nature climate change

Brief Communication

https://doi.org/10.1038/s41558-023-01754-w

Systemic risks from climate-related disruptions at ports

Received: 18 February 2023

Accepted: 29 June 2023

Jasper Verschuur [1], Elco E. Koks [1,2] & Jim W. Hall [1]

Disruptions to ports from climate extremes can have systemic impacts on global shipping, trade and supply chains. By combining estimated climatic-related port downtime at 1,320 ports with a global model of transport flows, we pinpoint systemic risks to global maritime transport, trade and supply-chain networks. We estimate a total of US\$81 billion of global trade and at least US\$122 billion of economic activity being at-risk on average annually.

Ports handle around 80% of the volume of global trade[1]. However, many ports are exposed to operational disruptions from extreme weather events, causing costly downtime[2]. The most extreme events can cause extensive physical damage and render ports inoperable for longer periods of time. For instance, operations at the ports of Shanghai and Ningbo are disrupted for 5 to 6 days each year on average because of extreme wind conditions[3]. In the aftermath of Hurricane Katrina (2005), the port of New Orleans was shut for almost 4 months[4]. Such climatic shocks to ports can have systemic impacts, including knock-on effects to other ports and across supply chains. For example, ref. 5 revealed that every dollar of trade that is disrupted at the port of Los Angeles-Long Beach could have a multiplier effect of 2.9 through domestic supply chains.

In ref. 6, we quantified the annual expected downtime days per year (downtime risk) associated with operational disruptions (due to weather extremes), as well as the reconstruction time associated with physical damage to ports from climate extremes (cyclone wind and coastal, fluvial and pluvial flooding), for the 1,320 most critical ports globally. Together, climate-related disruptions were found to have a downtime risk of 1.4 days across ports globally but >5 days for 5% of ports. Here, we combine these estimates of port downtime risk with a dataset of (1) ship movements between ports, (2) maritime transport freight flows and (3) dependencies between ports and global supply chains[1]. This allows us to quantify the systemic exposure of transport, trade and supply chains to port disruptions (Methods). This information is essential to identify cross-border vulnerabilities, as well as preparing ports, firms and countries for port-related shocks, which are not adequately quantified using best practice tools for risk assessment, for example in the insurance sector.

We start by extending our previous analysis of port downtime risk[6] to quantify the (first-order) knock-on delays at the ports of trading partners. Specifically, we calculate the delays in ship arrivals at a port because of disruptions at a port where the goods are loaded (Methods). Others[7] found that when a European port is subject to coastal flooding, other European ports are most prone to knock-on disruptions but so are ports in North America, northern Africa and the Middle East. Extended Data Fig. 1a reproduces our previous results for average climate-related downtime, whilst Extended Data Fig. 1b shows how these impacts propagate to other ports through port-to-port shipping delays. Both of these versions of disruption are high in cyclone-prone regions, making the two correlated (Spearman's rank correlation = 0.50), as ports tend to be connected to ports in their geographic proximity. Moreover, ports having a lower number of trading partners (Supplementary Fig. 1) tend to have higher port-to-port downtime risk because they do not benefit from diversification of partners (Supplementary Methods). In relative terms, the potentials for port-to-port disruptions are particularly high in Southern Australia, the Middle East, Western Africa, South America, the Western United States and parts of Northern Europe (Extended Data Fig. 2). The average disruption at ports in these regions is relatively low, but the potential for knock-on effects from disruptions at transport dependent ports is relatively high (>80% of total downtime risk). In fact, these knock-on port-to-port disruptions are found to be larger than direct downtime risk for around two-thirds of ports.

Port disruptions can have wider impacts for international trade and economic activity. For instance, in 2017, the shutdown of Australian coal exporting ports as a result of Cyclone Debbie led to supply shortages in Indian and Chinese steel mills[8]. To capture such systemic risks, we start by calculating the amount of each country's maritime imports and exports at-risk due to port downtime and quantify domestic (domestic ports used for imports/exports) and cross-border downtime risk (foreign ports used for transhipments and import/exports at trading partners). In value terms, out of the 207 countries considered, domestic port downtime risk dominates for 30 (26) countries for their imports (exports), while for the remaining countries the

---

[1]Oxford Programme for Sustainable Infrastructure Systems (OPSIS), Environmental Change Institute, University of Oxford, Oxford, UK. [2]Institute for Environmental Studies, Vrije Universiteit Amsterdam, Amsterdam, the Netherlands. e-mail: jasper.verschuur@keble.ox.ac.uk

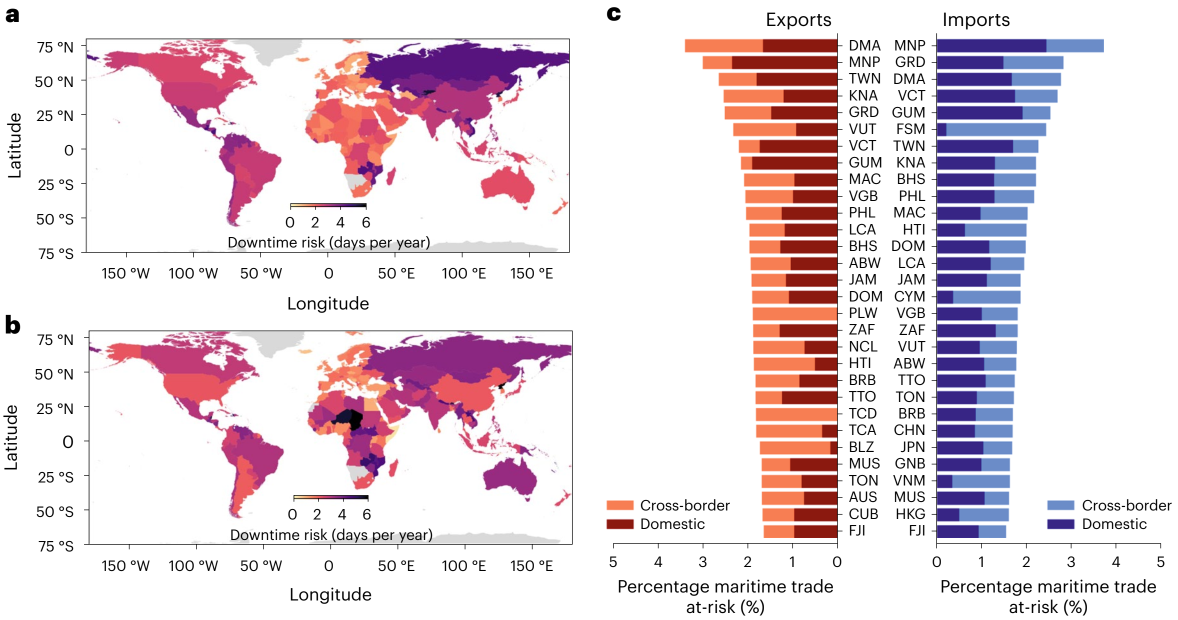


Fig. 1 | Maritime trade at-risk. a, Cross-border downtime risk for import flows of countries. **b**, Same as **a** but for exports. **c**, Top 30 countries in terms of maritime trade at-risk (in value terms), including a breakdown between domestic and cross-border downtime risk. Basemaps in **a**,**b** from GADM (gadm.org). The country codes refer to country ISO-alpha3 code.

cross-border risk dominates. Out of the total maritime trade at-risk, which equals US$81 billion per year (~117 billion tonnes), 63% (58%) of imports (exports) is cross-border risk, although with sectoral differences (Supplementary Tables 1 and 2).

Countries with large import cross-border risks include small Pacific islands (Micronesia and Tonga) and countries in Central Asia (Kyrgyzstan, Kazakhstan and Uzbekistan) and Central America (Nicaragua and Guatemala) (Fig. 1a). In terms of exports, several landlocked countries have high cross-border risks, including Chad, Malawi, Andorra and Bhutan (Fig. 1b). Figure 1c shows the top 30 countries in terms of total relative maritime trade at-risk in value terms (Supplementary Fig. 2 shows the same in volume terms). At the top of the list are several small island developing states (SIDS), including Northern Mariana Islands (MNP), Grenada (GRN), Dominica (DMA), Saint Vincent and the Grenadines (VCT) and Micronesia (FSM). Many of the SIDS have a high domestic contribution to trade at-risk, while also depending on a relatively few hazard-prone partner ports, including transhipment ports, for their trade, contributing to elevated cross-border risk. Still, within the top 30, there are also some of the world's large economies (China, Japan, Australia, South Africa, Vietnam and the Philippines).

The impact of port disruptions may propagate (first and higher order effects) in unexpected ways because of complex dependencies on specific supply chains that are routed through ports. We therefore quantify how much of the activity of each economic sector (industry output or final consumption) depends directly (firms directly relying on traded goods through ports) or indirectly (firms relying on other firms that traded goods through ports, either first-order or higher order suppliers) on trade flows through each port (11 sectors, 184 countries, 1,320 ports; Methods). Globally, an average of US$95.8 billion of industry output and US$26.3 billion of consumption is exposed every year to port disruptions, of which 64% and 60% are cross-border risk, respectively (Supplementary Table 3 shows sectoral differences). This is only considering forward (or downstream) supply-chain dependencies, while backward (or upstream) dependencies could put another US$173 billion of industry output at-risk every year (Supplementary Fig. 3).

Some countries have a large share of their industry output and consumption at-risk every year (Fig. 2a,b). In terms of industry output, countries in Southern Africa, Southeast Asia and Central America have the largest percentage of industry output at-risk from port disruptions. Countries whose final consumption is most exposed to port disruption are more dispersed. The top ten most at-risk countries include Taiwan, Macau, Hong Kong and some SIDS, having more than 26% of their final consumption dependent on imports via critical ports and on average more than 0.5% of all final consumption expected to be disrupted each year.

The aggregate risk numbers hide some specific supply chains that are at-risk from port downtime, both in terms of consumption and industry output (Fig. 2c). Some of the most at-risk supply chains are wood and paper manufacturing in Taiwan and South Korea, mining and quarrying in France and petroleum, chemical and non-metallic mineral products in Macau and Aruba. In terms of industry output, the most at-risk supply chains of >US$1 billion output are the mining and quarrying industry in Hong Kong, textiles and wearing apparel in Mauritius, electrical and machinery in the Philippines and transport equipment in South Africa and the Dominican Republic.

Our results highlight the scale of global trade and economic activity exposed to port disruptions and pinpoint the systemic vulnerabilities within maritime transport, trade and supply-chain networks. The results highlight that many SIDS are very susceptible to systemic risks given high direct exposure and cross-border vulnerabilities due to limited trade and transport diversification. Whilst all our results are presented in terms of annual averages, the impacts in any given year may be much greater or lower. In addition, risks estimated are influenced by, among others, specific extreme events affecting multiple ports simultaneously[4] and the level of resilience in the interconnected systems.

Countries and firms that are highly dependent on ports with a large risk of climate-related disruptions should consider the resilience options at their disposal, which fall into four categories: (1) enhancing resilience of ports to climate-related disruptions, (2) reducing dependence on maritime trade by enhancing domestic production, (3) trade or transport diversification and (4) increasing inventories and stocks to make supply chains less vulnerable to port-related disruptions. Our analysis has revealed which ports each port, country and supply-chain critically depends upon

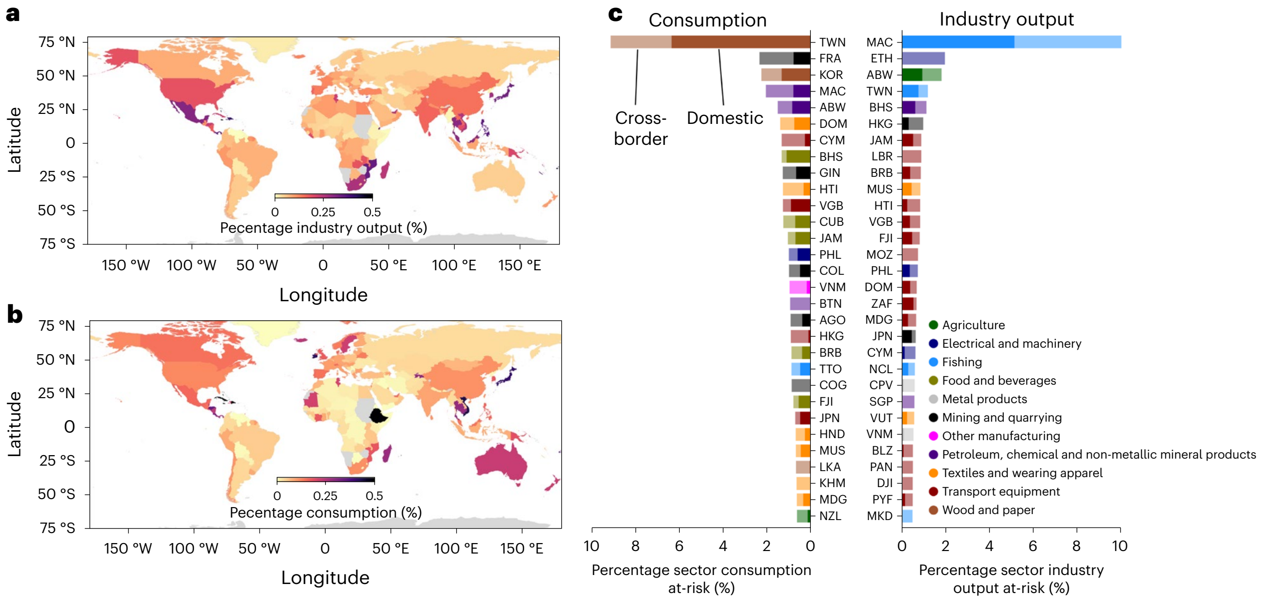


Fig. 2 | Supply chains exposed to port disruptions. a, The fraction of industry output exposed annually to systemic port failures. **b**, Same as **a** but for consumption. **c**, The top 30 most at-risk supply chains per country, including the contribution of domestic and cross-border systemic risks to the risk. Only forward dependencies are considered in here. Basemaps in **a**,**b** from GADM (gadm.org).

(see Supplementary Figs. 3–6 for examples), providing crucial information for policy prioritization. First, countries may wish to take regulatory steps to enhance the resilience of critical domestic ports, whilst using our data to scrutinize the reliability of foreign ports with which they trade. Second, our analysis illustrates the extent to which trade relationships are diversified across ports and allows identifying alternative commodity exporting countries where port disruptions are less frequent or strategies to improve the resilience of the national port system, for instance by building in spare capacity (for example, as done in Japan after the 2011 Tōhoku earthquake and tsunami)[9]. Where this is not feasible, additional steps, such as increasing back-up inventories or promoting domestic production may be justified[10]. Finally, our analysis can be further supplemented with projections of future changes in port downtime due to climate change, allowing countries and firms to build resilience against future systemic disruptions.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-023-01754-w.

References

1. Verschuur, J., Koks, E. E. & Hall, J. W. Ports' criticality in international trade and global supply-chains. *Nat. Commun.* **13**, 4351 (2022).
2. Esteban, M., Webersik, C. & Shibayama, T. Methodology for the estimation of the increase in time loss due to future increase in tropical cyclone intensity in Japan. *Clim. Change* **102**, 555–578 (2010).
3. Zhang, Y. & Lam, J. S. L. Estimating the economic losses of port disruption due to extreme wind events. *Ocean Coast. Manag.* **116**, 300–310 (2015).
4. Verschuur, J., Koks, E. E. & Hall, J. W. Port disruptions due to natural disasters: insights into port and logistics resilience. *Transp. Res. D* **85**, 102393 (2020).
5. Wei, D., Chen, Z. & Rose, A. Evaluating the role of resilience in reducing economic losses from disasters: a multi-regional analysis of a seaport disruption. *Pap. Reg. Sci.* **99**, 1691–1722 (2020).
6. Verschuur, J., Koks, E. E., Li, S. & Hall, J. W. Multi-hazard risk to global port infrastructure and resulting trade and logistics losses. *Commun. Earth Environ.* **4**, 5 (2023).
7. Christodoulou, A., Christidis, P. & Demirel, H. Sea-level rise in ports: a wider focus on impacts. *Mar. Econ. Logist.* **21**, 482–496 (2019).
8. Lenzen, M. et al. Economic damage and spillovers from a tropical cyclone. *Nat. Hazards Earth Syst. Sci.* **19**, 137–151 (2019).
9. Akakura, Y., Ono, K., Watanabe, T. & Kawamura, H. Estimation of alternative ports for container transport after large-scale disasters—estimation method and application to Port-BCPs-. *J. Integr. Disaster Risk Manag.* **5**, 135–152 (2015).
10. Lewis, B. M., Erera, A. L., Nowak, M. A. & Chelsea, C. W. Managing inventory in global supply chains facing port-of-entry disruption rsks. *Transp. Sci.* **47**, 162–180 (2013).

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Methods

Port downtime at the port-level (1,320 ports) is associated with the annual exceedance of various operational thresholds and natural disaster impacts. Operational disruptions include extreme wind, temperature, waves and overtopping, which shut down a port above some set thresholds. The downtime associated natural disaster impacts, including earthquakes, cyclone and coastal, pluvial and fluvial flooding, cover the time needed to restore damaged infrastructure, resulting in downtime for the port. Details of the methodology are included in ref. 6 and described in the Supplementary Methods.

The systemic risk analysis of the maritime transport network is based on a satellite-derived dataset of vessel movements for 2019 and 2020, from which a port-to-port transport network was constructed, including the loaded capacity (payload times carrying capacity of the vessel) of vessels on a given route. Details of the dataset are described in ref. 1 and the Supplementary Methods. The port-to-port downtime risk (PtPDR) for any given port (p) depends on the loaded capacity (LC) between the number (n) of origin ports (o) and the port of interest and the downtime risk (DR) at the origin port:

$$\mathrm{PtPDR}_p = \sum_{o=1}^{n} \frac{\mathrm{DR_o} \times \mathrm{LC}_{o,p}}{\mathrm{LC_p}}$$

This only includes forward network effects and not any backward network effects of downtime at destination ports (that is, reduced traffic if destination ports are shut).

To determine import and export dependencies between countries and ports, we use the model output of the OxMarTrans global maritime transport model, which include for the year 2015 the simulated maritime routes of all maritime bilateral trade flows. Using this dataset, for both flow (f) directions (import and export), we can determine the systemic risk associated with port downtime. The trade at-risk (TaR) is determined by the number (n) of ports (p) a country (c) depends on, the fraction of the country's maritime trade (MT) flow through p and the downtime at these ports:

$$\mathrm{TaR}_{f,c} = \frac{\mathrm{MT}_{f,c}}{365} \sum_{p=1}^{n} \frac{\mathrm{DR_p} \times \mathrm{MT}_{f,c,p}}{\mathrm{MT}_{f,c}}$$

The TaR can be subdivided between the fraction that is domestic, which includes part of the TaR associated with ports located in the country of interest and the share associated with ports in foreign countries.

To evaluate the economic activity at-risk because of port disruptions, we use data from ref. 1, which linked the downscaled port-to-port trade network to the EORA multiregional input–output tables (MRIO). By extracting ports from the (downscaled) MRIO tables, the industry output and consumption in any country directly or indirectly linked to this port could be evaluated (the Supplementary Methods give a detailed description). The economic activity at-risk (EAaR) for the two metrics considered (m, industry output or consumption) is associated with the economic activity (EA) of country (c) linked to a port and the downtime at that port:

$$\mathrm{EAaR}_{m,c} = \frac{\mathrm{EA}_{m,c}}{365} \sum_{p=1}^{n} \frac{\mathrm{DR_p} \times \mathrm{EA}_{m,c,p}}{\mathrm{EA}_{m,c}}$$

This can be done on an aggregated basis or on a country-sector basis. In the main text, the economic activity linked to a port is only associated with the forward supply-chain dependencies (supply shocks due to trade bottlenecks) and not any backward supply-chain dependencies (demand shocks due to trade bottlenecks), which are shown for reference in Supplementary Fig. 3.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

This research relies on publicly available data which are referenced. The data required to reproduce the analysis can be found in a Mendeley Data repository[11].

Code availability

The code needed to analyse the data and reproduce the figures is provided in a Mendeley Data repository[11].

References

11. Verschuur, J. Systemic risk ports datasets. *Mendeley Data*. https://data.mendeley.com/datasets/nddrc4wkcc/1 (2023).

Acknowledgements

This research has been conducted as part of the Oxford Martin School Programme on Systemic Resilience. J.V. acknowledges funding from the Engineering and Physical Sciences Research Council (EPSRC) under grant no. EP/W524311/1. E.E.K is supported by the Netherlands Organization for Scientific Research NWO (grant no. VI.Veni.194.033). We would like to thank S. Arslanalp, R. Koepke, A. Sozzi and P. Kamali for constructive comments that have helped to improve the paper.

Author contributions

J.V. conceptualized the research, performed the analysis and led the writing of the manuscript. E.E.K. and J.W.H. conceptualized the research, provided input and helped with writing the manuscript.

Competing interests

The authors declare no competing interests.

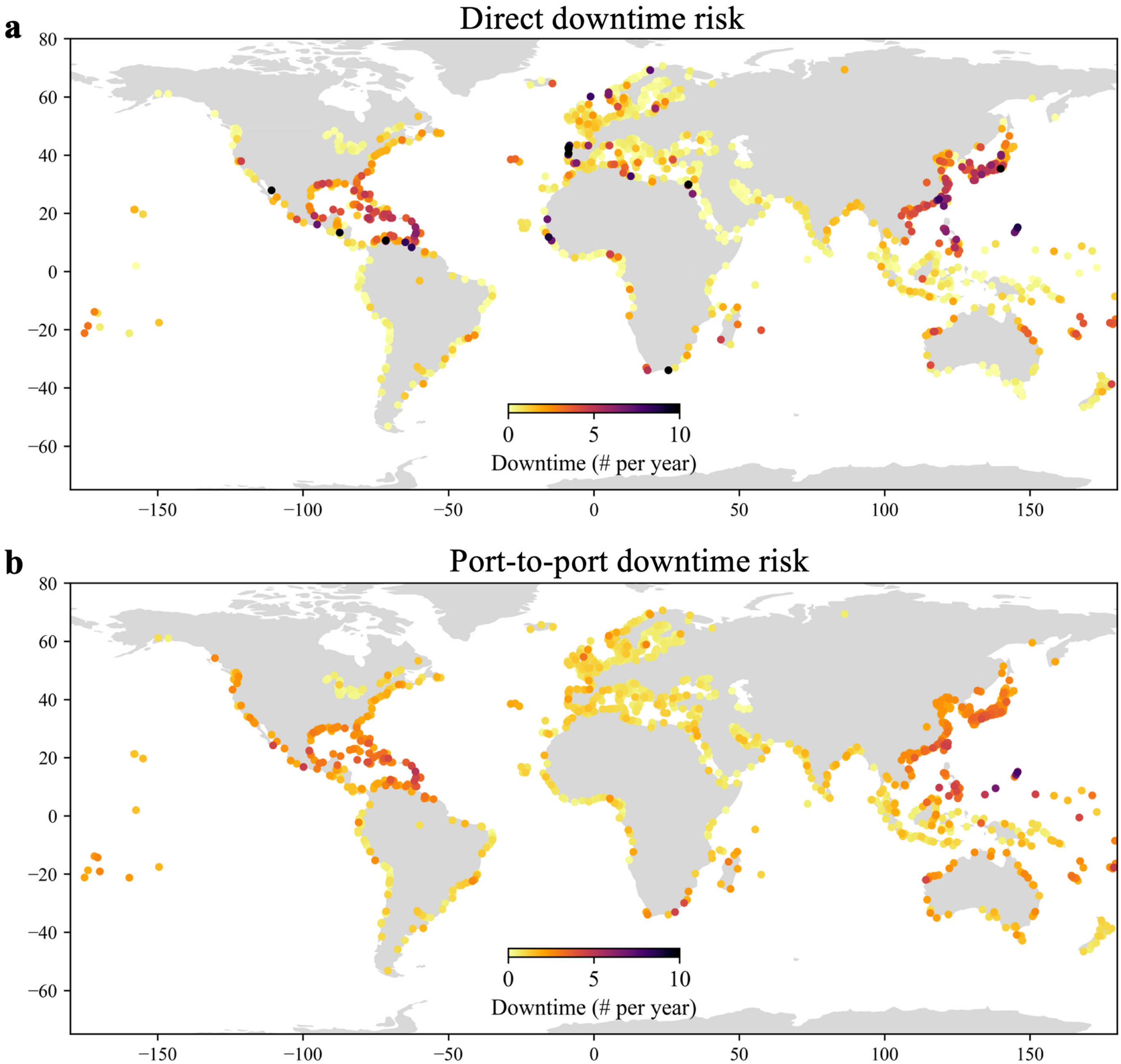
Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41558-023-01754-w.

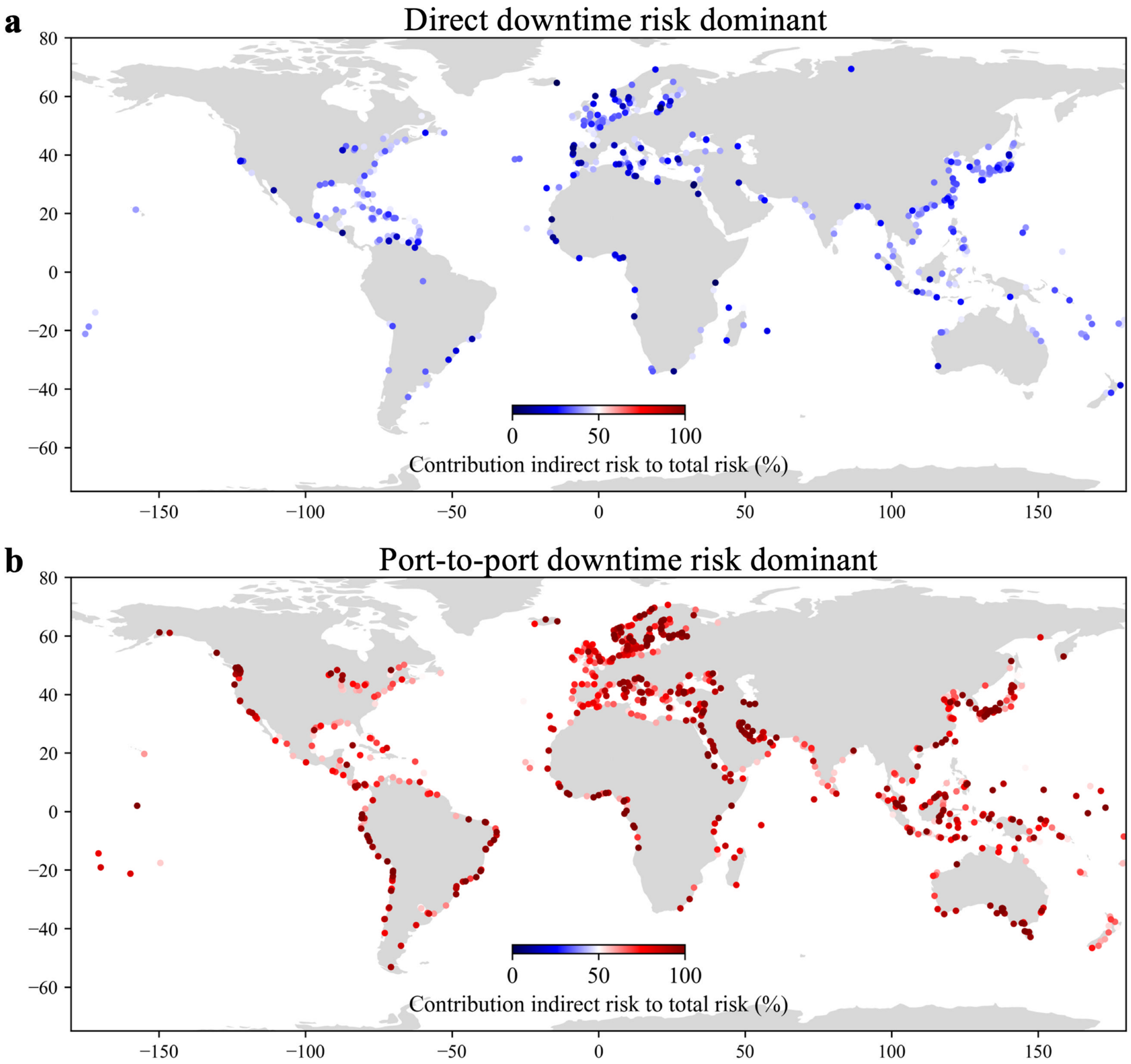
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41558-023-01754-w.

Correspondence and requests for materials should be addressed to Jasper Verschuur.

Peer review information *Nature Climate Change* thanks Austin Becker, Yang Zaili and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.



Extended Data Fig. 1 | Systemic risks of maritime transport networks. (**a**) The direct downtime risk (annual expected days per year) at the port-level. (**b**) The port-to-port downtime risk, showing the number of days of expected annual downtime or delays because of downtime at the ports that are visited by vessels before these vessel visit the port of interest. The base map is derived from Global Administrative Areas (GADM) dataset (available at gadm.org).



Extended Data Fig. 2 | Relative contribution of direct and port-to-port downtime. (**a**) The ports where the direct downtime risk is the dominant risk factor in the total downtime risk (direct + port-to-port). (**b**) Same as (a) but with the port-to-port downtime being the dominant risk contributor. The base map is derived from Global Administrative Areas (GADM) dataset (available at gadm.org).

nature portfolio

Corresponding author(s): Jasper Verschuur

Last updated by author(s): Jun 26, 2023

Reporting Summary

Nature Portfolio wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Portfolio policies, see our Editorial Policies and the Editorial Policy Checklist.

Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a	Confirmed	
☐	☒	The exact sample size (*n*) for each experimental group/condition, given as a discrete number and unit of measurement
☒	☐	A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☒	☐	The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
☒	☐	A description of all covariates tested
☒	☐	A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
☒	☐	A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☒	☐	For null hypothesis testing, the test statistic (e.g. *F*, *t*, *r*) with confidence intervals, effect sizes, degrees of freedom and *P* value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☒	☐	Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	All data was collected from previously published data sources, which are mentioned in the text.
Data analysis	Python coding was used to analyse the data and generate new output.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

While all input code is already publicly available at the sources mentioned in the manuscript, all final data to reproduce the results+code is made available in this paper. A Zenodo link is added.

Human research participants

Policy information about studies involving human research participants and Sex and Gender in Research.

Reporting on sex and gender	*Use the terms sex (biological attribute) and gender (shaped by social and cultural circumstances) carefully in order to avoid confusing both terms. Indicate if findings apply to only one sex or gender; describe whether sex and gender were considered in study design whether sex and/or gender was determined based on self-reporting or assigned and methods used. Provide in the source data disaggregated sex and gender data where this information has been collected, and consent has been obtained for sharing of individual-level data; provide overall numbers in this Reporting Summary. Please state if this information has not been collected. Report sex- and gender-based analyses where performed, justify reasons for lack of sex- and gender-based analysis.*
Population characteristics	*Describe the covariate-relevant population characteristics of the human research participants (e.g. age, genotypic information, past and current diagnosis and treatment categories). If you filled out the behavioural & social sciences study design questions and have nothing to add here, write "See above."*
Recruitment	*Describe how participants were recruited. Outline any potential self-selection bias or other biases that may be present and how these are likely to impact results.*
Ethics oversight	*Identify the organization(s) that approved the study protocol.*

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☒ Behavioural & social sciences ☐ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	Quantitative data was used on port-level information, maritime transport networks, and port supply-chain connections.
Research sample	Sample of ports and countries.
Sampling strategy	NA
Data collection	NA
Timing	NA
Data exclusions	NA
Non-participation	NA
Randomization	NA

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging