Acclimate* we obtain an output ensemble with 21 time series. In the following, each output time series is aggregated to one year and results are given in median annual changes with corresponding likely ranges. The economic structure and baseline corresponds to the year 2015, unless otherwise stated. For the rest of the study we present calculated medium-term effects (at the annual level), which arise due to reactions of economic agents to unpredictable and short-term impacts. Short-term perturbed transport of goods are not rerouted, but demand might be redistributed temporarily (cf. Secs. 3.3 and 5).

4.2.1. Exports increase in quantity

Our model results suggest, that despite imminent typhoon-induced maritime transport restrictions, China is able to increase its annual exports in quantity (Fig. 7a). 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. 7a). So the annual inter-regional trade of the economic blocs depict gains – at least in the amount of exports – even 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 is calculated to decrease in most blocs (Fig. 7b). 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 model 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 fill up and inter-regional buyers are absent, a regional oversupply is created, causing prices to fall (Fig. 7c). 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. 7a). 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. 7c).

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 and the resulting computed economic repercussions. 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). Our model results show a different export change for China if only trading routes in East China Sea or South China Sea are disturbed compared to all five West Pacific trading routes (Fig. 8a). Transportation delays in East China Sea cause Chinese export losses in 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). Using the generated geographic transport network, Chinese provinces are divided into "Northern" China, which uses East China Sea to NAFTA, and "Southern" China, which uses South China Sea to export commodities to NAFTA (Fig. 8b). 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. 8c). Our modeled results hint that 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.

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.

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



Fig. 7. Perturbed trading routes yield price changes which mostly intensify internal trading losses or decreases export gains in value. Economic repercussions are calculated using 21 typhoon-induced transportation perturbation times series (2000–2020). Annual changes are relative to the economic baseline of 2015. Colored lines, boxes and whiskers indicate median changes for each estimate, the 25–75 and 5–95 percentile ranges, respectively. (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.

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

So far, our computed results and interpretations base on the trade structures of 2015. In this section, we examine export changes for other economic networks in order to reveal factors for the identified trade resilience. Using the same impact derived from the 2000–2020 typhoon seasons, we compute the export changes to different economic baselines from 2000 to 2015 (Fig. 9). 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 exports between 2000 and 2015, East Asia's and NAFTA's share decreases



Fig. 8. Chinese export resilience to transport disruption depend on affected trading route. For (a) and (c): Economic repercussions are calculated using 21 typhoon-induced transportation perturbation times series (2000–2020). Annual changes are relative to the economic baseline of 2015. Colored lines, boxes and whiskers indicate median changes for each estimate, the 25–75 and 5–95 percentile ranges, respectively. (a) The computed Chinese export changes differ depending if the transportation perturbation on all five West Pacific trading routes (left), only on South China Sea (middle) or only on East China Sea (right) are considered. Disruption of the latter causes export losses in quantity and value. (b) Regarding model-internal maritime trading routes 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) compared to "Northern" China.



Fig. 9. Most blocs become over time more resilient against perturbations to West Pacific transport. Annual computed export change per quantity (blue) and value (orange) relative to the baseline of the corresponding economic network 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. Economic repercussions are calculated using 21 typhoon-induced transportation perturbation times series (2000–2020). Colored lines, boxes and whiskers indicate median changes for each estimate, the 25–75 and 5–95 percentile ranges, respectively.

roughly by a third (Fig. 10a). At the same time ASEAN increases its share by 20% and Europe's share is more or less stable at a high level. Nevertheless, our model results hint that resilience increases collectively in the later economic networks.

We find that the reason that the computed 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. 10b). 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



Fig. 10. Inter-connectivity of economic blocs change for different economic structures. 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 regarding the economic network from 2000 to 2015. (b) Number of foreign connections per firm within the economic bloc for different economic baselines. (c) Median annual export change in quantity per bloc over number of foreign connections per firm. Export resilience tends to increase with more foreign connections.

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 supports to buffer export losses and may turn export losses to export gains (Fig. 10c). 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 the computed changes in trade between the five main economic blocs. So in this section, our numerical analysis bases again on the economic baseline of 2015. As we present trade changes only for the five blocs considered so far (Fig. 11), calculated median trading results between any two blocs are listed in Tables S4 and S5. The blocs' exports in the baseline and its corresponding share of exports can be found in Table 4.

In *Acclimate*, every flow between agents is attached with a price. As a demand-driven model purchasers offer a price, based on estimations on their suppliers, for each input good and to each supplier. From this the suppliers take the decision of how much to produce and how to distribute this production given the offered prices. Thus, the price signal (as well as the slower quantity signal) can travel both ways — up-chain or down-chain. So, for example, the price changes due to delayed delivery from China to NAFTA firms would affect their customers as input prices and accordingly production capacities of NAFTA firms change (which their customers take into account). But additionally, the NAFTA firms will offer changed prices to other, even non-affected suppliers, e.g. when trying to substitute for the delayed input. Overall, each price and quantity change has repercussions up-stream as well as down-stream, again with consequences there in both directions and so forth. We here report the net effects to be observed from this kind of complex interactions.

4.5.1. China's export losses and adaptation mechanism

Our model results depict that China decreases its exports in quantity to almost any other economic bloc (Fig. 11a). 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. 11b). 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, we compute that 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

Our model result suggest that 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 (Tbl. 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

We compute that, due to West Pacific typhoons, 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 are projected to lower pressure on the export problems between China and Europe.

4.5.5. NAFTA is net-export winner

The results of our model setup hint that 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.



Fig. 11. Changes of bilateral trade concerning quantity, value, and price. Economic repercussions are calculated using 21 typhoon-induced transportation perturbation times series (2000–2020). Annual changes are relative to the economic baseline of 2015. Colored lines, boxes and whiskers indicate median changes for each estimate, the 25–75 and 5–95 percentile ranges, respectively. (a) Annual supply change per supplier (row) and purchaser (column) due to West Pacific typhoons. 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 typhoons. Bloc-internal (domestic) trade price change is shown on the diagonal graphs. China depicts the highest export price drop to any other economic bloc.

4.6. Sensitivity analysis

In this study we use a novel model approach to estimate the economic impact due to maritime transport disturbances caused by typhoons. There are physical impact parameters and economic parameters that might impact the results of our study. For these parameters we made comprehensive sensitivity analyses which we present and explain in this section, beginning with the physical impact parameters.

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. S4). For higher passage capacity during a disturbance (Fig. S4a), the computed effect of higher export quantity gains decrease moderately as to be expected. If the passage limit during a storm is attenuated (limit closer to 100%) more goods can be transported through the trading route. This results in fewer expected supply shortages of firms, which leads to less demand shifts, which causes a fewer regional price reduction. But the price drop causes mainly a rise in international trade in the typhoon aftermath. So higher passage limits cause less price drops which leads to a reduction in export increase, which changes the quantity of the results but not their general trend. When increasing the wind speed threshold for a perturbation, the export changes decrease slightly (Fig. S4b). A higher wind speed threshold causes fewer days of transport perturbation, especially for South China Sea (Fig. S2). Again, less perturbations cause less demands shifts, a smaller resulting price reduction and therefore a lower trade increase in the typhoon aftermath. But even with fewer transport disturbances and thus less economic repercussion, the trend of export changes is preserved.

Besides the parameters for modeling typhoon hazards, there are *Acclimate* internal parameters which drive the decisions of the economic agents. The ratio of the transportation price per ton mile via sea and via land determines the route decision. For example, if the relative transport price p^l via land increases it may make more economic sense for China to use more sea routes; but this may render Chinese trade flows more vulnerable to typhoons. A sensitivity analysis shows that increasing transportation cost via land, Chinese typhoon-induced export changes decrease slightly while export gains of the other blocs increase moderately (Fig. S5). When p^l is higher, China uses more sea routes and thus faces increased trade disruption due to typhoons. It is less able to compensate for this trade disruption through aftermath increases in demand and trade. The other blocs function more as substitutes for China and can further increase their exports. However, the main trend of our results stay robust, which is understandable since the majority of Chinese transportation routes already rely the perturbed West Pacific trading routes.

The ability of firms to exceed the baseline production in the face of increased demand is reflected in *Acclimate* by the possible production overcapacity parameter. So if a firm receives more demand it can fulfill this demand (if economically reasonable) until it reaches the production overcapacity. 50% overcapacity means that 1.5 times the baseline production can maximum produces. A sensitivity analysis shows that this parameter barely affects the results of this study (Fig. S6a). This is because that the maximum production overcapacity is rarely reached in this model setup due to two reasons. First, demand changes caused by transportation disruptions due to typhoons tend to be small and hardly reach the maximum overcapacity. Second, many firms have multiple suppliers, which allows to spread the shifted demand over multiple production sites.

Since overproduction is only a short-term change and not a long-term adjustment of a firm, the prices of commodities produced in overcapacity rise non-linearly. In *Acclimate*, overcapacity price increases are determined by the price increase by production extension (PIPE) parameter. The larger PIPE is, the more additional costs arise from overproduction. Our sensitivity analysis shows that with increasing PIPE the computed effect of annual export gains increases (Fig. S6b). If firms have to shift their demand due to transport perturbations, then the prices for the commodities from firms with overproduction rise with higher PIPE. When the transportation disruption is over, the price difference between original and substitute suppliers increases with higher PIPE. As a result, demand is even higher for the original supplier in the typhoon aftermath. Therefore, the annual export gains rise even further. Again, changing this parameter does not reverse the trend of our results.

5. Discussion

In this study, we model the economic repercussions caused by transport perturbations induced by typhoons in the West Pacific. Our simulation results suggest that during the perturbation directly affected trade blocs such as China or East Asia become less attractive for 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 lead to reductions in trade within the respective trade blocs as well. The corresponding price drops cause a temporal increase in demand, production, as well as internal and external trade above their pre-disaster levels once the perturbation has ceased.

Analyzing the economic repercussions that are computed via *Acclimate* using transportation perturbation time series derived from the West Pacific typhoon seasons 2000–2020, we find that the annual median export volume increase for all trade blocs. This suggests that inter-regional trade is partially resilient against typhoon-induced transport disruptions. Trade between Europe and East Asia, and China 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, our numerical analyses suggest that the resilience of the exports of the trade blocs are correlated with the number of outside connections per firm: export gains increase with the number of connections to external trade partners. Since the connectivity of firms in China, ASEAN and East Asia to external trade partners has substantially increased between the economic networks 2000–2015, they shifted from net-export losers in the early 2000s to net-export winners in 2015.

We point out that our results base solely on numerical model computation. On the input side we use global trade networks from the Eora data base (Lenzen et al., 2012) and typhoon trajectories from IBTrACS (Knapp et al., 2018). Unfortunately, on the model output side it is rather unfeasible to validate our results. Using the agent-based model *Acclimate*, we compute production of regional sectors (firms), local prices, and commodity flows between firms on a daily level. The current available econometric data for trade or production are temporally aggregated between 3 months to 1 year. On this time scale, the effect of transportation disturbances of a few days is hardly measurable next to the other economic impacts, like political conflicts or other disaster shocks. Furthermore, economic networks from the Eora database rely on observed annual trade flows, thus, such economic networks have impacts like weather extremes or political crises already included. Hence, the validation of computed output based on these networks becomes rather challenging. However, what agent-based modeling with *Acclimate* can provide is justified and well-argued hypotheses. In computing a complex system it can provide more information that is logically sound in itself, in the sense that the basic axiomatic behavior that is prescribed for each agent, leads to the observed macroscopic behavior. In doing so, the model allows to find emergent macroscopic behavior from prescribed microscopic rules.

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. For important model parameters, sensitivity analyses reveal that parameter choices have only marginal impact on the trend of the study results (cf. Sec. 4.6). In this study, we focus on unforeseeable and short-term transport disruptions (a few days) due to typhoons and the resulting computed 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 unlimited 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. However, the underlying assumption of the baseline is that it is optimal as the unperturbed "status quo", thus leading to optimal (of course finite) usage of passage capacities. Only after a delay passages will be suddenly used over this capacity, but some additional capacities in shortterm reaction after such a perturbation can be reasonably assumed. 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 reduction of complexity and a constraint on the adaptation measures of the transportation planners. However, it is justifiable since we only consider unforeseeable and short-term transportation disruptions in time scales of a few days. Most prominent example to support this assumption was the Suez canal obstruction in early 2021, where the most ships did not change their transportation routes during the short-term (six days) transport blockage. Besides this recent anecdote, we found no evidence in the literature that ships completely adjust their route due to a few days of delay.

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 (Verschuur et al., 2020) or to shipping analysis (Wang et al., 2014). Next to this, our sensitivity analyses reveal, that the choice of disturbance threshold and intensity does not change the trend of our results. If alternative model-internal economic parameters are chosen, the quantitative results change moderately as expected, but the qualitative trend of our findings remains robust. To tackle the problem with climate variability, our results base on an ensemble of time series derived from 21 different typhoon seasons (which included measured storm tracks). Facing these challenges of socioeconomic modeling we advert that the results of our study shall be read as a qualitative estimate rather than quantitative statements.

At a first glance, our findings that exports increase in the disaster aftermath contrast with estimated export losses of previous studies (Chang, 2000; Okuyama, 2015). 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. The evaluation of multiple impact channels, e.g. interrupted firms and perturbed transportation routes, would most likely yield a more intense impact. However, in this particular study, we exclusively analyze the supply chain dynamics and resulting macroeconomic impacts of typhoon-induced transportation perturbations in detail using the advanced *Acclimate* model. Since 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. 10). 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 (Landi et al., 2018) whether more dense and complex networks are more stable (van Altena et al., 2016; Fyodorov and Khoruzhenko, 2016) or less stable (van Altena et al., 2016; Moran and Bouchaud, 2019) 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.

6. Conclusion

In this study, we use the agent-based macroeconomic network model *Acclimate* to show that West Pacific typhooninduced maritime transport perturbation may cause short-term shifts in demand and supply. In the short run, more directly affected economic blocs like China or East Asia forfeit demand whereas Europe and NAFTA face increased demand. However, if we focus on the computed annual changes of trade, we find that annual export volumes increase despite short-term transportation disruption in the West Pacific trading routes. Our results, which base on computed transportation perturbation time series of the last 21 West Pacific typhoon seasons, suggest a inter-regional trade resilient against typhoon-induced trade disruption. The trade resilience of the discussed trade blocs tend to grow with an increasing number of outside connections per firm. This suggests that stronger economic linkages are rather beneficial to mitigate economic impacts from unpredictable severe weather events.

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 trends in results, which hint that 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 may mitigate local economic perturbations.

Data and materials availability

The implementation of the agent-based loss-propagation model *Acclimate* with the geographic transportation module is available as open source on https://github.com/acclimate/acclimate/tree/transport-module with identifier 10.5281/zenodo. 7788859. The used data for categorization of the maritime entities and the geographic network are available at 10.5281/zenodo.5807332). The input data, final output data, and the python scripts to reproduce the figures of this study are available at 10.5281/zenodo.7786840).

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript the authors did not use any generative AI and AI-assisted technologies.

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Supplementary material

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