

# **Port disruptions due to natural disasters: insights into port and logistics resilience**

J.Verschuur<sup>1,\*</sup>, E.E. Koks<sup>1,2</sup> and J.W. Hall<sup>1</sup>

<sup>1</sup> Environmental Change Institute, University of Oxford, Oxford, United Kingdom

<sup>2</sup> Institute for Environmental Studies, Vrije Universiteit Amsterdam, Amsterdam, Netherlands

\* corresponding author: [jasper.verschuur@keble.ox.ac.uk](mailto:jasper.verschuur@keble.ox.ac.uk)

Environmental Change Institute, 3 South Parks Road, OX1 3QY, Oxford, United Kingdom

## **Abstract**

**Ports are located in low-lying coastal and riverine areas making them prone to the physical impacts of natural disasters. The consequential disruptions can potentially propagate through supply chains, resulting in widespread economic losses. Previous studies to quantify the risks of port disruptions have adopted various modelling assumptions about the resilience of individual ports and marine network logistics. However, limited empirical evidence is available to validate these modelling assumptions or to provide deeper understanding of the ways in which operations are adapted during and after disruptions. Here, we use vessel tracking data to analyse past port disruptions due to natural disasters, evaluating 141 incidences of disruptions across 74 ports and 27 disasters. Results show a median disruption duration of six days with a 95<sup>th</sup> percentile of 22.2 days. All analysed events show multiple ports being affected simultaneously, challenging some of the studies that only focus on single port disruptions. Moreover, we find that the duration of the disruption scales with the severity of the event, with an increment of 1.0m storm surge or 10m/s wind speed associated with a two day increase in disruption duration. In contrast to commonplace assumptions in model studies, substitution between ports is rarely observed during short-term disruptions. On the other**

**hand, production recapture happens in practice in many cases of port disruptions. In short, empirical vessel tracking data provides valuable insights for future modelling studies in order to better approximate the extent of the disruption and the potential resilience of the port and maritime network.**

**Keywords:** ports; disruptions; natural disasters; resilience; Automatic Identification System

**Highlights:**

- Empirical evidence of 141 incidences of past port disruptions across 27 events
- Ports disruptions have a median of 6 days with a 95<sup>th</sup> quantile of 22.2 days
- Additional 1.0m surge or 10m/s wind speed leads to a two day increase in disruption duration.
- All events cause simultaneous disruption at multiple ports.
- Production recapture more likely than port substitution

## **1. Introduction**

Ports are critical nodes in the global trade network. Ports form the linkages between hinterlands and determine the location and distribution of global supply-chains (Becker et al., 2013; Ng et al., 2015; Notteboom and Rodrigue, 2008). They are strategically located close to coastlines and riverine areas to provide access to global maritime and inland water transport networks. However, their location makes them potentially vulnerable to natural disasters, such as coastal flooding (e.g. tropical cyclones, hurricanes), riverine flooding and earthquakes. A survey by the UNCTAD in 2017 (UNCTAD, 2017) showed that 72% of the port authorities that responded have been impacted by extreme events, causing delays (60%), disrupting operations (76%) or causing physical damages (45%). Given a port's vital role in the global supply chains, port disruptions may induce shocks throughout the regional and global economy (Rose and Wei,

2013). Therefore, understanding past port disruptions and projecting future changes in port disruptions from natural disasters is vital for building resilience into the global port and trade network.

The impacts of natural disasters on transportation systems, including ports, can be multifaceted. A port disruption can first reduce the amount of freight a port can process for a certain duration, causing delays, the depreciation of goods and, in case cargo is re-routed, additional transportation costs (Achurra-Gonzalez et al., 2019a; Omer et al., 2012). Cyclone Yasi, in 2011, closed the port of Brisbane for ten days, causing a total of AUD50 million in losses and decreasing the annual throughput with 6.4 percent (Cahoon et al., 2016). In case of physical damages to ports, the functioning of ports may be severely impaired, with large costs involved to rebuild port assets and a long term disruption to the logistics network. Disruptions to vital transportation systems can further have large scale consequences for supply-chains that depend on these systems (Lam et al., 2017; Ng et al., 2015; Rose and Wei, 2013). For instance, Hurricane Katrina in 2005 caused USD 1.7 billion damages to the Louisiana ports, resulting in an estimated USD 882 million losses of agricultural trade (Santella et al., 2010; Trepte and Rice, 2014). Typhoon Maemi in 2003 left the Port of Busan inoperable for 91 days (Becker et al., 2018), disrupting global maritime trade (Lam et al., 2017).

## **2. Literature review**

Here, we will briefly discuss previous research that has focused on providing empirical evidence of past port disruptions (Section 2.1), potential economic consequences of port disruptions (Section 2.2), and the approaches to mitigate the negative consequences of port disruptions (Section 2.3).

## **2.1. Empirical evidence port disruptions**

Several studies have looked at the past occurrence of port disruptions due to natural disasters. Trepte and Rice (2014) collected data on 28 incidences of port disruptions (caused for various reasons) between 2004 and 2010, showing that the median disruption duration equals three days with a standard deviation of six days. Lam and Su (2015) discussed 15 disruptions between 2001 and 2011 in Asia, including seven natural disasters, with closure durations ranging from 1 to 91 days. Adam et al. (2016) elaborated on maritime disruptions in the UK from 1950 to 2014, identifying 88 events of which 48% were caused by wind storms or storm surges. Interestingly, an increase in wind-induced port disruptions is reported, while disruptions associated with storm surges have decreased. Cao and Lam (2019) assess weather-induced port disruptions between 2013 and 2017 for the Port of Shenzhen, finding a total number of 170 weather events that caused downtime. The authors find that the month March has an average monthly downtime of seven days between 2013 and 2017, mainly associated with fog, whereas the months of July and August have an average monthly downtime of around four days due to typhoons and rain. In short, port disruptions largely vary according to the type of event, magnitude, continent and port, making it hard to generalise the results.

A small numbers of studies have explored the empirical analysis of port functioning during and after natural disasters using empirical vessel tracking data (Farhadi et al., 2016; Touzinsky et al., 2018). These studies have focused on the port of New York/New Jersey during Hurricane Sandy (2012) (Farhadi et al., 2016) and the ports of Savannah, Charleston and Jacksonville during Hurricane Matthew (2016) (Touzinsky et al., 2018). They showed how port disruptions follow a classical resilience curve consisting of the initial shock, a recovery phase and an adaptation phase (Grafton et al., 2019; Linkov et al., 2014). Still, difference can be observed between events and ports, which raises questions what the critical drivers of ports resilience

are. This type of analysis has not yet been explored beyond the handful of ports in the United States, but provides a generic way to analyse port disruptions on a global scale.

## **2.2. Impact modelling port disruptions**

Research focused on modelling the economic impacts of port disruptions use a variety of approaches, depending on the level of the impact analysis (e.g. port-level, regional-level, national-level). Port-level approaches either use hydrodynamic or weather-simulating models in combination with operational thresholds of ports (Camus et al., 2019; Esteban et al., 2016; Sierra et al., 2017; Zhang and Lam, 2015) or a simulation model of the port functioning in order to estimate the economic losses of downtime for a port (Cao and Lam, 2019; Zhang and Lam, 2016). The abovementioned studies rely on a relationship between the event (e.g. wind speed, surge height, earthquake magnitude) and the resulting downtime, which is often hard to obtain from data. Ports often work under increased safety protocol before operational thresholds (e.g. wind thresholds for gantry cranes) are exceeded (Berle et al., 2011; Omer et al., 2012), which means that thresholds do not have to be exceeded before operations are disrupted. Apart from a curve that relates the port recovery to the severity of an earthquake in Japan (Akakura et al., 2015), such general relationships do not yet exist for ports.

System-wide approaches model the freight assignment in case of port disruptions using freight modelling (Jones et al., 2011) or empirical approaches (Akakura et al., 2015; Paul and Maloni, 2010). Although they can predict the optimal diversion paths of freight, they are often static models and do not provide insights into the dynamic assignment, including port and liner constraints, over time. Other approaches use dynamic liner optimisation models (Achurra-Gonzalez et al., 2019b, 2019a; Novati et al., 2015) to model the vessel assignment over time and associated cost of vessel rerouting after node or link perturbations. A different strand of

literature have quantified the economic consequences of a port disruption by assessing the inter-industry supply chain interlinkages of goods transported through a specific port (Pant et al., 2015; Park et al., 2008; Rose et al., 2018; Rose and Wei, 2013; Thekdi and Santos, 2016). Such evaluations use a combination of port disruption scenarios, a port simulation model, and a macroeconomic model to propagate the impacts of disruptions to the regional or national economy.

The abovementioned literature often rely on a scenario analysis of port disruptions, including the duration of the disruption and the occurrence of single versus multiple ports disruptions. Those focusing on disruptions from natural disasters or extreme weather have implemented durations in the order of 1 – 10 days (Cao and Lam, 2019; Jones et al., 2011; Pant et al., 2014; Zhang and Lam, 2016, 2015). Others have assumed longer closures such as 14 days (Pant et al., 2015; Paul and Maloni, 2010), 30 days (Thekdi and Santos, 2016) or two months (Achurra-Gonzalez et al., 2019b), with the latter focusing on a specific earthquake event. However, given the variety of scenarios, and the potentially sensitivity of the results to this, it is important to understand how these scenarios relate to past port disruptions in terms of severity. For instance, little substantiation is provided what the recurrence interval of these scenarios are (e.g. 10 day disruptions occurs once every x years). Moreover, most of the aforementioned studies only consider single port disruptions (Camus et al., 2019; Cao and Lam, 2019; Pant et al., 2015; Park et al., 2008; Rose et al., 2018; Rose and Wei, 2013; Thekdi and Santos, 2016; Zhang and Lam, 2016). However, a single versus multiple port disruption scenario might affect the results in terms of losses and system response. For instance, Paul and Maloni (2010) showed that a multiple port versus a single port disruption scenario (14 days) increases the resulting losses by a factor 4.6.

### **2.3. Mitigation strategies port disruptions**

The most prominent strategies to minimise the negative consequences of port disruptions from a logistics point of view are production recapture (i.e. ports can make up for disruption by shifting more cargo once they become operational again) and port substitution (i.e. part of cargo can be diverted to other port/ports). Most modelling studies assume that port substitution readily happens, either by modelling the alternative assignment options explicitly (Achurra-Gonzalez et al., 2019a; Jones et al., 2011; Novati et al., 2015; Paul and Maloni, 2010) or by including it as a resilience option in an impact analysis using macro-economic models (Rose et al., 2018; Rose and Wei, 2013). However, port substitution might not occur in practise, due to a variety of factors: the earlier mentioned simultaneous port disruptions, draught constraints, hinterland connections, specialised equipment, and contractual restrictions (Akakura et al., 2015; Hamano and Vermeulen, 2019; Trepte and Rice, 2014). The ongoing trends in port development are on the one hand an increasing specialisation of smaller ports and on the other hand a rise in large gateway ports, driven by the ever-increasing size of vessels that can only call at a limited set of ports (Ducruet et al., 2015; Notteboom and Rodrigue, 2008). Trepte and Rice (2014) pointed out that due to this trend, a disruption in a large port/set of ports in the U.S.A. will inevitably lead to losses to the economy given an insufficient capacity in substitution ports. On top of that, ports are becoming more horizontally embedded in supply-chains (Notteboom and Rodrigue, 2008; Notteboom, 2006; Rodrigue and Notteboom, 2009; Wendler-Bosco and Nicholson, 2019) with carriers owning stevedoring companies and hinterland connections, or carriers having long-term contracts with specific ports for cargo handling. This all makes the occurrence of port substitution limited, with carriers often choosing to either wait or implement strategies such as port swapping or port skipping (Li et al., 2015).

Recent empirical work (Friedt, 2018; Sytsma, 2017) analysed changing port-level trade flows during and after a number of hurricanes in the U.S.A. and found limited evidence of port substitution. Hamano and Vermeulen (2019), however, found evidence that in Japan about 40% of the export were substituted to other ports in the months after the Great East Japan Earthquake in 2011. However, this could be driven by the type of commodities Japan exports (e.g. car manufacturing) that generally have little inventories (and therefore a larger export push), the two month disruption of multiple ports, and because of the country's spatial configuration, which makes it relatively cost-efficient to switch from ports on one side of the country to the other (Akakura et al., 2015; Hamano and Vermeulen, 2019). The extent to which port substitution can occur does steer the resulting losses. For instance, Achurra-Gonzalez et al. (2019a) showed that disruption losses have an order of magnitude difference depending on the assumption of diversion rate incorporated (they apply cases 0 – 100% diversion). Therefore, diversion rates, such as the 90% diversion rate used by Rose and Wei (2013) and Rose, Wei and Paul (2018) as a potential resilience strategy, should be empirically tested for its viability.

Instead of diverting cargo to alternative ports, ports can recapture the delayed cargo that has not been cancelled (via port skipping or swapping) by increasing their productivity after the port has become operational again (Akakura et al., 2015). The ability of a port to do this depends on the level of utilisation of the port and the ability to temporarily increase throughput (level of storage, number of tugs and pilots, number of trucks and trains available to transport). Ports with a high utilisation rate and already large congestion problems (e.g. Port of Los Angeles and Long Beach) will face difficulties in recapturing cargo, whereas ports with lower utilisation rates (e.g. Port of Baltimore, Port of Charleston) (Fan et al., 2012) will more likely recapture their cargo. In case of ports transporting goods with a seasonal character (e.g. harvesting season

agriculture), the ability to recapture also depends on the timing of the disaster. However, this strategy is often not included in modelling approaches.

The occurrence of port substitution and production recapture in reality is mixed, making it hard to understand the current level of resilience already in the system and evaluate the viability and benefits of various strategies to improve port and supply-chain resilience.

### **3. Research gap and objectives**

As pointed out in the literature review, little empirical evidence is available about port disruptions in real-world situations. Providing an empirical database of past port disruptions can improve our understanding on the occurrence and extent of disruptions across different geographical scales. Using this data to derive a relationship between the severity of the event and the resulting downtime could support risk management purpose of ports. Furthermore, empirical data can support model-based studies by creating more realistic scenarios of port disruptions, in terms of duration and spatial extent (e.g. single versus multiple ports), and help refine some of the modelling assumptions made on the recovery and response of the logistic network. At last, analysing the dynamics of port disruptions over time can provide useful insights in the resilience of supply-chains and can be used a tool to evaluate how different strategies implemented by ports are enhancing the recovery after disruptions.

In this paper, we build upon previous analysis (Farhadi et al., 2016; Touzinsky et al., 2018) and use Automatic Identification System (AIS) data to provide empirical evidence of vessel movements in and around ports (both affected and non-affected ones) during and after disruptions. We use this data to fill in some of the research gaps by evaluating the disruption duration and the resilience of ports, and deriving a fragility curve for U.S.A. ports. In addition,

we evaluate the port and logistic level resilience by looking into the mitigation strategies implemented, either via ports trying to (partially) recapture goods or carriers seeking alternative, non-affected, ports to take over some of the goods destined for a disrupted port.

In total, we analyse 141 incidences of port disruptions due to natural disasters. Although we are constrained by data availability (U.S.A. 2011-2017, Australia 2012-2019 and globally April 2019 – December 2019), some valuable insights can be provided by the events analysed, including a number of implications for port authorities and future research efforts. We start by providing an overview of the data sources used and analytical approach adopted (Section 4). This is followed by a systematic analysis of the events, including duration of the disruptions and resilience of ports (Section 5.1). Next, evaluate the relationship between the magnitude of the event and the duration of the disruption for U.S.A. ports (Section 5.2) and the occurrence of multiple versus single port disruptions (Section 5.3). Moreover, we look at the recovery and adaptation approaches of ports and how real-world observations compare to assumptions made in simulation-based approaches (Section 5.4 and 5.5). We end with the implications of our work and provide a set of recommendations for further studies on port disruptions (Section 6), followed by a conclusion (Section 7).

## **4. Data and methods**

### **4.1. AIS data and coastal surge and wind speed data**

AIS was introduced by the International Maritime Organisation (IMO) to improve safety at sea and provides detailed data on location, speed and direction every few seconds to minutes for all vessels with an AIS transponder (>300 GT vessels need a mandatory AIS receiver) that send information to terrestrial or satellite receivers. AIS data has successfully been used to inform on fisheries monitoring, maritime emissions, spatial planning and trade estimation (Adland et

al., 2017; De Souza et al., 2016; Fournier et al., 2018; Liu et al., 2019; Metcalfe et al., 2018). Although the coverage of vessels has increased tremendously over the years, some challenges related to the reception of lower powered AIS transponders, the revisit time of satellites and general accuracy of the data still persists (Fournier et al., 2018).

For this study, AIS data is collected from various sources. Monthly AIS data for the U.S.A. is downloaded from the AIS database of MarineCadastre (MarineCadastre, 2019) that covers data collected by the U.S. Coast Guard. This includes raw data from 2009-2017 per UTM zone. For Australia, monthly AIS data can be downloaded from the data service of the Australian Maritime Safety Authority (Australian Maritime Safety Authority, 2019) for 2012-2019 for the whole country. Only data points with a minimum time interval between successive vessel position reports of 60 minutes are included in this dataset. For the globally covering data from 01-04-2019 till 01-12-2019, data was retrieved via a partnership with the UN Global Platform AIS Task Team initiative, which aims to develop algorithms and methodologies to make AIS data useful for a variety of fields and applications (traffic, economic trade, fisheries, CO2 emissions). Within the time period of available data, we search for natural disasters that have occurred in the vicinity of ports from different sources (EM-DAT database, NOAA Hurricane Centre, Australian Bureau of Meteorology and news articles). We focus particularly on hurricanes (here used interchangeably with tropical cyclones and typhoons), that are associated with extreme wind, waves and surges, and riverine flooding, that can disrupt port and hinterland infrastructure. This set of disasters and associated ports forms our initial set of ports to evaluate. Other natural disasters like heatwaves, precipitation and fog can affect port operations, but are often of short duration (order of few hours) (Cao and Lam, 2019) and hence hard to detect using the daily aggregation we adopt.

For the U.S.A. ports under consideration ( $N = 54$ ), we also collected the peak surge and wind speed of the hurricanes events to relate the extent of the disruption to the magnitude of the event. The peak surge and wind speed are collected from the National Oceanic and Atmospheric Administration (NOAA, 2020) with values taken from the closest gauge station that has data during the particular events. This may induce some bias as tide gauge/wind stations and have different distances to the ports of interest.

### **Figure 1**

Figure 1: Workflow of the analytical approach taken in this paper.

#### **4.2. Analytical approach**

An overview of the workflow is included in Figure 1. For every port under consideration, we derive a port activity time series by counting the number of unique vessels within a specifically defined port area over time using the AIS data. Moreover, we derive the vessel calls per port by looking at the ingoing and outgoing movements of vessels in our area of interest. As in Touzinsky et al. (2018), the total area of interest includes the port area and navigation channel(s). For some port clusters (multiple ports within same bay), we take strategic positions to count vessels (e.g. entrance Tokyo Bay, entrance Galveston Bay) to capture multiple ports in once. We solely extract cargo (container, general cargo, dry bulk etc.) and tanker (oil, chemical, refined oil and chemical products etc.) vessels to focus on goods-carrying vessels and retrieve data over a period of three months for each event (the month before, during and after the event), thereby excluding other purpose vessels in the port area (e.g. tugs, piloting vessels, bunkering vessels, passenger ships, fishing boats and private yachts). For the remainder, we use

port activity as our main metric, as it better resembles a port's operational status, but results are consistent if port calls have been used instead.

We filter out the incidences of port disruption where the vessel count reduction is less than 20% of normal operations and cases where it is hard to distinguish if a reduction is caused by the disaster or the natural variability in vessel activity (e.g. port Hampton Roads and port New York-New Jersey during 2017 Hurricane Maria). We have therefore also excluded smaller, less busy ports from the analysis (e.g. port Morehead City in U.S.A. and port Bunbury in Australia), as it is hard to distinguish the disruption from a time series that includes periods of inactivity. However, large gateways ports handle the majority of goods (Ducruet et al., 2010) and are therefore most significant from a trade perspective. In the end, our database consists of 141 incidences of disruptions across 74 ports (12 countries) during 27 events (9 hurricanes, 2 floods, 12 tropical cyclones and 4 typhoons) where port operations have been affected. These disruptions range from minor operational change (~20-50% reduction port activity) up to total shutdown of port operations for multiple days. Some examples of port disruptions are provided in Figure 2, including Hurricane Harvey (2017) affecting the ports of Houston-Galveston-Freepport (Figure 2a), Tropical Cyclone Veronica (2019) impacting Port Dampier (Figure 2b), Hurricane Sandy (2013) affecting the port of New York-New Jersey (Figure 2c), and Port Haimen during and after Typhoon Lekima (2019) (Figure 2d). For each incidence, we count the number of days that the port activity is in a state of Reduction (Red), Closure (if closed) (C) and Recovery (Rec) till pre-disaster level. Resilience is commonly defined as the ability to resist and recover from, and adapt to, adverse events (Linkov et al., 2014). It is hard to design an overarching resilience metric, because definitions of resilience differ in the academic literature, including which factors contribute to resilience and how these factors can be measured, maintained and enhanced (Grafton et al., 2019; Klein et al., 2003). We therefore focus on two

metrics that are subcomponents of resilience. First, we use the total number of affected days (TAD) as a metric to approximate the extent of the disruption, which is equal to the summation of Red, C and Rec. Second, we approximate the recovery-ability of ports by dividing the number of days a port activity is reduced and halted (closed) by the number of days its takes to recover (disruption/recovery ratio). In some cases, ports adapt to a new operational state after a disruption, either related to a lower pre-disaster state (part of the port or hinterland inoperable for a long period of time) or a higher post-disaster state (increasing the productivity of the operations).

### **Figure 2**

Figure 2: Overview of port disruptions for four ports and events: (a) Port of Houston/Freeport/Galveston (U.S.A.) during Hurricane Harvey, (b) Port Dampier (Australia) during Tropical Cyclone Veronica, (c) Port New York/New Jersey (U.S.A.) during Hurricane Sandy, and (d) Port Shanghai (China) during Typhoon Lekima. The grey shade represents the formation and dissipation of the event, whereas the grey line indicates the date of making landfall.

#### **4.3. Analysis**

We use the abovementioned data to do a number of analysis. First, we analyse the distribution of the TAD for both ports that are closed and not closed. We do a similar exercise for the distribution of the recovery-ability of ports. Second, for U.S.A. ports and events, we derive relationship between the severity of the events (in terms of wind speed and surge height) and the TAD by analysing the correlation coefficient and by fitting linear regression. Third, we study the likelihood of a simultaneous disruption at multiple ports. Fourth, we provide evidence for the occurrence of port substitution and production recapture using the time series of port activity.

## 5. Results

### 5.1. Duration disruptions and recovery

Figure 3a shows the normalised histogram together with the distribution (solid line) of the TAD for the events. Of the 141 disruptions we investigated, 69 ports showed a completely shut down, whereas the remaining 72 ports were only partially affected (ranging from only 20% affected to limited operations). The median TAD equals six days for the ports that have been closed with an 5-95 quantile of 4 – 22.2 days (red histogram Figure 3a). For the ports that did not completely close, the median TAD is 5 days with a 5-95 quantile of 2 – 11 days (green histogram Figure 3a). The distribution is highly skewed with the upper quantile values being influenced by some extreme cases like the 2011 Mississippi flood, which according to our data, closed the Port of Baton Rouge for 11 days and part of the inland water transport network, affecting transport at the Port of Rouge for 33 days and the Port of South Louisiana for 30 days (although not closed). Two other extreme cases are the 2019 Typhoon Lekima that caused flooding and landslides in the port city of Wenzhou, causing the port and inland water network to become inoperable for 45 days, and a 45-day disruption at the Port of Hay Point after the 2017 Tropical Cyclone Debbie. The latter was caused by flooding of the major railways connecting the port with the main supplying coal mine (ABC News, 2017). These examples show that hinterland disruptions can affect port operations significantly, in particular export-orientated ports that handle low-value bulky goods (like ores and cereals) that disproportionately rely on their hinterland infrastructure. Some of the most extreme disruptions in the database are Hurricane Dorian affecting operations at the Port of Freeport (21 days TAD), 2017 Hurricane Harvey disrupting the ports of Port Arthur and Beaumont (18 TAD), Port of Corpus Christi (14 TAD) and Houston (11 TAD), and 2019 Tropical Cyclone Veronica closing Port Walcott (16 TAD). These ports have important functions within the global supply-chain, such as Freeport's function as transshipment hub for U.S.A. ports, Port Walcott's role as one of the main iron ore exporting

ports for the Chinese and Japanese industry (Beresford et al., 2011) and the central role of the Gulf of Mexico ports in the international trade of refined oil products (Santella et al., 2010).

The distribution of the recoverability metric for both closed and non-closed ports is shown in Figure 3b, which larger values indicating enhanced recoverability. The median recoverability is close to 2.0, indicating that the number of days it takes to recover is on average half the time of the original disruption by reduction or closure. However, especially for ports that are closed the spread is large and multimodal. For instance, during Hurricane Harvey, the port of Corpus Christi was affected ten days and took four days to recover, whereas the port of Lavaca was also affected ten days (and closed two days longer), but recovered in only two days. A similar observation for the Port Hedland and Port Dampier during Tropical Cyclone Veronica. The former was affected five days and took five days to recovery, whereas the latter was affected eight days and took three days to recover. Port Walcott needed seven days of recovery after being affected for nine days (seven days closed). Port Walcott, compared to the other two ports, has no breakwater or natural shelters and hence more vulnerable for the impacts of tropical cyclones.

### Figure 3

Figure 3: (a) The distribution of the total affected days across all events where ports have been closed (red) or partly affected (green) with the median (black marker) and 5-95th percentile values depicted by the bar, (b) same as (a) but for the recovery-ability of the events, (c) The relationship between the peak surge height and the total number of affected days for all events and ports considered in the U.S.A. for ports. (d) The relationship between the peak wind speed and the total number of affected days for all events and ports considered in the U.S.A. The grey area depicts condition ZULU corresponding to gale winds that require a port to stop operations. The markers with a black edgecolor are associated with Hurricane Harvey.

## **5.2. Relationship between the magnitude event and total number of affected days**

For the U.S.A. ports, we investigate the relationship between the magnitude of the event and the TAD. Curves that relate the magnitude of the event to the severity of the consequences are referred to as fragility curves in the disaster risk community (Aerts et al., 2018; Meyer et al., 2013). Fragility curves are valuable sources of information for various stakeholders, such as port authorities and logistics companies, as they can be used to identify critical thresholds (e.g. risk of getting delays more than a 5 days) per port, and how the likelihood of such threshold may change in the future due to climate change.

Results are shown in Figure 3c-d for peak storm surge versus TAD and peak wind speed versus TAD. A linear trend can be observed with the magnitude of the event and the TAD, with an overall correlation of 0.45 for surge and TAD and 0.52 for wind speed and TAD. As expected, the largest surge and wind speed events are associated with port closures and longer TAD. This is related to the ‘Hurricane Port Conditions’ safety protocol in place in the U.S.A., which states that all waterfront operations should be suspended when condition ZULU is reached. Condition ZULU corresponds to sustained gale force winds ( $\sim 17.5 - 24.2$  m/s) that are predicted 12h before the hurricane makes landfall (see grey area Figure 3d). Correlations are smaller for the separated data, with a correlation of 0.33 (0.33) for surge and TAD for closed ports (non-closed ports) and 0.42 (0.34) for wind speed and TAD for closed ports (non-closed ports). Ports affected by Hurricane Harvey (indicated with black colour at edges markers) are some extreme cases here given that the magnitude of surge and wind speed was moderately high, but the number of TAD very high. Hurricane Harvey was a slow-moving hurricane that reversed direction when moving over Texas (Kossin, 2018), affecting the area for a long duration and causing long-lasting limitations to operations. This example shows the importance of the event’s duration for the inoperability, with recent projections showing an increase of the number

of slow-moving hurricanes in the future associated with anthropogenic climate change (Zhang et al., 2020). By fitting a linear regression through the data points (see graph for fitted line), the observation can be made that an additional 1m increase in storm surge is associated with 2.05 (2.00) increase in TAD for ports that are being shut (not shut). For wind speed, a 10m/s increment in wind speed results in a 1.97 (1.34) increase in the number of TAD for ports that are being shut (not shut).

### **5.3. Simultaneous port disruptions**

Disasters like hurricanes can affect large areas simultaneously, either because multiple ports experience extreme conditions within their terminal areas or due to extreme conditions at sea that delay multiple vessels within a region. Figure 4 shows the TAD and the amount of days that ports are fully closed per event. Single port disruptions rarely happen and all events have multiple ports being simultaneously affected to some extent. Of these events, 15 out of 27 have simultaneous full port closures, showing that full port closures can be more localised. Given that the simultaneously affected ports are usually closely located to each other, simultaneous closures will affect the possibilities of diverting goods in a cost-efficient way (that is without significant rerouting costs). Therefore, freight assignment models that model single port disruptions may be overly optimistic about the spare capacity in potential substitution ports during events like hurricanes, whereas with more localised disasters (e.g. river flooding, landslides) this is a more realistic modelling assumption.

#### **Figure 4**

Figure 4: Overview of number of days affected and number of days closed per port and per event.

#### **5.4. Port substitution**

In our sample of ports, we have identified the closest (unaffected) ports for potential substitution options and analyse the time series to assess if there are clear signs of increased vessel activity. In contrast to the dominance of port substitution as a mitigation mechanism in model-based studies, we find very limited evidence of substitution occurring. Two incidences stand out as exceptions: the 2019 Hurricane Barry that caused a temporally spike in cargo vessel calls at the port of Fourchon (U.S.A.) (Figure 5a-b) and reported evidence of coal export substitution from the port of Abbot Point towards the neighbouring Hay Point, Dalrymple and Gladstone ports during the 2019 Queensland floods (Financial Review, 2019). The latter is hard to observe in the data for port Hay Point and port Gladstone given an overall reduction in vessel activity. Port Dalrymple (Figure 5c), however, received some extra vessels at the same time Abbot Point (Figure 5d) experienced a decrease, but the limited number of vessels makes it hard to make well-backed statements about this.

The lack of port substitution could however be explained by the fact that our sample of disruptions is simply too short in duration to observe structural port substitution. For instance, after the 1995 earthquake that disrupted the port of Kobe, cargo flows were diverted to the ports of Osaka, Nagoya and Yokohama while transshipment flows were diverted to Busan (South-Korea) and Kaohsiung (Taiwan), some of which not returning back after the port got operational again 2 years later (Chang, 2000). Within our dataset, the port of Wenzhou, which was affected 45 days, has never reached its pre-disaster level of daily vessel activity again (around 50%), even 3 months after it became operational again. An analysis of the vessels that usually called at the port but never again after becoming operational again show that some of the vessels have diverted their port calls to the ports of Ningbo, Zhoushan and Shanghai, which agrees with previous work (Li and Oh, 2010) that identified these ports are competitors of one another.

## Figure 5

Figure 5: Port substitution from the Port of Abbot Point (a) towards Port Dalrymple (b) during the 2019 Queensland Floods that disrupted the railway between the coal mines and the Port of Abbot Point. The grey shade represent the formation and dissipation of the event, whereas the grey line indicates the date of making landfall.

### 5.5. Production recapture

We use to time series to assess to what extent ports increased their productivity after the recovery from an event and thereby recapture part of their production losses. Figure 6 shows four ports with visible evidence of production recapture after a port disruption. For the Port of Baltimore (Figure 6a) after Hurricane Sandy, the Port of Jacksonville in the aftermath of Hurricane Irma (Figure 6b) and the Port of Savannah after Hurricane Matthew (Figure 6c), the productivity reaches the highest point over the three months following a few days after becoming operational again. These three ports show clear signs of the ability to temporality ramp productivity or increase capacity after short-term disruptions. For the port of Freeport after Hurricane Dorian (Figure 6d), a longer and more sustained recovery has taken place with production recapture spread out over the end of September and early October. Freeport, an important transshipment hub in the Caribbean, most likely works closer to maximum capacity to maintain its position in the competitive transshipment industry (Notteboom et al., 2019), thereby taken longer to recapture their cargo flows. Whether or not production recapture is a feasible option and within what time range, depends very much on the duration of the disruptions, the type of cargo and the characteristics of the port with respect to its ability to ramp up production.

## Figure 6

Figure 6: Evidence of production recapture after a port disruption: (a) Port Baltimore (U.S.A.) during Hurricane Sandy, (b) Port Jacksonville (U.S.A.) during Hurricane Irma, (c) Port Savannah during Hurricane Matthew (2016) and (d) Port Freeport (Bahamas) during Hurricane Dorian. The grey shade represent the formation and dissipation of the event, whereas the grey line indicates the date of making landfall.

### 6. Discussion

The disruption scenarios used in previous modelling work, which ranged from a few days up to 1-2 months, all fall within the distribution of port disruptions in our database. Moreover our findings of port disruptions fit well with other empirical reporting on the duration of disruptions (Adam et al., 2016; Cao and Lam, 2019; Lam and Su, 2015; Trepte and Rice, 2014). Short-term disruptions (order of few days) can be interpreted as events that caused a port to close or to work under reduced operability without causing devastating structural damages to the port. Closures in the order of 30 days or more can be considered as events where natural disasters have damaged the port or hinterland infrastructure that prevents the port from operating until the damage has been repaired. This data can be used to create more realistic scenarios of downtime, including a first indication of the likelihood of observing a certain disruption severity. Moreover, the downtime related to natural disasters can be compared to the downtime due to other unforeseen events, such as electricity failure or oil spill, to improve risk management plans for port authorities. Alternatively, one can use the AIS data to assess how certain resilience indicators of ports have changed over time, and whether this can be attributed to certain measures taken (e.g. construction breakwater, increased safety protocol).

As mentioned, few studies have particularly focused on, and tested various configurations of, multiple port disruptions happening at the same time. We have showed that single port disruption due to hurricanes rarely occur, which has important implications for the potential losses (e.g. rerouting, physical damages, economic losses) and possible mitigation strategies

(e.g. cargo diversion). Therefore, modelling studies that focus on a regional to national scale should consider creating scenarios of synchronous port disruptions to test the system, in particular when certain port clusters are affected (e.g. Gulf of Mexico ports in U.S.A. for export of refineries or Australian iron ore exporting ports). Predicting the occurrence of synchronous port disruptions, using for instance joint probability functions, is also relevant for business contingency plans and national-level policies to effectively respond to and accelerate the restoration of the logistic network after such an event.

From the fragility curve, a relationship (although weak) was found between the severity of the event and the duration of the disruption. Such scaling relationship can be used by port authorities to assess how changing conditions due to anthropogenic climate change will change the probability of occurrence of certain downtime periods. Moreover, it can be used to understand what type of events create the largest downtime. For instance, port disruptions associated with Hurricane Harvey were considerably longer given the severity of the event due to the slow movement of the hurricane. Hence, the relationship as observed today may shift in case these type of hurricanes are becoming more likely in the future, as predicted (Zhang et al., 2020), with resulting negative consequences for port operations and supply-chains.

In terms of port substitution options, modelling assumptions on the diversion rate should be carefully chosen to comply with reality and not be too optimistic. Values such as the 90% diversion rate, as chosen by Rose and Wei (2013), seem high but can be justified by the specific type of port under consideration (Port Arthur and Beaumont) that have large ports such as Houston, New Orleans and Louisiana in their direct vicinity that can take over most of the tanker vessels calling at the Port Arthur and Beaumont. In general, a distinction should be made between short-term disruptions where port substitution is less likely and longer-term disruptions

where cargo is structurally diverted to competitive ports in the area. Sensitivity testing of port diversion rates, as done in Achurra-Gonzalez et al. (2019a), is a recommended approach.

More generally, we have shown how AIS data can be used as an open-source tool to monitor port disruptions over time. This opens up ways to evaluate the resilience of supply-chains, for instance, by seeing how port activity changes in trade-dependent ports or countries, whether ports with different network positions (e.g. a hub) experience different durations of downtime and recovery, and how the post-disaster dynamics vary for different port specialisations (e.g. containers versus raw materials).

## **7. Conclusion**

Ports are important nodes in the global trade network, but given their location in coastal and riverine areas, they are vulnerable to the impacts of natural disasters. Although much work has focused on modelling port disruptions, various modelling assumptions (such as the duration of disruption, the amount of port substitution, single versus multiple port disruptions and the ability to recapture cargo flows) have not yet been challenged against empirical evidence. In this paper, we have analysed 141 incidences of port disruptions due to natural disasters across 74 different ports globally. Using vessel tracking data (AIS), we provide empirical evidence of the dynamics of port functioning before, during and in the aftermath of port disruptions.

In our sample of port disruptions, median port disruptions equal six days (five days) for ports that have been closed (have not been closed) with a 95<sup>th</sup> percentile of 22.2 days (11 days). However, some incidences of longer disruptions occur, mainly associated with damage to hinterland infrastructure that prevent the port from fully functioning. Moreover, the ability to recovery from disasters also varies strongly per port and event. On top of that, we find a

relationship between the magnitude of an event and the duration of the disruption for U.S.A. ports. Most extreme events tend to close, or affect, multiple ports simultaneously, which can affect the spare capacity at potential substitution ports. Therefore, freight assignment models that simulate the distribution of freight after single port closures should consider scenarios of multiple port closures. We find little evidence of port substitution happening, most likely associated with the aforementioned simultaneous disruptions, and the short duration of the events considered that makes substitution not viable given physical (draught), infrastructure (port equipment, hinterland connection) and contractual constraints (contracts carriers and terminal operators). On the contrary, production recapture seems a more favourable adaptation option in case of relatively short disruptions (order few days), although a port's likelihood to recapture production depends on the utilisation rate of ports and ability to temporarily increase its capacity.

Future research should complement our disaster database with more disasters and disaster-related parameters that can be used to better identify what drives the duration of port disruptions and resilience of ports. Combining AIS data with other data sources (e.g. customs data) or modelling approaches (e.g. input-output modelling) can provide a more holistic view of the wider supply-chain impacts and recovery due to port disruptions, and how this varies among different types of ports and geographical locations. AIS-derived data can further complement modelling studies to better approximate model parameters and validate the results.

In conclusion, port disruption varies strongly depending upon the port and event, and the dynamics are shaped by various actors involved in minimising the potential negative consequences of port disruptions throughout the supply-chain. Empirical observations of port disruptions are vital sources of information for risk management purposes of ports and supply-

chains in order to better approximate the extent of the disruption, its drivers, and the potential resilience of the port and maritime network.

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The database of port disruptions will be available on [https://github.com/jasperverschuur/Port\\_Disruption\\_database](https://github.com/jasperverschuur/Port_Disruption_database). All python code to do the analysis can be requested from the corresponding author upon reasonable request. The AIS data for the United States and Australia is publicly available at the sources mentioned in the text, whereas the global AIS data is not publicly available.

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