CESifo WORKING PAPERS

11077
2024

April 2024

# Dangerous Waters: The Economic Toll of Piracy on Maritime Shipping

*Renato Molina, Juan Carlos Villaseñor-Derbez, Gavin McDonald, Grant McDermott*

CESifo

**Impressum:**

CESifo Working Papers
ISSN 2364-1428 (electronic version)
Publisher and distributor: Munich Society for the Promotion of Economic Research - CESifo GmbH
The international platform of Ludwigs-Maximilians University's Center for Economic Studies and the ifo Institute
Poschingerstr. 5, 81679 Munich, Germany
Telephone +49 (0)89 2180-2740, Telefax +49 (0)89 2180-17845, email office@cesifo.de
Editor: Clemens Fuest
https://www.cesifo.org/en/wp
An electronic version of the paper may be downloaded
· from the SSRN website: www.SSRN.com
· from the RePEc website: www.RePEc.org
· from the CESifo website: https://www.cesifo.org/en/wp

CESifo *Working Paper No. 11077*

# Dangerous Waters: The Economic Toll of Piracy on Maritime Shipping


## Abstract

Maritime transport has been historically susceptible to piracy. While broad assessments suggest the impact of modern piracy causes large economic losses, the literature lacks quantification of the magnitude of the costs and the behavioral responses that underpin them. Here, we combine theory and a unique geospatial dataset combining more than 25 million shipping voyages and thousands of pirate encounters across the globe to find that pirate encounters lead to significant and costly avoidance measures. Shippers modify their path along a route to avoid locations with known pirate encounters. This increases voyage distance and duration, which lead to significant increases in fuel and labor costs estimated to be over US$1.5 billion/year. Additionally, emission of CO2, NOx, and SOx due to increased fuel consumption results in environmental damages valued at US$5.1 billion per year. Together, our results provide the first global estimates linking the presence of pirates to individual behaviour and aggregate transportation cost, as well as its environmental impact, with major implications for the shipping industry and maritime security at a global scale.


JEL-Codes: Q500, F500, R400.

Keywords: piracy, shipping, avoidance.

*Renato Molina**
*Department of Environmental Science and Policy & Department of Economics*
*University of Miami / FL / USA*
*renato.molina@miami.edu*

*Juan Carlos Villaseñor-Derbez*
*Oceans Department, Doerr School of Sustainability, Stanford University*
*Stanford / CA / USA*
*juancvd@stanford.edu*

*Gavin McDonald*
*Marine Science Institute, Bren School of Environmental Science & Management, Environmental Markets Lab, University of California, Santa Barbara / USA*
*gmcdonald@bren.ucsb.edu*

*Grant McDermott*
*Department of Economics*
*University of Oregon*
*Eugene / OR / USA*
*gmcd@amazon.com*

*corresponding author

Preliminary work. All errors are our own.

> "As by means of water-carriage, a more extensive market is opened to every sort of industry than what land-carriage alone can afford it"
>
> *–Adam Smith, the Wealth of Nations*

# Introduction

As it has done for centuries, maritime transport provides the main conduit for the world's trading activities. The oceans today carry more than 70% of globally traded goods by value and more than 80% by volume (*1*). However, the industry remains susceptible to the threat of piracy. Piracy grabbed worldwide headlines during the late 2000s, after a sharp increase in violent encounters off the coast of Somalia. A recurring spate of attacks since then have disrupted key shipping routes worldwide, most recently the Gulf of Aden. Despite these ongoing and growing concerns, only limited efforts have been devoted to assess the behavioral underpinnings of modern-day piracy and its underlying mechanisms, and ultimately its economic costs and environmental impacts.

Historically coinciding with the earliest records of trade, the transportation of goods and the difficulty of enforcement has always offered an opportunity for pirates to predate on commerce routes (*2*). Maritime routes are particularly susceptible because they offer unique opportunities for ambush and escape. In addition, they often lack clear jurisdictions, which complicates capture and prosecution.[1] Beyond folklore and their occasionally romanticized origins, pirates remain a relevant problem today. Official global records point to more than 2,200 pirate attacks between 2013 and 2021, with 232 taking place in 2021 alone. Previous efforts to quantify the cost of this problem suggest annual losses in excess of US$20 billion/year (*6, 7*), although the mechanics behind these costs are not always clearly specified (see Supplementary Text S2.1 for additional background on global piracy and an associated literature review). Something that is clear, however, is that most encounters concentrate in busy trade channels, where pirates target high-value vessels for robbery or capture-to-ransom (*8*). In this paper, we focus on three "hotspots"—the Gulf of Aden, the Gulf of Guinea, and the Malacca Strait in Southeast Asia—where piracy attacks have been particularly acute (Figure 1).

When deterrence or other enforcement options are too costly, then adaptation remains the best course of action for individual vessels facing a piracy threat. How might shippers respond to information of pirate presence along their route? Consider an example of change in shipping behavior following news of a pirate encounter in the Makassar Strait, Indonesia. On June 19, 2013 a Hong Kong-flagged bulk carrier was boarded by three to five robbers. Information on the attack was broadcast to other vessels in the region via the Anti-shipping Activity Messages (ASAM) communication network, allowing them to modify their routes.[2] Per Figure 2, there

[1] Historians point out that piracy often follows a well defined cycle involving a group of individuals from impoverished coastal areas that would band to predate on small-scale, poorly enforced shipments. These groups would then transition to a state of adjustment, for which "competition" dictates profitability and thereby their longevity in the piracy business (*2, 3*). Most of these observations are based on pirates from previous centuries, but the resemblance with modern pirates is evident. See Bahadur (*4*) and Bueger (*5*) for a detailed account of the cycle and organizational mechanisms in the case of the pirates of Somalia, which resembles very closely the documented paths for earlier pirates.

[2] The Worldwide Threat to Shipping Report reads: *On 19 June, the anchored Hong Kong-flagged bulk carrier OCEAN GARNET was boarded at 01-11S 117-12E, at the Muara Jawa Anchorage, Samarinda. Deck watch keepers onboard the anchored bulk carrier noticed three to five robbers with long knives near the forecastle store. They raised the alarm and retreated into the accommodation. On hearing the alarm, the robbers escaped in their waiting boat. Upon investigation, it was discovered that ship's stores had been stolen. Port control was informed.* The entry is available at `https://t.ly/bsNk7` [Last visited on 04/12/24]

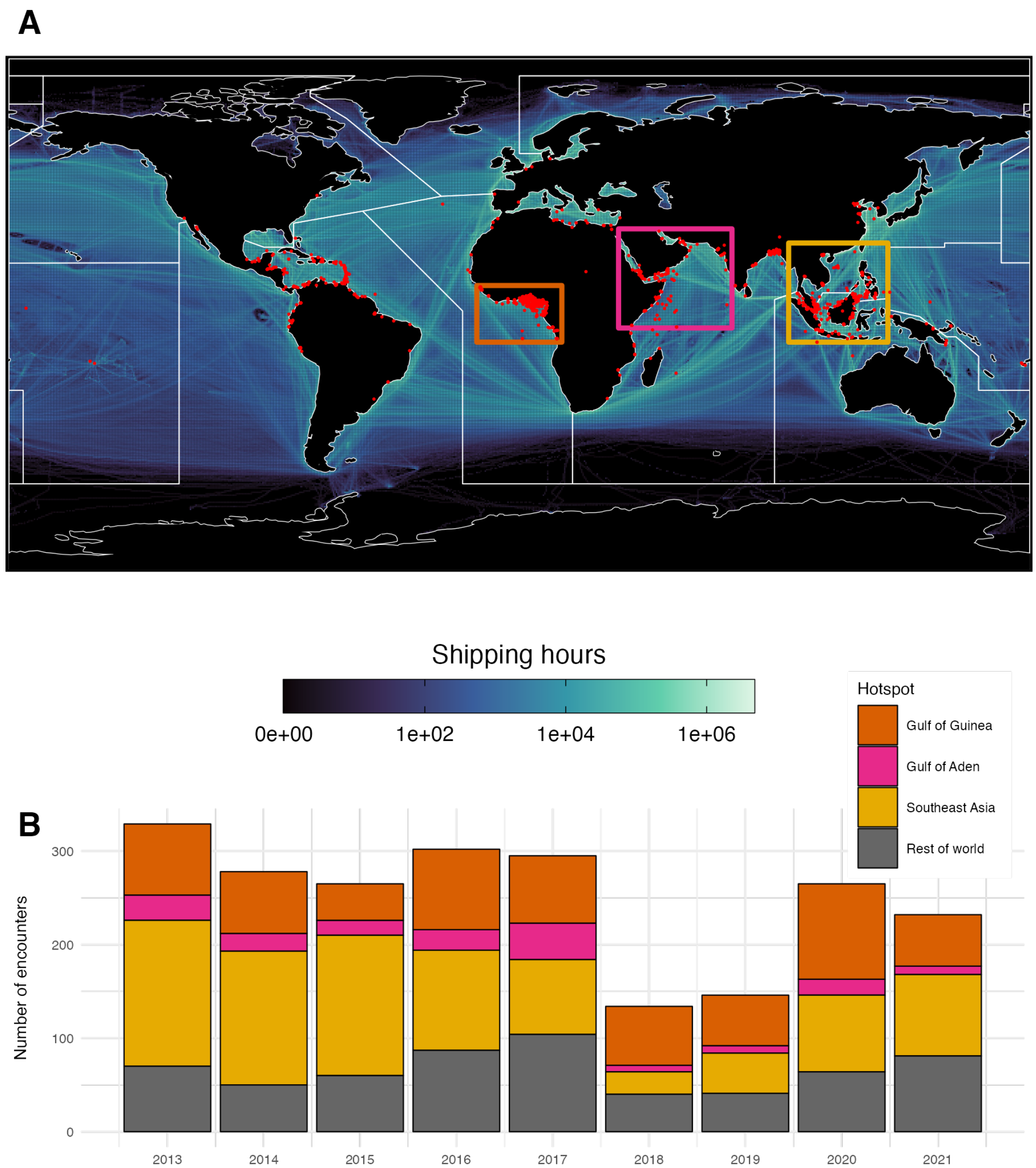


Fig 1: **A global view of modern-day maritime transport and piracy.** Panel **A** shows the spatial overlap of shipping activity and anti-shipping encounters from 2013 to 2021. Note that data are $\log_{10}$-transformed for visualization purposes and represented using a 0.5°x0.5° grid in geographic coordinates, with the fill color of each pixel represents the total shipping transit time from 2013-2021 (hr). Pirate encounters are shown as red points. The colored overlay bounding rectangles correspond to the three main piracy hotspots, namely: 1) Gulf of Guinea, 2) Gulf of Aden, and 3) Southeast Asia. The bounding boxes are defined by an empirical density-based clustering approach (see Materials and Methods). Outlines of the major Anti-shipping Activity Messages (ASAM) regions are shown as white lines. Panel **B** shows a number of pirate encounters across hotspots and the rest of the world from 2013 to 2021.

is a near-total avoidance of the attack area following the ASAM broadcast; the previous cluster of shipping activity near the Muara Jawa Anchorage all but disappeared and was replaced by a new one further South (Panel **A**). The number of voyages in the affected area also dropped from an average of 48 per day to just 3 per day (Panel **B**).

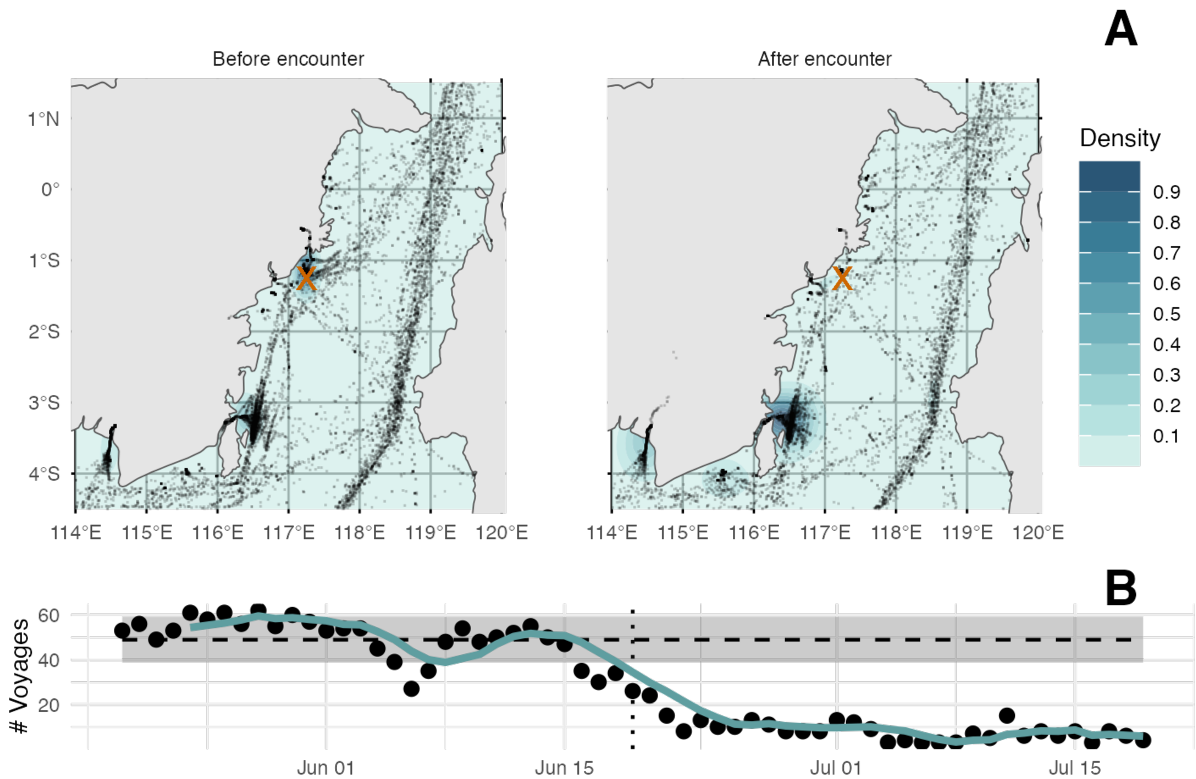


Fig 2: **Example of change in shipping vessel transit following an encounter with pirates on June 19, 2013 off the coast of Indonesia.** Panel **A** shows maps of the Muara Jawa Anchorage before (left) and after (right) the encounter. "**X**" marks the spot of the encounter. Points show all vessel positions recorded one week before or after the attack, and background colors show a 2-dimensional kernel estimate of vessel density. Panel **B** shows a time series of daily number of voyages crossing the affected grid cell (at 117E, 1.5S, indicated with an orange "X" in A). Each point shows the total daily number of voyages, and the blue line shows the mean number in a 5-day rolling window. The horizontal dashed line and shaded area show the baseline number of daily voyages (mean ± standard-deviation) before the attack.

The contributions of this paper are threefold. First, we develop a formal theoretical model that explains the optimal avoidance behaviour of individual vessels following incidents like the

2013 Makassar Strait attack. Second, we test our model predictions on a rich dataset that combines detailed voyage information with piracy events. Third, we determine the aggregate costs that can be attributed to recent pirate attacks and the knock-on effects on vessel behavior and global shipping. We achieve these goals by merging theoretical insights with data on shipping voyages and pirate encounters to credibly assess the causal effect of piracy on the shipping industry. We formalize the decision-making process of sea captains based on warning reports, and compile a unique geospatial dataset to test those insights. The dataset includes high resolution spatio-temporal information on pirate encounters from the US National Geospatial Intelligence Agency ASAM database,[3] as well as individual vessel tracks of all known cargo, tanker, and refrigerated vessels that use Automatic Identification System (AIS) due to (*9*). Our empirical results show that a pirate encounter along a shipping route causes vessels to extend their trips by an average of 28 ($\pm$45) kilometers in the subsequent months, as they engage in avoidance behavior. When aggregated at the industry level, and taking into account prevailing fuel and labour costs, these adjustments suggest additional transportation costs of US$1.7 billion as of 2021. Moreover, we estimate that surplus emission of air pollutants ($CO_2$, $NO_x$, and $SO_x$) due to increased fuel usage results in an additional cost of US$5.1 billion in environmental damages. These estimates highlight a previously undocumented loss in terms of operational cost, but also in terms of global fuel consumption and the associated added emissions of both greenhouse gasses and local pollutants.

[3]Information reported as The Worldwide Threats to Shipping Report by Office of Naval Intelligence. Recent reports are available at [Last checked 04/12/24]

# Results

## A model of pirates and shippers

To guide our empirical analysis, we propose a theoretical framework that characterizes rational avoidance behavior under the threat of piracy. The model details, derivations and proofs are provided in Supplementary Text S2.2. Summarizing, the model yields three high-level and testable predictions. First, shippers will never ignore the threat of piracy. Second, they will avoid pirates following an assessment of the relative costs of partial and total avoidance, which in turn is based on their potential shipping route(s) and their beliefs about the pirates' capabilities. Third, shippers will incorporate past pirate encounters to inform their avoidance decisions.

With these testable predictions in hand, and to avoid ambiguity, it will prove helpful to define precisely several terms that we use in our empirical analysis. A *route* is a port-to-port combination, a *voyage* is a trip made along a route, and a *path* is the sequence of coordinates chosen by the vessel to travel a route.

## Empirical evidence of behavioral adjustments by shippers

Our theory model predicts vessel captains will adjust their paths along a route if they receive new information about the risk of a piracy attack. Just as we saw in Figure 2, this implies that a piracy-afflicted region will receive fewer transits, in expectation, after an attack. We evaluate this prediction empirically by testing for systematic changes in daily transit activity within all 0.5°x0.5° grid cells that experienced reported pirate activity between 2013 and 2021 (see Supplementary Text S2.4 for detailed summary statistics). The results are displayed in Table 1. Summarizing, we find that an additional pirate encounter within the preceding 90 days generally leads to a significant reduction in vessel activity within the affected grid cell. This finding holds across a variety of transit measures across all three of our designated hotspot regions. For example, a piracy event in the Gulf of Aden correlates to 26.5 fewer kilometers traveled through each grid cell within the region during the subsequent three months, as well as 0.7 fewer hours of travel time, and approximately 0.6 fewer voyages and vessels passing through. The equivalent impacts are less pronounced in magnitude for the Gulf of Guinea and southeast Asia. However, the negative coefficients remain statistically significant for these other hotspots too. The picture is murkier when zooming up to the global level and possibly reflects a reallocation (spillover) effect between regions and routes for which it is difficult to control. Regardless, and while we do not observe statistically significant coefficients for the global sample, these results are robust to a variety of specification and data checks (see Supplementary Text S2.7.1).

Moving beyond grid-level impacts, how do these adjustments manifest at the level of individual voyages? Bearing in mind the empirical challenges described in Supplementary Text S2.3, we test for changes in core voyage characteristics in Table 2. Summarizing, we observe that a piracy encounter along a vessel's likely voyage path leads to longer average travel distances and prolonged travel times (summary statistics are available in the Supplementary Text S2.4). The global estimate suggests that an additional pirate encounter within the preceding three months translates to respective increases of 27.83 km in distance and 2.25 hrs in travel time along a given route. We find consistent results when restricting the sample to voyages that traverse hotspots, although the effect is much more pronounced for voyages passing through the Gulf of Aden (210.9 km and 10.44 hr, respectively). Supplementary Text S2.6 includes an auxiliary analysis using instrumental variables that corroborates the results presented here.

In contrast to the economically meaningfully impacts on travel distance and time, the effect on speed is minimal. We interpret these results as an indication that adjustments to speed are a less cost-effective avoidance measure, or technically infeasible due to engine and vessel limitations. This behavior is consistent with optimal avoidance since the cost of each additional unit of distance traveled grows linearly, while the cost per each additional unit of cruising speed grows exponentially (*10*). These results are robust to specification, subsamsampling, and data

Table 1: Effect of Piracy on Grid-level Ship Transit.

| | Global | G. of Aden | G. of Guinea | S.E. Asia |
|---|---|---|---|---|
| *Panel (A): Total Distance (km)* | | | | |
| Encounters (3 mo) | -4.90 | -26.50* | -4.58*** | -3.69 |
| | (11.53) | (13.78) | (1.32) | (21.18) |
| Observations | 1,939,330 | 305,691 | 440,458 | 489,763 |
| *Panel (B): Occupancy (hr)* | | | | |
| Encounters (3 mo) | 8.42 | -0.70 | -0.26 | 15.97 |
| | (6.73) | (1.20) | (0.62) | (9.89) |
| Observations | 1,939,330 | 305,691 | 440,458 | 489,763 |
| *Panel (C): Voyages (#)* | | | | |
| Encounters (3 mo) | 0.32 | -0.67** | -0.11*** | 0.79 |
| | (0.44) | (0.34) | (0.04) | (0.68) |
| Observations | 1,939,330 | 305,691 | 440,458 | 489,763 |
| *Panel (D): Vessels (#)* | | | | |
| Encounters (3 mo) | 0.35 | -0.65* | -0.10*** | 0.83 |
| | (0.45) | (0.34) | (0.04) | (0.69) |
| Observations | 1,939,330 | 305,691 | 440,458 | 489,763 |

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ The unit of observation is a grid cell (N = 590 unique cells). The sample spans from 2013 to 2021. Each panel examines a measure of grid-level ship transit in terms of total distance in kilometers (km), total occupancy time in hours (hr), and the number of unique voyages or vessels transiting through the grid cell. Each column is a different sample: Global is the analysis using the whole sample. G. of Aden, G. of Guinea, and S.E. Asia restrict the sample to cells within each hotspot. Every panel-column combination is a different regression analysis. Encounters (3mo) is the count of pirate encounters recorded within the grid cell in the preceding 90 days. All specifications include Fixed-effects by Grid ID, ASAM Subregion, and ASAM region by year by month. Numbers in parentheses are Conley Standard Errors (100 km cutoff).

Table 2: Effect of Past Pirate Encounters on Shipping Voyages.

| | Global | G. of Aden | G. of Guinea | S.E. Asia |
|---|---|---|---|---|
| *Panel (A): Total Distance (km)* | | | | |
| Encounters (3 mo) | 27.83*** | 210.90*** | 26.97*** | 22.43*** |
| | (3.20) | (19.58) | (1.54) | (3.50) |
| *Panel (B): Total Time (hr)* | | | | |
| Encounters (3 mo) | 2.25*** | 10.44*** | 1.96*** | 2.06*** |
| | (0.33) | (0.89) | (0.14) | (0.39) |
| *Panel (C): Average Speed (km/hr)* | | | | |
| Encounters (3 mo) | -0.01* | 0.18*** | 0.04*** | -0.02*** |
| | (0.01) | (0.02) | (0.01) | (0.01) |
| Observations | 25,632,233 | 1,034,377 | 276,245 | 6,335,661 |
| Hotspot FE | X | • | • | • |

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ The unit of observation is a voyage. Each panel examines an observed feature in terms of total distance in kilometers (km), total time of the voyage in hours (hr), and the average speed of the voyage (km/hr). The sample spans from 2013 to 2021. Every column is a different sample: Global is the analysis using the whole sample. G. of Aden, S.E. Asia, and G. of Guinea restrict the sample to vessels passing through one of the hotspots, respectively. Every panel-column combination is a different regression analysis. Encounters (3mo) is the count of pirate encounters recorded in the projected path of the vessel in the preceding 90 days from the departure date using a 5 degree spatial footprint. Controls include average wind speed along the voyage and the wind-resistance index. Fixed effects include country-to-country combination, vessel type, vessel size, hotspot, and a battery of month by year and top port-to-port combination for country-to-country combination dummies.

construction decisions (see Supplementary Text S2.7.2).

## The private and public costs of modern-day piracy

Having established robust empirical evidence about the statistical and directional impacts of piracy encounters, we now consider their economic impact. Put simply, how much does the avoidance behaviour of vessels cost in monetary terms? We answer this question by using vessel characteristics to determine fuel and labor requirements along a given voyage, and then empirically estimate changes in operational costs at the voyage level. The results are available in Supplementary Text S2.4 and, consistent with our other findings, suggest that an additional pirate encounter during the preceding three months translates to an average increase of US$830 in input costs (comprising US$580 in fuel and US$260 in labor). While this estimate remains largely consistent across data samples, again we observe a considerably larger effect in the Gulf of Aden. Specifically, our estimates suggest that the marginal effect of a pirate encounter to be over US$5,000 in terms of fuel and over US$1,000 in terms of labor. This discrepancy is striking and it likely reflects the margins of adjustments that captains would pursue while transiting different shipping routes.

We next explore how avoidance actions translate to emissions by establishing the link between pirate encounters and additional $CO_2$, $NO_x$ and $SO_x$ emissions by shipping vessels. The regression results are provided in Supplementary Text S2.4. Overall, it follows that excessive fuel consumption leads to concomitant emissions across the spectrum of related pollutants. Specifically, we estimate that a single pirate encounter leads to an approximate increase of 4 tons of $CO_2$, 85 kg of $NO_x$, and 70 kg of $SO_x$ per voyage, respectively. $NO_x$ and $SO_x$ excess emissions are relatively less voluminous, though this is a direct consequence of their smaller concentrations in bunker fuel relative to carbon. Once again, limiting the analysis to the Gulf of Aden suggests impacts that are an order of magnitude larger.

To contextualize the practical significance of these estimates, we contrast the implied operational and pollution costs of avoidance behaviour during our full 2013–2021 sample with a counterfactual scenario that is absent any pirate activity at the global level. Figure 3 maps the average annual costs to the shipping industry (fuel and labour costs), and additional emission of air pollutants. To monetize these impacts, we use the social cost of each pollutant (*11, 12*) and derive an aggregate measure of the global costs of piracy that averages US$6.6 billion/year. This figure corresponds to about 1.95% of the total private and public cost generated in by the shipping sector in our sample. Approximately US$1.5 billion of this topline number is attributable to private operational (fuel and labor) costs, while US$5.1 billion is attributable to public damages (due to air pollution). ASAM regions 7 and 9 (containing the Southeast Asian hotspot) account for US$2.8 billion and US$1.9 billion, ASAM region 6 (containing the Gulf of Aden) accounts for US$643 million, and ASAM region 5 (Gulf of Guinea) accounts for US$623 million. The results underlying Figure 3 are reported in detail in Supplementary Text S2.5.

These results are intuitive. Adjustments by individual vessels may appear small, but the relatively high density of shipping transit in places where pirate encounters occur makes the total economic impact quite substantial, especially in terms of public damages.

# Discussion

This paper has examined the effect of piracy on the shipping industry. We have documented the mechanisms through which shippers adjust their behavior in response to reported pirate encounters along a route, and the implied costs of shipping delays and environmental damages. While our estimated adjustments may seem relatively small at the individual level, cumulatively they translate to a significant economic welfare loss in the aggregate. Specifically, taking the total flow of global shipping routes into account together with the prevalence of pirate attacks

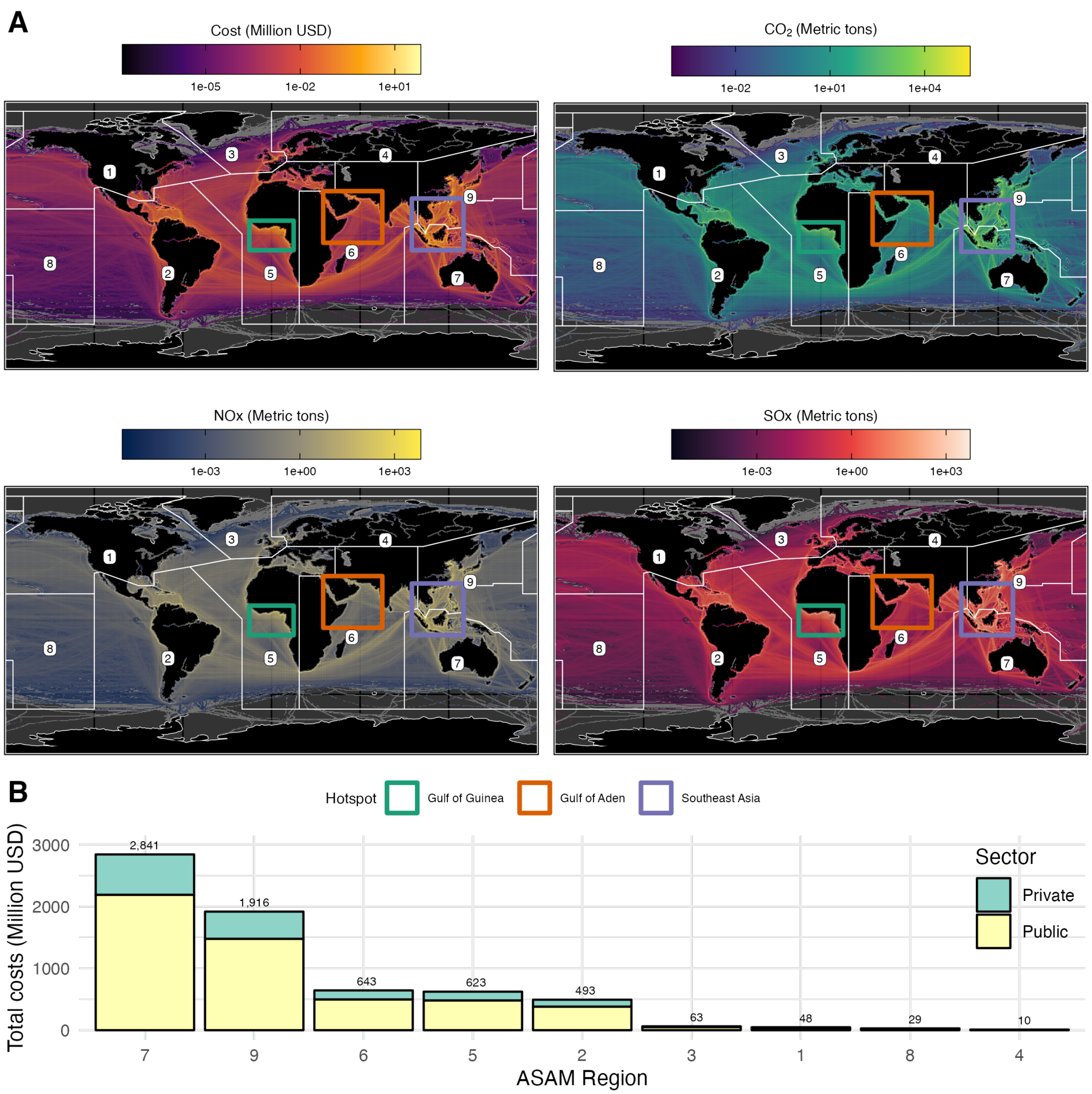


Fig 3: **Additional Operational Costs and Emissions due to Piracy.** Panel **A** shows maps of mean annual private costs to shippers (labor and fuel costs; Million USD), and additional $CO_2$, $NO_x$, and $SO_x$ emissions (Metric tons). Note that data are $\log_{10}$-transformed for visualization purposes and represented using a 0.5°x0.5° grid in geographic coordinates. Panel **B** shows the total costs (Million USD) associated with piracy by ASAM region, where we sum private costs to shippers as well as the cost of damages imposed by additional emissions based on the social-cost of each pollutant.

in some of the busiest shipping channels, we find that piracy avoidance is a considerable cost to the shipping industry, as well as an overlooked source of environmental externalities.

The economic theory underlying our analysis suggests that ships will optimally adjust to reduce the probability of pirate encounters. But those adjustments do not necessarily mean a complete change of routes (i.e., start and end points remain the same). This intuition holds up well in the data, where we observe ships traveling longer voyages, albeit at the cost of higher fuel consumption and labor time. Each additional encounter amplifies this behavioural response, and the effects have long-term implications after a single encounter is reported.

As we tried to emphasize, the Gulf of Aden is something of an anomaly in our empirical results, yielding effects that are up to an order of magnitude larger even than other piracy hotspots. Why would the Gulf of Aden present such a different level of adjustment? This result could be attributed to the prominence that Somali pirates and other armed assaults have occupied in the public perception. But it could also reflect the geographical characteristics of the region, which allows larger margins of adjustment for a given route. For example, vessels destined for Europe can decide between going through the Gulf of Aden and crossing through Egypt, or circling around the Cape of Good Hope. All vessels going to Nigeria must go through the Gulf of Guinea hotspot. As suggested by our theory, the way in which captains assess the relative piracy risk of following a given path and the potential cost of doing so in different regions affects the magnitude of their adaptation.

We note a few caveats. The first and most important to our causal identification, is the assumption that prior pirate encounters occur at random, relative to the date of departure of a given voyage. This assumption seems to hold in many instances, but some of the documented cases put the randomness assumption into question. In particular, hijacks that target certain types of ships, or the possibility of encounters targeting one particular vessel or poorly-enforced ports and anchorages. We control for all available observables, and use the nature of shipping contracts to minimize the risk of presenting biased results. Given the robustness of our results across a suite of model specifications (Supplementary Text S2.7) and the results from an auxiliary instrumental variable analysis (Supplementary Text S2.6), we believe that we have minimized the potential for these issues.

With these caveats in mind, we emphasize that the effect of piracy is clear and consistent across the grid-level (reductions in measures) and voyage-level (increases in measures) portions of the analysis. The consistency of the results highlights how problematic piracy is for the shipping industry. But it also underscores the potential for piracy to have wider impacts that ripple across the global economy. We can posit several channels through which these wider impacts manifest. The first channel is a simple waste of capital. Because individual shippers implement avoidance measures to reduce the probability of an encounter, they must allocate capital to cover these actions. Such capital could have been used somewhere else, either in the form of additional voyages, or as an input to other productive activities. A second channel is environmental impacts. The adjustments to piracy are not emission-neutral. In the aggregate, maritime commerce remains as one of the most emission-intense forms of transportation, with direct contributions to both global greenhouse emissions and local air pollutants that may disproportionately affect different areas and populations (*13*). Our calculations of additional emission burdens shed some light on these potential effects, and highlight how piracy may indirectly result in significant and harmful increases in emissions globally. A third channel for wider economic impacts is the potential for indirect trade costs. Depending on the level of competitiveness of the affected industry, and the routes in question, the associated costs in transportation could simultaneously affect both producers and consumers. Previous studies have tried to explore this problem using a trade framework (*6, 7*), and we believe that our approach of examining individual voyages helps further clarify the mechanism behind trade effects, both at a local and a global scale. Further investigation of this issue could unveil important implications for developing legislation that ensures maritime security and fluid trade between nations.

Stepping back, three key insights derive from our results. First, the piracy problem remains prevalent at a global scale. Second, because of the volume of voyages associated with the shipping industry, individual avoidance behaviours accumulate into an economically meaningful loss in aggregate welfare. These losses not only reflect the direct impact on trade flows and transportation inputs (e.g., fuel costs), but also the indirect environmental costs from pollution. Third, our results highlight the value of enforcement and anti-piracy measures for piracy-prone areas. According to available public data (*14*), a cost-effective defense task could be deployed for roughly $330M/year (adjusted for inflation). Enforcement spending would thus cost only a fraction of the total value currently lost due to piracy, and could help reduce large private and public costs (*14*). Addressing this missing enforcement will require active cooperation from multiple sectors and nations. The benefits, however, can be enjoyed widely.

Finally, an important angle of this issue relates to tackling the roots of the piracy problem in the developing world: poverty. Partnerships involving both public and private participation could potentially prove highly cost-effective and generate benefits at a large scale. Studying the design and implementation of such policies is a promising area for future research.

# References and Notes


1. R. Asariotis, *et al.*, Review of maritime transport, 2017, *Tech. rep.*, United Nations Conference on Trade and Development (2017).

2. P. Gosse, *The history of piracy* (Courier Corporation, 2012).

3. J. L. Anderson, *Journal of World History* pp. 175–199 (1995).

4. J. Bahadur, *The pirates of Somalia: Inside their hidden world* (Vintage, 2011).

5. C. Bueger, *Third World Quarterly* **34**, 1811 (2013).

6. A. Burlando, A. D. Cristea, L. M. Lee, *Review of International Economics* **23**, 525 (2015).

7. S. Bensassi, I. Martínez-Zarzoso, *Review of International Economics* **20**, 869 (2012).

8. P. Hallwood, T. J. Miceli, *Scottish Journal of Political Economy* **60**, 343 (2013).

9. D. A. Kroodsma, *et al.*, *Science* **359**, 904 (2018).

10. S. Wang, Q. Meng, *Transportation Research Part E: Logistics and Transportation Review* **48**, 701 (2012).

11. Interagency Working Group on Social Cost of Greenhouse Gases [United States Government], Technical support document: Social cost of carbon, methane, and nitrous oxide interim estimates under executive order 13990, Online (2021).

12. M. Mier, J. Adelowo, C. Weissbart, Taxation of carbon emissions and local air pollution in intertemporal optimization frameworks with social and private discount rates (2021).

13. J. J. Corbett, P. Fischbeck, *Science* **278**, 823 (1997).

14. D. C. Sonnenberg, Maritime law enforcement a critical capability for the navy, Ph.D. thesis, Monterey, California. Naval Postgraduate School (2012).

15. D. J. McCauley, *et al.*, *Science* **351**, 1148 (2016).

16. G. F. Watch, Anchorages, ports and voyages data (2021).

17. S. Betz, Reducing the risk of vessel strikes to endangered whales in the santa barbara channel, Ph.D. thesis, University of California, Santa Barbara (2011).

18. J. J. Corbett, H. Wang, J. J. Winebrake, *Transportation Research Part D: Transport and Environment* **14**, 593 (2009).

19. C. Wang, J. J. Corbett, J. Firestone, *Environmental science & technology* **41**, 3226 (2007).

20. M. Ester, H.-P. Kriegel, J. Sander, X. Xu, *et al.*, *Kdd* (1996), vol. 96, pp. 226–231.

21. T. G. Conley, *Journal of econometrics* **92**, 1 (1999).

22. A. P. Rubin, *Int'l L. Stud. Ser. US Naval War Col.* **63**, 13 (1988).

23. T. Gray, *Reports of the Transactions of the Devonshire Association for the Advancement of Science* **121**, 161 (1989).

24. G. V. Scammell, *Modern Asian Studies* **26**, 641 (1992).

25. K. R. Andrews, *The Spanish Caribbean: trade and plunder, 1530-1630* (Yale University Press New Haven, 1978).

26. J. F. Warren, *The Sulu Zone, 1768-1898: The dynamics of external trade, slavery, and ethnicity in the transformation of a Southeast Asian maritime state* (NUS Press, 2007).

27. A. Tenenti, *Piracy and the Decline of Venice, 1580-1615* (Univ of California Press, 1967).

28. R. Wright, *Financial Times, November* **20** (2008).

29. A. Bowden, K. Hurlburt, E. Aloyo, C. Marts, A. Lee, *The economic costs of maritime piracy* (One Earth Future Foundation, 2010).

30. R. J. O'Connell, C. M. Descovich, Decreasing variance in response time to singular incidents of piracy in the horn of africa area of operation, *Tech. rep.*, Naval Postgraduate School Monterey CA Department of Information Sciences (2010).

31. B. Guha, A. S. Guha, *Economics letters* **111**, 147 (2011).

32. C. Liss, *Private Military and Security Companies* (Springer, 2007), pp. 135–148.

33. M. Flückiger, M. Ludwig, *Journal of Development Economics* **114**, 107 (2015).

34. S. Axbard, *American Economic Journal: Applied Economics* **8**, 154 (2016).

35. P. T. Leeson, *Journal of political economy* **115**, 1049 (2007).

36. G. A. Psarros, A. F. Christiansen, R. Skjong, G. Gravir, *Journal of transportation security* **4**, 309 (2011).

37. J. Bahadur, *US Naval Institute Proceedings* (2011), vol. 137, pp. 73–74.

38. ICC-IMB, Piracy and armed robbery against ships: Report for the period 1 january - 31 december 2017, *Tech. rep.*, International Maritime Bureau of the International Chamber of Commerce (2018).

39. J. Jansson, *Liner shipping economics* (Springer Science & Business Media, 2012).

40. M. Stopford, *Maritime economics* (Routledge, 2013).

41. S. R. Massel, *Ocean surface waves: their physics and prediction*, vol. 36 (World scientific, 2013).

# Acknowledgements

We thank Christopher Costello, Anca Cristea, Javier Birchenall, Kyle Meng, Olivier Deschenes, Owen Liu, and Christopher Severen for helpful comments on the paper. We also acknowledge valuable feedback from participants at the Econometrics Lunch and the Environmental

Lunch at the University of California at Santa Barbara (UCSB), the Workshop in Environmental Economics and Data Science at the University of Oregon, and the Summer Conference of the Association of Environmental and Resource Economics. We thank Global Fishing Watch for providing the data processing and data management infrastructure for the shipping data. We would also like to thank Google for providing in-kind computational support.

## Funding

Partial funding for this project was provided by the Research Provost Award at the University of Miami, the Latin American Fisheries Fellowship at the University of California Santa Barbara, the Chilean Government through the Becas Chile program, and the Environmental Markets Laboratory at the University of California, Santa Barbara.

## Author Contribution

Conceptualization was performed by R.M, J.C.V.D., G.McDo., and G.McDe. Data curation was performed by R.M, J.C.V.D., and G.McDo. Formal Analysis was performed by R.M and J.C.V.D. Funding acquisition was performed by R.M. Investigation was performed by R.M, J.C.V.D., and G.McDo. Methodology was performed by R.M, J.C.V.D., G.McDo., and G.McDe. Project administration was performed by R.M. Supervision was performed by R.M. Validation was performed by R.M, J.C.V.D., G.McDo., and G.McDe. Visualization was performed by J.C.V.D. and G.McDo. Writing – original draft was conducted by by R.M, J.C.V.D., G.McDo. Writing – review & editing was performed by R.M, J.C.V.D., G.McDo., and G.McDe.

## Competing interests

The authors declare no competing interests.

## Data and materials availability

All data and materials will be available at `https://github.com/renatomolinah/piracy-shipping`

# Supplementary Materials

- Materials and Methods
- Supplementary Text
- Figs. S1 to S11
- Tables S1 to S23
- References 15 to 41

# **Supplementary Materials for:**
# ***Dangerous Waters: The Economic Toll of Piracy on Maritime Shipping***

Renato Molina, Juan Carlos Villaseñor-Derbez,
Gavin McDonald & Grant McDermott

# S1 Materials and Methods

## S1.1 Data

We construct a unique dataset for global shipping and piracy that provides both temporal and spatial variation. Specifically, we compile a panel dataset from 2013 to 2021 that includes individual shipping voyages and recent anti-shipping encounters along the route of each voyage. The panel includes the most important operational components that determine the cost of shipping voyages (e.g., engine size, number of crew members, route taken) as well as environmental factors affecting it (e.g., wind speed and direction).

### S1.1.1 Shipping activity

Individual shipping vessel voyage-tracks come from the Automatic Identification System (AIS) satellite latitude and longitude data. AIS transponders are required on all vessels greater than 300 gross registered tons while operating on international voyages, and by many countries while operating in certain exclusive economic zones (*15*). The dataset from 2013-2021 includes over 100,000 unique known cargo, tanker, and reefer vessels as defined by vessel identification data provided by Global Fishing Watch (GFW) (*9*). We include vessels that are classified by GFW as one of *cargo*, *cargo* or *tanker*, *bunker* or *tanker*, *tanker*, *cargo* or *reefer*, *specialized reefer*, *container reefer*, *reefer*, or *bunker*. These vessels broadcast more than 10 billion individual AIS messages during our study period, which we assigned to more than 26 million individual voyages. We leverage GFW's datasets of ports and voyages in order to assign every single AIS message to a specific port-to-port voyage by a specific vessel (*16*).

Data on operational costs come from two sources: fuel consumption and labor. We calculate fuel consumption using main engine power, gross tonnage, auxiliary engine power, and design speed. Main engine power and gross tonnage come from the Global Fishing Watch vessel characteristics database (*9*). For each vessel, we determine these characteristics using a hierarchy based on data availability: 1) the official registered information of the vessel; and 2) values inferred by the Global Fishing Watch vessel characteristic neural network when available. Auxiliary power is a function of main engine power, and is calculated using known empirical relationships (*17*), which link main propulsory requirements with vessel characteristics and auxiliary needs. Design speed is a function of main engine power and gross tonnage (*17*).

Using these vessel characteristics, we calculate fuel consumption using a standard approach that combines fuel consumed by both the main and auxiliary engines (*18*). Fuel consumption of the main engine is defined by hours of operation, main engine power, main engine specific fuel consumption rates (*19*), and a cubic law of operational speed relative to design speed. Fuel consumption of the auxiliary engine is defined by operating hours, auxiliary engine power, and auxiliary engine specific fuel consumption rates (*19*). Fuel consumption was calculated for each individual AIS ping which were then summed for each voyage.

Daily fuel price data come from Bunker Index. We use the 380 CST Bunker Index, which is the global average price from all ports selling 380 centistoke fuel, the most commonly used fuel in maritime transport. For dates with missing price data, we impute the missing value using the most recent reported price. Most gaps in the data do not exceed more than two days. Total fuel cost for each voyage is then calculated by multiplying the total fuel consumption of the voyage by the fuel price on the date of departure.

We also keep track of labor requirements for individual voyages. Using the ratio suggested in the literature (*17*), we estimate the crew needed to operate a vessel as a function of its size and type. The crew wage is calculated using the 2018 International Transport Worker's Federation wage scale for the average non-officer seafarer.[4]

We also calculate emissions of $CO_2$, $NO_x$, and $SO_x$ for each voyage. $CO_2$ emissions are calculated using a linear relationship (*18*), which relies on total fuel consumption of the voyage. $SO_x$ emissions are calculated similarly, under the assumption of 3.3% sulfur content for each kilogram of fuel (*13*). Similarly, $NO_x$ emissions are calculated using a separate conversion rate for both the main engine fuel consumption (which we assume to be a slow-speed engine) and auxiliary engine (which we assume to be a medium-speed engine) (*13*).

Finally, we incorporate a weather proxy in the form of average wind speed and direction along each voyage. We call this proxy the wind-resistance index. Wind data come from the NOAA Global Forecast System Atmospheric Model. Mean monthly wind speed and direction information is calculated for 5°x5° grid cells. We take into account wind direction by decomposing the pitch angle relative to the vessel; the resistance is concave or convex depending on the vessel going against, or with the wind. This measurement is symmetric in absolute terms along each 90° portion of a full circumference and it goes from 0 to 1. Scaling this measurement by the wind speed gives the final wind-resistance index. For each voyage, the time-weighted mean wind-resistance is then calculated based on the voyage's time spent in each 5°x5° cell.

The final panel covers all global valid cargo and tanker voyages between 2013 and 2021, with each entry reporting vessel characteristics (type, size, crew), departure and arrival dates, departure and arrival ports and countries, total distance traveled (km), time traveled (hr), speed (km/hr), fuel consumption (kg), fuel and labor cost (US$), and emissions (kg).

### S1.1.2 Pirate encounters

We operationalize pirate encounters by using the anti-shipping data provided by the United States National Geospatial Intelligence Agency, which includes dates and locations of sittings and hostile acts against ships by pirates, robbers, and other aggressors. We include all anti-shipping encounters in our dataset except those categorized as "Suspicious Approach," as those are not confirmed.[5] We then divide the ocean into two global grids: one of 0.5° latitude by 0.5° longitude pixels and one of 5° latitude by 5° longitude pixels. We use the 0.5°x0.5° data for a fine-scale pixel-level analysis, and use the 5°x5° data for a port-to-port voyage-level analysis.[6]

[4] Current and projected wages are available at `https://t.ly/JADDs` [Last Visited on 04/12/24]

[5] This dataset is available at: `https://t.ly/jbmqG` [Last Visited on 04/12/24]

[6] At the equator, a cell of 5° by 5° is roughly equivalent 345 by 345 miles, which is a reasonable spatial area over which shipping vessel operators might make route and speed adjustment decisions in relation to recent anti-

For each gridded dataset, we then calculate the number of anti-shipping encounters that occurred in each pixel on each day. For any given pixel and any given day of shipping operation in that pixel, this therefore allows us to calculate the number of days since the most recent encounter in that pixel, as well as the number of encounters that occurred within that pixel over a rolling time window. For the pixel-level analysis, we calculate the number of encounters within three different rolling window of the past 3, 6, and 12 months for every 0.5°x0.5° pixel and every day in the dataset.

For the voyage-level analysis, we first calculate the number of encounters within the 5°x5° pixels along each port-to-port voyage that occurred within a rolling window of the past 3 months. This provides the number of recent pirate encounters in the area that each voyage passes through. This represents, for any given voyage departure date for any given port-to-port route, the captain's expectation of how many encounters they might expect could occur along the route they are about to embark on.

Using the locations of individual anti-shipping encounters that occurred from 2010 through 2021, we also determine hotspots of encounters using density-based clustering as described by (*20*). Implementing a cluster reachability distance of 10 km, and a minimum number of encounters per cluster of 300, we find that attacks correspond to three hotspots of intensive pirate activity for the entire panel: the Gulf of Aden, the Gulf of Guinea, and Southeast Asia. For each of these hotspots we generate a rectangular bounding box that is snapped to the nearest 5° latitude and 5° longitude markers that fully enclose each set of hotspot attacks, and then for each voyage we then determine whether the vessel transited through one or more of these areas.

The final overlap between shipping voyages and pirate encounters, which is the dataset used in the empirical analysis, is shown in Figure 1. Note that pirate encounters concentrate in a few areas in the map. Particularly in the Caribbean, the Gulf of Guinea, the coast of East Africa, the Arabian Sea, and the jurisdictional waters of the Philippines and Malaysia. The relevant hotspots for this study are enclosed by the rectangles.

## S1.2 Empirical analysis

### S1.2.1 Grid-level analysis

To establish the effect of piracy on shipping we will rely on several estimation procedures. First, we begin by generally asking if shipping transit is apparently affected by pirate encounters. The analysis is performed under an Eulerian framework, with the units of analysis as grid cells along a 0.5°x0.5° grid. In particular, we are interested in how measures of shipping traffic (i.e., total distance traveled within a grid cell or total time spent by ships in a grid cell, number of voyages and vessels crossing a grid cell) change following a pirate encounter. Summary statistics for this dataset are provided in Table S1.

We extend this analysis with a fixed-effect regression approach connecting pirate encounters

shipping encounters. Moving at 10 knots, this is an area that potential attackers could cover in just 30 hours.

and shipping traffic within grid cell $i$ at time $t$. The model takes the following form:

$$y_{it} = \beta TNE_{it} + \gamma' G_i + \theta' X_t + \eta_i + \epsilon_i \tag{S1}$$

$y$ is the response variable, and $TNE$ is the total number of encounters during the past three months, relative to date $t$. $\beta$ is the average marginal change related to an additional encounter on mean traffic over a cell. $\gamma' G_i$ is a vector of fixed effects for the subregion used by the Anti-shipping Activity Messages (ASAM subregion), $\theta' X_t$ captures temporal fixed effects by ASAM region-year-month, while $\eta_i$ correspond to grid-specific fixed effects. We estimate spatial HAC standard errors with a 100 km cutoff (*21*). This analysis restricts the sample to grids with at least one attack during our analysis window (2013-2021; N = 590 cells). The identification assumption is that the timing and location of past encounters are exogenous to a voyage after controlling for temporal and grid-specific fixed effects.

In addition, we estimate dynamic treatment effects by regressing ship traffic on dummy variables indicating relative time (days) to treatment. We include the same battery of fixed effects as in the aggregate effect approach. This ancillary analysis retains only cells that have at least five days without other encounters before and after the focal encounter date (N = 233 cells).

### S1.2.2 Voyage-level analysis

We then analyze the effect of piracy at the voyage level. We are interested in the feature of a given voyage $i$ (i.e., distance, duration, and speed) along country-to-country route, $r$, at time $t$, and their associated consequences in terms of operational costs and emissions. The model is as follows:

$$y_{irt} = \alpha + \beta TNE_{rt} + \delta_i VC_i + \lambda_i W_i + \eta_r R_i + \theta' X_t + \epsilon_{irt} \tag{S2}$$

$y$ is the response variable, and $TNE$ is the total number of encounters during the last three months, with $\beta$ as the average marginal effect of an additional encounter on the mean path of a voyage. $VC$ is a vector of fixed effects according to vessel characteristics (i.e., type of vessel and size), while $W$ is the time-weighted mean wind-resistance index and average wind speed for a given voyage. Finally, $R$ is a vector of fixed effects by route, while $X_t$ is a battery of month by year fixed effects. In the results we will also specifically control for additional factors such as crossing hotspots or the voyage being part of the most common port-to-port combination between countries. To account for potential route and temporal correlation, we cluster standard errors by country-to-country route by year. The identification assumption is that the timing and location of past encounters are exogenous to the date of departure of a given vessel.

# S2 Supplementary Text

## S2.1 Background

### S2.1.1 Piracy and trade

Modern piracy is fundamentally an enforcement problem that can be traced to poorly defined property rights and duties over maritime territory. This misalignment is especially acute in international settings, where the establishment and enforcement of anti-pirate regulations usually conflicts with sovereign rights (*22*). These institutional settings reduce the probability of pirates being prosecuted, or even apprehended, which in equilibrium encourages the continued predation of sea commerce.

From a welfare perspective, Anderson suggests several types of losses associated with piracy (*3*). First, the direct capital losses to violence, which manifest either in the form of damages to the ship or cargo, or as the loss of life. Second, the indirect losses in the form of resources channeled toward evasion and protection that could have been used for other productive activities. For example, the additional bulk of fuel used to maintain evasive maneuvers, or the additional amount of capital required to sustain a steady flow of goods *vis-á-vis* the same exchanges in the absence of piracy. It follows that the magnitude of these responses can lead to both intensive and extensive margin adjustments, which in turn can cause dynamic losses in the form of diminished incentives for producers and merchants to continue with or expand production (*3*).

Historical data suggest that piracy events have often been followed by extremely negative impacts to commerce channels and local economies. For example, during the seventeenth century, the "Turkish pirates" completely paralyzed several parts of west England (*23*). During the same period, the predominance of pirate organizations in the Arabian sea also led to severe decreases in trade flow, with devastating consequences for all industries in the region (*24*). These two cases are not unique. Similar links have been documented for other trade regions in the Caribbean (*25*), the Philippines (*26*), and Venice (*27*). All of these examples illustrate how thriving economies suffer considerable negative effects due to piracy.

Modern piracy has had similar effects. In fact, piracy remains a problem worldwide. There were over 2,200 pirate and anti-shipping encounters globally between 2013-2021, with over 600 taking place between 2019-2021. Most encounters, however, take place in a few hotspots; namely: the Gulf of Aden (known for the Somali pirates), the Gulf of Guinea (mostly within the Nigerian EEZ), the Malacca Straits (the shipping channel formed by Sumatra and the Malay peninsula) and the South China sea. For the remainder of the paper we will refer to both the Malacca Straits and the South China sea as one group that we call Southeast Asia. The distribution of the actual number of encounters in each region over time is shown in Figure 1. From this figure, note that pirate encounters are consistently concentrated in the African region and Southeast Asia.

Although sparse, there are several assessments regarding the economic impact of modern piracy. Past estimates suggest that the losses in trade volume due to pirate activities in Somalia accrued to about \$24 billion/year (*6*). Other estimates are more conservative and suggest that the loss ranged between \$1 billion and \$16 billion, when accounting for the addition of 20 days per voyage due to re-routing around Africa, and increased insurance, charter rates, and inventory costs (*28–30*). Another study estimates that 10 additional hijacks in either the Gulf of Aden or the Strait of Malacca reduce the volume of exports between Asia and Europe by about 11%, with an estimated cost of about \$25 billion per year (*7*). These studies estimate losses through the examination of overall trade patterns, but to the best of our knowledge, there is no study focusing on the behavior of individual shipping vessels. We believe the latter is a more direct way to disentangle the cost of piracy. It is plausible that the gap in the literature regarding the effect of piracy on shipping patterns is due to the difficulty of obtaining data on individual shipping voyages, but also because of the sparse data on pirate activities. Both of these issues are accounted for in this paper.

On the other hand, theoretical insights regarding the piracy problem can be traced to two studies. Namely, Guha and Guha (*31*), who model optimal patrolling and penalties under the option of self insurance, and Hallwood and Miceli (*8*), who explore optimal patrolling and penalties taking into account strategic interactions between pirates and shippers. Although very valuable contributions in terms of formalizing the theory behind pirate behavior, neither paper explored vessel adjustments along shipping routes as they focus on penalties and enforcement.

Other related literature has devoted efforts to several topics on both past and modern piracy. One of those topics relate to anti-piracy efforts. Anderson (*3*) documents the historical evolution of state and individual actions to control for piracy along shipping routes. Similarly, Liss (*32*) describes how modern piracy incentivizes shippers to employ private military companies or acquire their own defense mechanisms. Other empirical settings, including Flückiger and Ludwig (*33*), as well as Axbard (*34*), study how poor fishing conditions lead to an increase in pirate activity in Africa and Indonesia, respectively.

Finally, other authors such as Leeson (*35*) and Psarros, Christiansen, and Skjong (*36*) study the factors that contribute to pirates being more or less effective in terms of finding vessels, as well as extracting the most value out of these encounters. In addition and specific to the Somali case, references O'Connell and Descovich (*30*), as well as Bahadur (*37*) document the social and economic institutions associated with pirate activities by identifying ransom procedures, operational supply chains, and community support.

#### S2.1.2 The business model of modern piracy

Establishing how pirate operate globally presents several challenges. First, pirates often have little or no incentive to make the details of their operations known to the public. Nonetheless, there are still a few credible sources that allow us to establish the mechanics behind pirate encounters, and more importantly, use them as means for identification in the empirical section. In particular, we make use the information documented by Bahadur (*4*), which relies on a number of interviews with individuals who claimed to be associated, directly or indirectly, with pirates in Somalia in 2009. Considering the sensitivity of the piracy issue, these interviews provide the best available information on the actual behavior and incentives of pirates.

Pirates in Somalia appear to not discriminate between vessels. Instead they opportunistically hijack vulnerable vessels that cross their path. Once the potential target is identified, pirates pursue the vessel until eventually capturing it, or the vessel is realistically out of reach. Neither the search or the pursuit are constrained by the jurisdictional boundaries of Somalia. The boarding strategy entails the pirate crew splitting into several skiffs, which approach the target vessel from all sides while waving and firing their weapons to scare the ship's crew. If the vessel stops, or the skiffs are able to keep up with it, the pirates would toss rope ladders onto the deck and then proceed to boarding. According to the accounts, crews rarely resist boarding once the pirates successfully get on the deck. The average reported success rate of the pirates used to be about 20 to 30% (*4*).

Once the pirates successfully take control of the ship, they steer the vessel to a friendly port. At this location, an additional set of guards and translators would board the ship, and ransom negotiations will start. Most ransoms would be handled by insurance companies. Upon reaching an agreement, the money is usually delivered via parachute drop-off onto the deck of the ship, and then split amongst the pirates. The amount that each of them would receive is a fixed fraction of the total ransom, and it would vary depending on the task (*4*). About half of the pot would go to the actual men boarding the ship, one third to the investors financing the operation, and a sixth to everyone else assisting with logistics and enforcement.

We note that although 2017 saw a spike in pirate activities in the Gulf of Aden, this region seems to be no longer affected at same scale as it used to be during the 2000's.[7] According to the latest reports on encounters by the US government (Figure 1B) and the International Maritime Bureau of the International Chamber of Commerce (ICC-IMB), most encounters are now reported to take place in the Gulf of Guinea and Southeast Asia (*38*). The business model of piracy in these regions, however, differs from the Somali pirates.

Pirates in the Gulf of Guinea follow a similar approach when it comes to intercepting a vessel. The difference comes after they have successfully hijacked the ship. Specifically, besides hijacking the vessel and its crew, these pirates appear to focus on kidnapping only a subset of crew members for ransom (*38*). Another regular practice in this region is the robbery of cargo, especially liquid fuel.[8]

Pirate encounters in Southeast Asia seem to follow a variation of the previous business model. According to recent reports, and in addition to the practices listed above, encounters include large-scale and sophisticated operations targeted at siphoning fuel from tanker vessels.[9] In this type of attack, vessels are also approached and hijacked, but then they are steered towards a siphoning facility on the shore that retrieves the entire cargo. Under this model, the crew and

---

[7] See for example *Piracy threat returns to African waters* by CNN, available at: `https://t.ly/qKlZo` [Last Visited on 04/12/24]

[8] See *Abduction of Crew Off Nigeria Brings Piracy Back to Indian Agenda* by The Wire, available at: `https://t.ly/gVVXJ` [Last Visited on 04/12/24]

[9] See *Pirates in Southeast Asia: The World's Most Dangerous Waters* by Time, available at: `https://t.ly/Ano8q` [Last Visited on 04/12/24]

the ship are usually freed several days after a successful attack (*38*).

Finally, pirate encounters have also increased in the Caribbean, especially along the coast of Venezuela. Their approach, however, seems to be fundamentally different. Recent reports indicate that due to harsh economic conditions in Venezuela and northern Colombia, many of the coast inhabitants target private yachts for small robbery.[10] These encounters are suggested to be sporadic, and usually deriving in opportunistic predation of groceries and other valuable items that tourists carry. To our knowledge, no hijacks or ransoms for cargo vessles have been reported in this region.

[10]See *La piratería regresa al Caribe motivado a la crisis de Venezuela* by El Nacional, available at `https://t.ly/ug4O-` [Last Visited 04/12/24]

## S2.2 An economic model of pirates and shippers

This section establishes the intuition behind shipping behavior in the face of piracy. In particular, we illustrate the mechanisms behind pirate encounters, and their effect on shipping routes. It follows that all relevant costs associated with piracy can be attributed to deviations from cost-effective behavior in the absence of the threat. The model we propose builds on the previous efforts (*8, 31*), who championed the theoretical understanding of piracy under an economic framework.

For simplicity, assume a situation where there is only one pirate and one shipper. There is a continuum of paths, $x \in \mathbb{X} = [0, \bar{x}]$, for a certain route. The cost-effective path is given by $x = 0$, while $x = \bar{x}$ represents the most expensive, but feasible, path. One way to think about this idea would be vessels having to sail farther from the coast than optimal due to the threat of piracy. The cost of deviating from the optimal path, $c(x)$, is strictly convex in $x$, and $c(0) = 0$. In the presence of piracy, the shipper chooses the route taking into account the possibility of encountering and being attacked by the pirate.

An encounter might occur when the shipper transits through the area monitored by the pirate, which is given by the segment $x : x = [0, \bar{a})$. Because physical limitations prevent pirates from monitoring all possible transportation paths, it follows that $\bar{a} < \bar{x}$. The probability of an encounter, however, is strictly positive along the $[0, \bar{a})$ interval, and zero everywhere else. One way to think about this feature is the shipper taking an extremely long path with no risk of piracy, or using other transportation methods such a trains or airplanes. Formally, this relationship can be expressed as:

$$\phi(x;\theta) \begin{cases} > 0 & ; \quad 0 \leq x < \bar{a} \\ = 0 & ; \quad \text{Otherwise} \end{cases} \tag{S3}$$

with $\theta$ being the vector of parameters that characterize the distribution, including $\bar{a}$ and the search effort with which pirates patrol the susceptible waters. The probability function satisfies $\phi_x(x, \theta) < 0$ and $\phi_{xx}(x, \theta) > 0 \; \forall \; x \in [0, \bar{a})$, and $\phi_x(x, \theta) = \phi_{xx}(x, \theta) = 0 \; \forall \; x \in [\bar{a}, \bar{x}]$.

In this model, the pirate decides to attack only after an encounter takes place, in which the shipper loses $h$. From the pirate's perspective, however, the assault can be either successful (the pirate gets away) or unsuccessful (the pirate gets caught). An attack implies the pirate obtaining a monetary prize or booty, $b$, which is not necessarily equal to $h$, and that he cannot determine until the encounter occurs. This assumption implies that the pirate treats $b$ as a randomly distributed variable with cumulative distribution $F(b)$ over support $[0, \bar{b}]$. One way to think about this realization is the assessment of the ship being "worth" pursuing (*4*).

Before attacking, the pirate assesses the monetary value of the booty with the expected costs of being apprehended with probability, $p$, and fine, $f$. As the pirate does not serve time incarcerated,[11] it follows that an attack occurs whenever $b \geq pf$. Therefore, conditional on an

[11] Reference (*31*) notes that a major problem in modern piracy is the lack of credible punishment after aggressors have been apprehended.

encounter, the probability of an attack is given by:

$$\psi(pf) = [1 - F(pf)] \tag{S4}$$

Finally, the model assumes the shipper cannot observe the patrolling effort of the pirate, but a finite number of paths previously taken for the origin-destiny combination. Denote this history set as $\mathbf{z} = \{z_1, ..., z_m\}$ for $m$ different voyages. The shipper also knows which paths have experienced encounters in the past (e.g., through access to the monthly *Worldwide Threat to Shipping* reports published by the Office of Naval Intelligence, or by contracting intelligence firms that provide such information). This complimentary history set is given by $\mathbf{y} = \{y_1, ..., y_n\}$, for a total of $n$ encounters. With this information, the shipper can estimate the parameters of the encounter probability distribution, including the span of the monitored area, as:

$$\hat{\theta} = \arg\max_{\theta} \{\mathcal{L}(\theta; \mathbf{y}, \mathbf{z})\} \tag{S5}$$

with $\mathcal{L}(\theta; \mathbf{y}, \mathbf{z})$ as the likelihood function of $\phi(x, \theta)$. If the market price of the voyage is given by $\pi$, it follows that the expected net return for the shipper, $R$, would be finally given by:

$$R(\pi, x, \hat{\theta}) = \pi - \phi(x, \hat{\theta})\psi(pf)h - c(x) \tag{S6}$$

Assuming risk neutrality, the shipper's problem can be solved using standard optimization techniques, and it follows that the optimal path is characterized by the proposition below:

**Proposition 1.** *The optimal path for a shipper in the face of piracy, $x^*$, depends on the information of past voyages and pirate encounters, $\{\mathbf{y}, \mathbf{z}\}$, and it satisfies:*

$$-\phi_x(x^*, \hat{\theta})\psi(pf)h = c'(x^*) \tag{S7}$$

*with*

$$\hat{\theta} = \arg\max_{\theta} \{\mathcal{L}(\theta; \mathbf{y}, \mathbf{z})\} \tag{S8}$$

*All proofs are provided in Supplementary Text S2.2.2.*

Proposition 1 indicates that the optimal path equalizes marginal expected savings to the marginal cost of deviating from the cost-effective one. The set of feasible optimal paths is then given by the Lemma below:

**Lemma 1.** *The optimal path for a shipper in the face of piracy is contained in the set $x : x \in (0, \bar{a}]$.*

Lemma 1 suggests two points regarding optimal paths. First, the shipper will never ignore the threat of piracy. Expected losses from encountering and being attacked by a pirate will always be taken into account and thus avoided following the equimarginal principle. Second and consistent with cost minimizing behavior, if the cost of deviating is low enough, total avoidance will never exceed $\bar{a}$. These ideas are illustrated in figure S1, with panel (a) corresponding to interior solutions and panel (b) corresponding total, or maximum, avoidance.

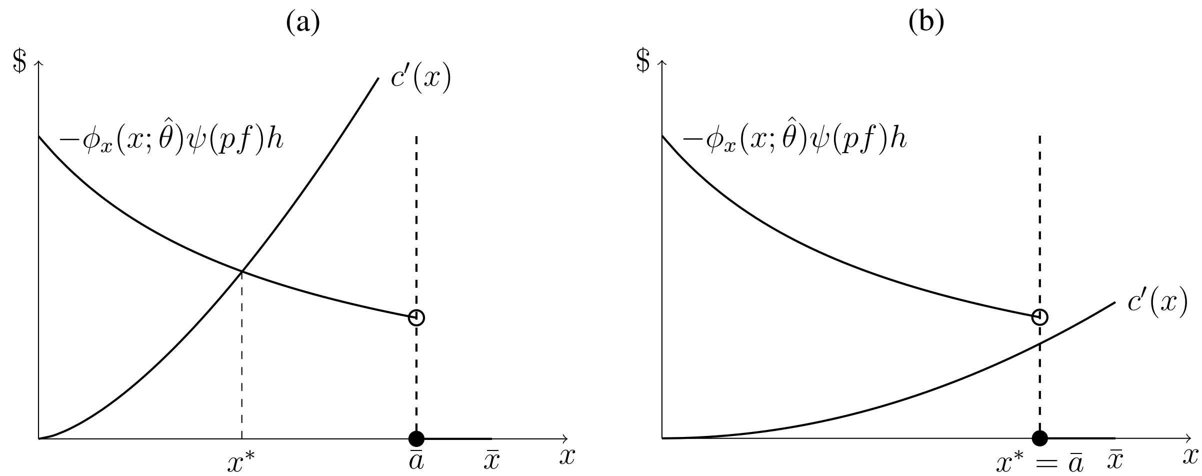


fig S1: **The shipper's path selection problem.** Panel (a) shows interior solutions, while panel (b) shows the maximum optimal level of avoidance a shipper will ever take when deviating from the cost-effective path is relatively inexpensive.

Now that the shipper's path decision is fully characterized, we turn to establishing the effect of the information set on optimal decisions. In particular, we want to establish how past encounters affect the shippers decision making process today. In line with the empirical analysis, we will focus on the frequency of encounters for path $x$, which is given by the following ratio:

$$k(x) = \frac{|\mathbf{y} : y_i = x|}{|\mathbf{z} : z_j = x|}; \quad i \in \{1, ..., n\}, j \in \{1, ..., m\} \tag{S9}$$

The expected effect of this observable on optimal paths is formalized in the proposition below:

**Proposition 2.** *The effect of the frequency of encounters, $k(x)$, on optimal path, $x^*$, is given by:*

$$\frac{\partial x^*}{\partial k(x)} = -\frac{\psi(pf)h\phi_{x\theta}(x^*, \theta)}{\psi(pf)h\phi_{xx}(x^*, \theta) + c''(x^*)}\frac{\partial \hat{\theta}}{\partial k(x)}, \ \forall\, x \in \mathbb{X} \tag{S10}$$

Proposition 2 is fairly intuitive: adjustments to optimal paths are linked to their effect in the estimated parameters of the probability function, as well as their effect on the probability of an encounter. In other words, marginal optimal adjustments incorporate any information regarding past encounters along the route to inform the expected probability of encounters. This information is then translated into the adjustments prescribed in Proposition 1. As a Corollary, the sign of this relationship is given by:

**Corollary 1.** *The direction of the effect of the frequency of encounters, $k(x)$, on optimal path, $x^*$, is given by the sign of the product:*

$$-\phi_{x\theta}(x^*, \hat{\theta})\frac{\partial\hat{\theta}}{\partial k(x)} \tag{S11}$$

The sign of the above relationship depends on two components: the cross derivative of the probability function, and the effect of observing more encounters along a given route on the estimate of $\theta$. When this expression is positive, it is optimal to deviate more from the cost-effective path, while the opposite is true if the expression is negative. The reason why the sign switches relates to convexity of the probability of an encounter and the generality assumed for the relationship between the observed encounters and their effect on the probability estimate.

As an illustration, suppose encounters are observed farther from the cost-effective path. Operationally, this means an increase in the estimate for $\bar{a}$ and a change in the slopes of the probability function for any $x$ to the left of $\bar{a}$. The actual change will depend on the searching capability of the pirate. Consider the case in which the pirate can allocate only so much time to search every particular section of the feasible paths. The pirate searching farther implies a decrease in the intercept of $-\phi_x(x;\hat{\theta})\psi(pf)h$, or an increase in its slope, or both. Any of these changes effectively reflect a decrease in the probability of encountering the pirate. When this is the case, the intercept with the marginal cost shifts to the left, and thus less avoidance is optimal. Other responses will then be a function of how effective the pirate is when it comes to searching different sections of the path set.

Our main task is to establish the above relationship empirically in the main text. With this result, we are then able to estimate the cost of avoidance behavior in the shipping industry due to piracy. The characterization of the pirate's behavior is also provided for completeness.

#### S2.2.1 Optimal pirate behavior

In this section, we expand the theoretical insights of the main model to include the behavior of the pirate when deciding on how intensely to search for the target vessels. The working assumption of the model was that the pirate encounters occur whenever $b \geq pf$. The expected value of a successful encounter is then given by:

$$G(pf) = \int_{pf}^{\bar{b}} (b - pf)dF(b) \tag{S12}$$

In this model, the pirate cannot directly observe the routing of the shipper, but he can still build an estimate. This estimate follows from observing past encounters, $\mathbf{y} = \{y_{(1)}, ..., y_{(n)}\}$, and its own search effort, $\theta$. Further, the pirate knows the probability of an encounter is given by $\phi(x, \theta)$. He is then able to estimate the path of the shipper and the associated probability of an encounter as:

$$\hat{x} = \arg\max_{x} \{\mathcal{L}(x; \theta, \mathbf{y})\} \tag{S13}$$

with $\mathcal{L}(x; \theta, \mathbf{y})$ as the likelihood function of $\phi(x; \theta)$. If the pirate has a search cost $s(\theta)$, which is increasing in $\bar{a}$, the expected return to piracy is then given by:

$$R^p(\theta) = G(pf)\phi(\hat{x}, \theta) - s(\theta) \tag{S14}$$

In addition, the pirate has a total time constraint, $h = b + t(\theta)$, with $b$ denoting the time working in non-pirate activities for wage $w$. $t(\theta)$ is a function that denotes the total time devoted to searching for vessels. The pirate's concave utility of income is then given by:

$$u(m, \theta) = wb + R^p(\theta) \tag{S15}$$

The time constraint can be rearranged as:

$$b = h - t(\theta) \tag{S16}$$

and the utility function can be solely expressed as a function of $\theta$ as:

$$u(m, \theta) = w(h - t(\theta)) + R^p(\theta) \tag{S17}$$

Taking partials with respect to $\theta$ and equalizing to zero gives:

$$-u'(\bullet)(bt'(\theta) + G(pf)\phi_\theta(\hat{x}, \theta) = 0 \tag{S18}$$

This expression defines optimal set adjustments for the pirate, which are captured by $\theta^*$, and implicitly defined by:

$$\phi_{\theta^*}(\hat{x}, \theta^*) = \frac{bt'(\theta^*)}{G(pf)} \tag{S19}$$

This expression suggests that optimal pirate effort equates the marginal expected gain of increasing the probability of an encounter with the marginal opportunity cost of working in non-pirate activities. Following the same approach as with the shipper, it is straight forward to show that the optimal pirate response to changes in the estimated path are given by:

$$\frac{\partial \theta^*}{\partial \hat{x}} = -\frac{\phi_{x\theta}(\hat{x}, \theta^*)}{\phi_{\theta\theta}(\hat{x}, \theta^*) - \frac{b}{G(pf)} t''(\theta)} \tag{S20}$$

Our setting does not allow to sign the above expression. Nonetheless, with a few assumptions regarding both the probability and the time requirement function, clear predictions associated with the pirate behavior in the face of different observables are possible.

#### S2.2.2 Proofs

#### Proposition 1

*Proof.* The shipper's problem is given by:

$$\max_x \{\pi - \phi(x, \hat{\theta})\psi(pf)h - c(x)\} \tag{S21}$$

Taking partials with respect to $x$ and equalizing to zero:

$$-\phi_x(x, \hat{\theta})\psi(pf)h - c'(x) = 0 \tag{S22}$$

Rearranging and multiplying by minus one:

$$-\phi_x(x^*, \hat{\theta})\psi(pf)h = c'(x^*) \tag{S23}$$

Finally, $\hat{\theta}$ is estimated by examining the sequence of where past encounters took place, $\mathbf{y} = \{y_1, ..., y_n\}$, as:

$$\hat{\theta} = \arg\max_{\theta} \{\mathcal{L}(\theta; \mathbf{y}, \mathbf{z})\} \tag{S24}$$

These two equations define the optimal path for the shipper based on past encounters, and complete the proof. □

#### Lemma 1

*Proof.* First, consider the case of zero avoidance, or $x^* = 0$. From the shipper's problem we know that optimal deviation must satisfy:

$$\phi_x(x, \hat{\theta})\psi(pf)h = -c'(x) \tag{S25}$$

Because $c(x)$ is convex and $c(0) = 0$, it follows that $c'(0) = 0$. Substituting into the optimality condition then gives:

$$\phi_x(0, \hat{\theta}) = 0 \tag{S26}$$

which is equivalent to say that the only possibility for $x$ to be equal to zero is if $\phi_x(0, \theta) = 0$, which is never true by design.

Second, consider the case of total avoidance, or $x^* \geq \bar{a}$. Recall that

$$\phi_x(x, \theta) = 0 \; ; \; \forall \, x \geq \bar{a} \tag{S27}$$

This condition implies that any deviation beyond $\bar{a}$ renders no further reduction in the probability of an encounter. Because of the convexity of $c(x)$, it follows that any $x > \bar{a}$ is strictly inferior to $x = \bar{a}$. Therefore, if $\nexists \; x \in [0, \bar{a}) : \phi_x(x, \hat{\theta})\psi(pf)h = -c'(x)$, optimal decision making dictates $x^* = \bar{a}$. All other scenarios are described by the optimality condition, which completes the proof. □

**Proposition 2**

*Proof.* Consider the optimality condition:

$$-\phi_x(x^*, \hat{\theta})\psi(pf)h = c'(x^*) \tag{S28}$$

Totally differentiating with respect to $k(x)$ gives:

$$-\psi(pf)h\left(\phi_{xx}(x^*, \hat{\theta})\frac{\partial x^*}{\partial k(x)} + \phi_{x\theta}(x^*, \hat{\theta})\frac{\partial \hat{\theta}}{\partial k(x)}\right) = c''(x^*)\frac{\partial x^*}{\partial k(x)} \tag{S29}$$

Rearranging with the respect to the partial effect on optimal routing $x^*$:

$$\frac{\partial x^*}{\partial k(x)} = -\frac{\psi(pf)h\phi_{x\theta}(x^*, \hat{\theta})}{\psi(pf)h\phi_{xx}(x^*, \hat{\theta}) + c''(x^*)}\frac{\partial \hat{\theta}}{\partial k(x)} \tag{S30}$$

This equation characterizes the total effect of $k(x)$ on $x^*$, and completes the proof. □

**Corollary 1**

*Proof.* The total effect of $k(x)$ on $x^*$ is given by:

$$\frac{\partial x^*}{\partial k(x)} = -\frac{\psi(pf)h\phi_{x\theta}(x^*, \hat{\theta})}{\psi(pf)h\phi_{xx}(x^*, \hat{\theta}) + c''(x^*)}\frac{\partial \hat{\theta}}{\partial k(x)} \tag{S31}$$

By design, $\phi_{xx}(x^*, \hat{\theta}) > 0$ and $c''(x^*) > 0$, which implies that the sign of the relationship between $k(x)$ and $x^*$ is completely characterized by the inverse of the product between $\phi_{x\theta}(x^*, \hat{\theta})$ and $\partial\hat{\theta}/\partial k(x)$. This statement completes the proof. □

## S2.3 Empirical challenges

Establishing the effect of piracy on shipping behavior posses several challenges. One possibility is a self-selection process that arises when pirates target specific ships, or it may be also plausible that some vessels are actively looking to be hijacked. In the presence of any of these possibilities, any estimate will be polluted with omitted variable bias.

For example, in Supplementary Text S2.1.2 we note that according to the documented testimonies, most of the initial encounters occur at random. In other words, pirates decide to attack after observing the vessel that they happen to run into. The randomness behind these encounters would normally be sufficient for identification, but the presence of sophisticated pirates challenges this claim. That is, it is plausible that the encounters could actually be planned by pirates or the crew, which implies that they do not occur at random. This issue may be more likely to occur in Southeast Asia, where the attacks appear to be more sophisticated.

The nature of the shipping industry, however, allows us to propose a solution for this problem. By most accounts, the shipping industry operates on a set schedule regardless of the type of cargo or location. That is, the date at which vessels depart is pre-determined and plausibly exogenous to pirate encounters in the past (*39, 40*). As these schedules are contracted years in advance (*40*), the timing at which pirates encounters occur in the past is likely exogenous for any given voyage departure. We construct the empirical model around this unique characteristic of both the criminal activity, as well as the shipping industry. For robustness, however, we also conduct an instrumental variable analysis in Supplementary Text S2.6.

Maritime transportation is also highly susceptible to weather conditions. It could be possible that route adjustments after pirate encounters are merely a result of spurious correlation between weather patterns and the timing of any given encounter. To account for this possibility, we control for wind patterns along each individual voyage. Wind speed and direction are valid controls for sailing weather conditions as, along with fetch (area of water over which the wind blows), it determines the size of waves in the ocean (*41*).

## S2.4 Supporting material for regression analysis

In this section, we provide supporting material for the regression analyses in the study. First, we provide the tables with the summary statistics for the data used in the grid and voyage analyses, respectively. Table S1 shows that the average traffic per grid is highly variable across the globe, with the Gulf of Aden and Southeast Asia having much higher distance, occupancy time, voyages and unique vessels transiting in their respective areas than the rest of the world combined. For example, the average daily occupancy is 38.2 and 78.1 hours in the Gulf of Aden and the Southeast Asia hotspots, respectively, while in the rest of the world the daily occupancy is 35.1 hours instead. This pattern persists for all the variables in the dataset, though there is considerable spread among all sub-samples and variables.

Table S2 shows that when analyzed at the voyage level, the pattern is slightly modified. Here, in average, vessels crossing hotspots travel longer distances and for more time than vessels table S1: Summary Statistics for Daily Ship Transit by Grid Cell.

| | Distance (km) | Occupancy (hr) | Voyages (#) | Unique vessels (#) |
|---|---|---|---|---|
| **Gulf of Aden** | | | | |
| Mean | 708.6 | 38.2 | 14.3 | 14.1 |
| SD | 1,002.7 | 59.5 | 20.7 | 20.2 |
| Median | 126.4 | 9.4 | 3.0 | 3.0 |
| Max | 8,742.6 | 1,038.4 | 157.0 | 146.0 |
| **Gulf of Guinea** | | | | |
| Mean | 137.8 | 11.9 | 3.3 | 3.3 |
| SD | 154.5 | 20.0 | 3.4 | 3.4 |
| Median | 97.8 | 5.8 | 3.0 | 2.0 |
| Max | 2,110.1 | 407.6 | 37.0 | 37.0 |
| **Southeast Asia** | | | | |
| Mean | 1,085.3 | 78.1 | 18.5 | 17.6 |
| SD | 2,369.4 | 178.3 | 41.2 | 39.9 |
| Median | 247.0 | 20.8 | 4.0 | 4.0 |
| Max | 30,165.2 | 4,156.4 | 407.0 | 399.0 |
| **Rest of the World** | | | | |
| Mean | 391.1 | 35.1 | 11.4 | 10.8 |
| SD | 919.6 | 79.1 | 26.6 | 25.4 |
| Median | 106.2 | 7.6 | 3.0 | 3.0 |
| Max | 16,593.6 | 2,172.6 | 261.0 | 247.0 |

table S2: Summary Statistics for Individual Voyage Features.

| | Distance (km) | Time (hr) | Speed (km/hr) | Encounters (#/3 mo) |
|---|---|---|---|---|
| **Gulf of Aden** | | | | |
| Mean | 1,753.3 | 94.6 | 18.7 | 0.5 |
| SD | 3,060.6 | 217.5 | 7.4 | 1.2 |
| Min | 0.2 | 0.0 | 0.0 | 0.0 |
| Max | 421,538.8 | 37,861.1 | 115.5 | 25.0 |
| **Gulf of Guinea** | | | | |
| Mean | 3,014.9 | 149.6 | 20.1 | 4.6 |
| SD | 4,040.2 | 238.4 | 7.5 | 5.8 |
| Min | 0.1 | 0.0 | 0.0 | 0.0 |
| Max | 468,276.4 | 33,372.3 | 58.6 | 45.0 |
| **Southeast Asia** | | | | |
| Mean | 1,130.7 | 65.5 | 17.7 | 1.9 |
| SD | 2,768.4 | 266.8 | 6.6 | 5.0 |
| Min | 0.1 | 0.0 | 0.0 | 0.0 |
| Max | 813,656.8 | 51,409.2 | 130.2 | 44.0 |
| **Rest of the World** | | | | |
| Mean | 608.8 | 30.9 | 21.5 | 0.1 |
| SD | 1,506.3 | 102.0 | 8.3 | 0.6 |
| Min | 0.0 | 0.0 | 0.0 | 0.0 |
| Max | 464,388.8 | 53,031.0 | 1,060.9 | 27.0 |

not crossing through hotspots, though there is also a relatively high degree of spread on the voyage features. Importantly, the hotspots with the highest mean observed piracy encounters in the preceding three months along routes take place in the Gulf of Guinea. The distribution of the remaining variables in the analysis (i.e., costs and emissions) follow directly from these observed features.

Second, we provide the regression tables not presented in the main text. The results for the linear average effect of piracy are stacked in Table S4 for fuel, labor, and total operational costs in thousands of US dollars, respectively. Across all samples, the results show that path adjustments increase fuel cost the most. One additional encounter relates to hundreds or thousands of dollars in additional fuel spent. These estimates are consistent with path adjustments. The results also suggest that vessels passing through the Gulf of Aden face the biggest burden with an additional US$5 thousand per encounter, while those in the Southeast Asia face the least.

These adjustments are also meaningful in terms of labor cost. The effects of additional encounters are positive and significant, but at most half of the adjustment cost when compared to additional fuel consumption. We note that this result is consistent across samples.

table S3: Effect of Past Pirate Encounters on Shipping Cost.

| | Global | G. of Aden | G. of Guinea | S.E. Asia |
|---|---|---|---|---|
| *Panel (A): Fuel Cost (TUSD)* | | | | |
| Encounters (3 mo) | 0.58*** | 5.12*** | 0.41*** | 0.49*** |
| | (0.08) | (0.58) | (0.06) | (0.12) |
| *Panel (B): Labor Cost (TUSD)* | | | | |
| Encounters (3 mo) | 0.26*** | 1.31*** | 0.25*** | 0.23*** |
| | (0.03) | (0.12) | (0.02) | (0.04) |
| *Panel (C): Total Cost (TUSD)* | | | | |
| Encounters (3 mo) | 0.83*** | 6.43*** | 0.66*** | 0.72*** |
| | (0.11) | (0.66) | (0.07) | (0.14) |
| Observations | 25,628,927 | 1,034,194 | 276,183 | 6,334,875 |
| Hotspot FE | X | ● | ● | ● |

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ The unit of observation is a voyage. Each panel examines a calculated cost in terms of fuel cost, labor cost, and total cost as the sum of both. All coefficients are in thousands of US$. The sample spans from 2013 to 2021. Every column is a different sample: Global is the analysis using the whole sample. G. of Aden, S.E. Asia, and G. of Guinea restrict the sample to vessels passing through one of the hotspots, respectively. Every panel-column combination is a different regression analysis. Encounters (3mo) is the count of pirate encounters recorded in the projected path of the vessel in the preceding 90 days from the departure date using a 5 degree spatial footprint. Controls include average wind speed along the voyage and the wind-resistance index. Fixed effects include country-to-country combination, vessel type, vessel size, hotspot, and a battery of month by year and top port-to-port combination for country-to-country combination dummies.

table S4: Effect of Past Pirate Encounters on Shipping Cost.

| | Global | G. of Aden | G. of Guinea | S.E. Asia |
|---|---|---|---|---|
| *Panel (A): Fuel Cost (TUSD)* | | | | |
| Encounters (3 mo) | 0.58*** | 5.12*** | 0.41*** | 0.49*** |
| | (0.08) | (0.58) | (0.06) | (0.12) |
| *Panel (B): Labor Cost (TUSD)* | | | | |
| Encounters (3 mo) | 0.26*** | 1.31*** | 0.25*** | 0.23*** |
| | (0.03) | (0.12) | (0.02) | (0.04) |
| *Panel (C): Total Cost (TUSD)* | | | | |
| Encounters (3 mo) | 0.83*** | 6.43*** | 0.66*** | 0.72*** |
| | (0.11) | (0.66) | (0.07) | (0.14) |
| Observations | 25,628,927 | 1,034,194 | 276,183 | 6,334,875 |
| Hotspot FE | X | • | • | • |

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ The unit of observation is a voyage. Each panel examines a calculated cost in terms of fuel cost, labor cost, and total cost as the sum of both. All coefficients are in thousands of US$. The sample spans from 2013 to 2021. Every column is a different sample: Global is the analysis using the whole sample. G. of Aden, S.E. Asia, and G. of Guinea restrict the sample to vessels passing through one of the hotspots, respectively. Every panel-column combination is a different regression analysis. Encounters (3mo) is the count of pirate encounters recorded in the projected path of the vessel in the preceding 90 days from the departure date using a 5 degree spatial footprint. Controls include average wind speed along the voyage and the wind-resistance index. Fixed effects include country-to-country combination, vessel type, vessel size, hotspot, and a battery of month by year and top port-to-port combination for country-to-country combination dummies.

We estimate the effect of piracy on total operational costs by aggregating both fuel and labor costs. These results are reported in Panel (C) of Table S4, and suggest that the average increase in operational costs due to avoidance measures per additional encounter ranges from over US$600 in the Gulf of Guinea to over US$6.4 thousand in the Gulf of Aden. Globally, this effect averages down to about US$800 for each additional pirate encounter.

The linear average effects of piracy on emissions are stacked in Table S5 for $CO_2$, $NO_x$, and $SO_x$, respectively. As expected from previous results, excessive fuel consumption leads to excessive emissions across the spectrum of relevant pollutants. In particular, increases in $CO_2$ range from 2.6 to 35.15 tons per voyage per past pirate encounter. $NO_x$ and $SO_x$ emissions due to piracy are relatively less voluminous, though this is a direct consequence of their significantly smaller concentrations in bunker fuel relative to carbon. Nonetheless, regression estimates point to dozens of kilograms, and hundreds in the case of the Gulf of Aden, of excess pollutants emitted due to the presence of pirates.

table S5: Effect of Past Pirate Encounters on Shipping Emissions.

| | Global | G. of Aden | G. of Guinea | S.E. Asia |
|---|---|---|---|---|
| *Panel (A): $CO_2$ (tons)* | | | | |
| Encounters (3 mo) | 3.50*** | 35.15*** | 4.29*** | 2.60*** |
| | (0.37) | (3.85) | (0.39) | (0.36) |
| *Panel (B): $NO_x$ (kg)* | | | | |
| Encounters (3 mo) | 85.70*** | 895.31*** | 106.15*** | 62.67*** |
| | (9.29) | (99.26) | (10.00) | (8.96) |
| *Panel (C): $SO_x$ (kg)* | | | | |
| Encounters (3 mo) | 72.95*** | 731.85*** | 89.29*** | 54.23*** |
| | (7.79) | (80.07) | (8.17) | (7.55) |
| Observations | 25,629,585 | 1,034,211 | 276,220 | 6,335,025 |
| Hotspot FE | X | • | • | • |

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ The unit of observation is a voyage. Each panel examines a calculated emission in terms of $textCO_2$ (tons), $NO_x$ (kg), and $SO_x$ (kg). The sample spans from 2013 to 2021. Every column is a different sample: Global is the analysis using the whole sample. G. of Aden, S.E. Asia, and G. of Guinea restrict the sample to vessels passing through one of the hotspots, respectively. Every panel-column combination is a different regression analysis. Encounters (3mo) is the count of pirate encounters recorded in the projected path of the vessel in the preceding 90 days from the departure date using a 5 degree spatial footprint. Controls include average wind speed along the voyage and the wind-resistance index. Fixed effects include country-to-country combination, vessel type, vessel size, hotspot, and a battery of month by year and top port-to-port combination for country-to-country combination dummies.

## S2.5 Counterfactual costs and emissions

We use the fully specified *global* model (5° grid, 3 month window) to predict voyage-level fuel and labor costs, as well as emissions of $CO_2$, $NO_x$, and $SO_x$. We make predictions using the observed number of pirate encounters and a counterfactual of no pirate encounters at all. We then take the difference between these two predictions to obtain a voyage-level estimate of the additional fuel and labor costs, and emissions of each pollutant. We then calculate the total annual costs and emissions across all voyages. These results are shown in Table S6 and Table S7, where we also provide information disaggregated by hotspot.

Having matched each voyage to its additional costs and emissions, we then divide a voyage's cost (or emissions) across all 0.5°x0.5° grid cells along which the vessel transited. For each grid cell, we calculate the total surplus costs (fuel + labor) or emissions of each pollutant. We then take the average across all years (2013-2021) and use these data to produce maps shown in Figure 3A.

We are also interested in estimating the total public and private costs of modern-day piracy. We monetize the environmental impacts caused by additional emission of local and global air pollutants using their social-cost. Specifically, we use estimates provided by the Interagency Working Group on Social Cost of Greenhouse Gases (*11*), which suggest that an additional ton of $CO_2$ or $NO_x$ induce damages valued at US$51 and US$18,000 (in 2020 US$ assuming a 3% discount rate). For $SO_x$ we use estimates from Mier, Adelowo, and Weissbart (*12*), which indicates an additional ton of SO2 inducing damages of US$14,694 (in 2020 US$). We then aggregate all information by ASAM region, and produce bar charts shown in Figure 3B.

table S6: Total Costs of Piracy to the Shipping Industry.

| | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|
| **Fuel (Million USD)** | | | | | | | | | |
| Global | 1,099 | 1,274 | 1,571 | 988 | 1,036 | 553 | 478 | 1,325 | 1,210 |
| G. of Aden | 50 | 34 | 18 | 42 | 66 | 17 | 23 | 42 | 38 |
| G. of Guinea | 108 | 75 | 52 | 91 | 82 | 106 | 51 | 114 | 72 |
| Southeast Asia | 838 | 1,129 | 1,431 | 619 | 663 | 319 | 327 | 1,032 | 914 |
| **Labor (Million USD)** | | | | | | | | | |
| Global | 491 | 569 | 702 | 442 | 463 | 247 | 214 | 592 | 541 |
| G. of Aden | 22 | 15 | 8 | 19 | 29 | 7 | 10 | 19 | 17 |
| G. of Guinea | 48 | 34 | 23 | 41 | 37 | 47 | 23 | 51 | 32 |
| Southeast Asia | 374 | 505 | 640 | 277 | 297 | 142 | 146 | 461 | 409 |
| **Total (Million USD)** | | | | | | | | | |
| Global | 1,590 | 1,843 | 2,273 | 1,430 | 1,499 | 801 | 692 | 1,917 | 1,751 |
| G. of Aden | 72 | 49 | 26 | 61 | 95 | 24 | 33 | 61 | 55 |
| G. of Guinea | 156 | 109 | 75 | 131 | 119 | 153 | 74 | 164 | 104 |
| Southeast Asia | 1,212 | 1,634 | 2,072 | 896 | 960 | 461 | 473 | 1,493 | 1,323 |

table S7: Total Emission of Air Pollutants due to Piracy

| | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|
| **$CO_2$ (Thousand metric tons)** | | | | | | | | | |
| Global | 5,325 | 6,226 | 7,622 | 4,740 | 5,144 | 2,727 | 2,356 | 6,479 | 5,968 |
| G. of Aden | 239 | 159 | 91 | 204 | 310 | 80 | 114 | 201 | 182 |
| G. of Guinea | 528 | 369 | 257 | 449 | 408 | 511 | 248 | 547 | 344 |
| Southeast Asia | 4,040 | 5,508 | 6,919 | 2,994 | 3,262 | 1,548 | 1,597 | 5,055 | 4,456 |
| **NOx (Metric tons)** | | | | | | | | | |
| Global | 130,242 | 152,280 | 186,422 | 115,938 | 125,818 | 66,712 | 57,625 | 158,464 | 145,986 |
| G. of Aden | 5,840 | 3,883 | 2,223 | 4,985 | 7,581 | 1,962 | 2,796 | 4,926 | 4,446 |
| G. of Guinea | 12,919 | 9,036 | 6,295 | 10,974 | 9,983 | 12,502 | 6,062 | 13,379 | 8,412 |
| Southeast Asia | 98,808 | 134,736 | 169,240 | 73,237 | 79,781 | 37,861 | 39,073 | 123,644 | 108,991 |
| **SOx (Metric tons)** | | | | | | | | | |
| Global | 110,861 | 129,620 | 158,682 | 98,686 | 107,096 | 56,786 | 49,051 | 134,885 | 124,263 |
| G. of Aden | 4,971 | 3,305 | 1,892 | 4,243 | 6,453 | 1,670 | 2,380 | 4,193 | 3,784 |
| G. of Guinea | 10,996 | 7,691 | 5,359 | 9,341 | 8,497 | 10,642 | 5,160 | 11,388 | 7,161 |
| Southeast Asia | 84,105 | 114,687 | 144,057 | 62,339 | 67,909 | 32,227 | 33,258 | 105,245 | 92,773 |

## S2.6 Instrumental variable analysis

In the main analysis, our identification assumption relies on the timing of shipping vessel departures. We assume that these are exogenous to the number of encounters in the preceding months due to shipment schedules. Nonetheless, as described in Supplementary Text S2.3, there is still a chance that sophisticated pirates or shippers might be self-selecting into treatment, thereby violating our exogeneity assumption.

To alleviate these concerns, we conduct an ancillary analysis that relies on an instrumental variable approach. Here, we will focus on the two hotspots that afflict the African continent, as they are relatively more condensed geographically and follow a similar business model. We conjecture that political stability is correlated with reported pirate encounters within the Economic Exclusive Zones (EEZ) comprising the Gulf of Aden and the Gulf of Guinea, respectively. This is consistent with previous studies on economic stability and the incidence of piracy (*33, 34*). In turn, political stability is only likely to affect a vessel's path through piracy.

Fist, we characterize the Gulf of Aden as the EEZs of Djibouti, Eritrea, Eritrea, Kenya, Kenya, Oman, Somalia, Tanzania, and Yemen. The Gulf of Aden is characterized by the EEZs of Angola, Benin, Cameroon, Equatorial Guinea, Gabon, Ghana, Liberia, Nigeria, Sao Tome and Principe, Sao Tome and Principe, and Togo. We then count the total number of pirate encounters, and use the observed vessel monitoring data from Global Fishing Watch for our sample of shipping vessels to summarize the total transit time (hr), distance traveled (km), and number of unique vessels that were observed annually in each EEZ from 2013 to 2021.

We then take data from the World Bank's Worldwide Development Indicators and track the Political Stability Index by country, which assesses the likelihood of government destabilization or overthrow through unconstitutional or violent means, including terrorism.[12] The index aggregates perceptions from various sources, including surveys and expert evaluations, and ranges from -2.5 (indicating low stability) to 2.5 (high stability). Summary statistics for the variables used in the analysis is shown in Table S8.

The analysis is implemented in two stages. The first stage is as follows:

$$TNE_{it} = \Lambda + \Phi PS_{it} + \Psi_i + \Pi' X_t + u_{it} \tag{S32}$$

$TNE$ is is the number of encounters, while $PS$ is the reported political stability in country $i$ in year $t$, respectively. $\Phi$ is the marginal change in yearly pirate encounters that follows a change in political stability. $\Psi$ is an indicator variable that takes a value of one if the country belongs to the Gulf of Guinea. $X_t$ is a dummy variable for year $t$. To account for potential geographical and temporal correlation, we cluster standard errors by hotspot by year.

In the second stage we are interested in the number of vessels that go through EEZ, the distance they travel within EEZs (km/vessel), and the time they spend in said EEZ (hr/vessel), as a function of the pirate encounters in that area. The model is as follows:

[12] In addition to political stability, the World Bank tracks a variety of indicators that relate to the economic and institutional stability of countries worldwide. These data updated on a yearly basis and are estimated by country. The data are available online here: `https://t.ly/UbR6y`

table S8: Summary Statistics for Variables Used in the Instrumental Variable Analysis.

| | Political Stability | Encounters (#) | Vessels (#) | Distance (km/vessel) | Time (hr/vessel) |
|---|---|---|---|---|---|
| **Gulf of Aden** | | | | | |
| Mean | -1.0 | 2.6 | 3,857.6 | 1,446.6 | 76.0 |
| SD | 1.0 | 5.1 | 3,148.3 | 1,277.3 | 59.2 |
| Min | -3.0 | 0.0 | 212.0 | 30.5 | 1.2 |
| Max | 0.8 | 36.0 | 9,958.0 | 4,547.0 | 190.1 |
| **Gulf of Guinea** | | | | | |
| Mean | -0.4 | 5.8 | 1,896.7 | 1,045.5 | 65.3 |
| SD | 0.7 | 11.6 | 721.6 | 607.6 | 36.8 |
| Min | -2.1 | 0.0 | 660.0 | 247.0 | 11.3 |
| Max | 0.6 | 67.0 | 3,736.0 | 2,248.5 | 144.7 |

table S9: First Stage IV Regression: Effect of Political Stability on Yearly Pirate Encounters.

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| Political Stability | $-3.72^{***}$ | $-3.73^{***}$ | | $-5.07^{***}$ |
| | (1.17) | (1.20) | | (1.40) |
| Gulf of Guinea Dummy | | | $3.12^{***}$ | $6.47^{***}$ |
| | | | (0.54) | (0.93) |
| Year FE | | X | X | X |

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ The unit of observation is a country. The sample spans from 2013 to 2021. Every column is a different specification. Political Stability is the index reported by the World Bank as part of its World Development Indicators. Additional covariates include a dummy variable if a country belongs to the Gulf of Guinea and yearly dummies. Standard errors are clustered by gulf by year. Number of observations is 180.

$$y_{it} = \alpha + \beta \widehat{TNE}_{it} + \Psi_i + \Pi' X_t + e_{it} \tag{S33}$$

$y$ is the shipping measure of interest, while $\widehat{TNE}_{it}$ is the predicted number of encounters in the first stage in country $i$ in year $t$. To account for potential geographical and temporal correlation, we continue to cluster standard errors by hotspot by year.

The results of the analysis are presented in Tables S9 and S10, respectively. Table S10 also shows the result for a simple ordinary least squares (OLS) for reference. Overall, the analysis provides support for the validity of the instrument in the first stage. Increases in political stability are correlated with a decrease in pirate encounters in a given EEZ (Table S9). This result is robust to the inclusion of the Gulf of Guinea dummy, and it highlights the potential importance of a country's economic and institutional state when it comes to the proliferation of piracy.

table S10: Instrumental Variable Analysis of the Effect of Pirate Encounters on Shipping Patterns

| | OLS | | | 2SLS | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| *Panel (A): Vessels (#)* | | | | | | |
| Encounters | 9.93 | 9.41 | 28.25* | -22.01 | -24.17 | -113.53** |
| | (12.73) | (10.56) | (13.49) | (37.47) | (36.53) | (48.67) |
| *Panel (B): Distance (km/vessel)* | | | | | | |
| Encounters | 19.03** | 19.60** | 23.98** | 83.26** | 83.33** | 52.01** |
| | (7.18) | (7.01) | (8.33) | (30.33) | (31.12) | (18.79) |
| *Panel (C): Time (hr/vessel)* | | | | | | |
| Encounters | 1.45*** | 1.51*** | 1.65*** | 4.59*** | 4.60*** | 3.41*** |
| | (0.23) | (0.23) | (0.28) | (1.26) | (1.28) | (0.80) |
| Gulf of Guinea Dummy | | | X | | | X |
| Year FE | | X | X | | X | X |
| F-Stat | | | | 25.73 | 25.56 | 46.20 |

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ The unit of observation is a country. Each panel examines an observed feature in terms of total number of vessels transiting an EEZ (#), total normalized distance traveled within an EEZ (hr/vessel), and total normalized time spent within an EEZ (hr/vessel). The explanatory variable is number of pirate encounters. The sample spans from 2013 to 2021. Columns (1) to (3) present the results of ordinary least squares (OLS), while columns (4) to (5) present the result from a two-stage least squares using political stability as an instrument for pirate encounters, respectively. Every panel-column combination is a different regression analysis. Additional covariates include a dummy variable if a country belongs to the Gulf of Guinea and yearly dummies. Standard errors are clustered by gulf by year. Number of observations is 180.

The instrumental variable analysis in Table S10 provides several insights. First, the results are consistent with the main analysis. That is, travel distance and time, per vessel, are increased in the presence of piracy, at least at the EEZ level. These increases follow our theoretical insights in Supplementary Text S2.2. We note, however, that there also seems to be a significant decrease in shipping EEZ total traffic following pirate encounters after accounting for geographical patterns across hotspots.

Compared with the OLS analysis, these estimates also suggest that failing to account for endogeneity can create a few issues. First, simple OLS would suggest that there are more vessels sailing in these EEZs. The instrumental variable estimates show that the relationship is negative instead. Second, and while the estimates have the right sign, that OLS tends to underestimate the level of adjustment within EEZs.

These results do not replace the insights in the main paper but tell a cohesive story. Captains are aware of the risk that pirates represent and adjust their paths accordingly. Increases in operational cost and emissions follow directly from these results.

## S2.7 Robustness tests

Here, we show robustness checks for all of the empirical results: how pirate encounters affect total shipping traffic within spatial grids, and how pirate encounters affect the features of individual voyages. The two sets of robustness checks largely follow the same pattern. Pirate encounters reduce traffic within grid cells. These adjustments result in adjustments at the individual voyage level, which is then demonstrated by increase in the average total distance time traveled for the same port-to-port combination.

### S2.7.1 Grid-level analysis

Here, we show evidence of the robustness of the grid-level analysis. First, we show robustness to different sets of fixed effects in tabular form. The first set of results uses a global sample (Table S11). Then, we repeat the exercise for the subset of grid cells belonging to each of the three hotspots. The results for the Gulf of Aden, Gulf of Guinea, and Southeast Asia are presented in Table S12, Table S13, and Table S14, respectively. In all tables, the fourth column presents the same results as Table 1 in the main text, which are the preferred specification including fixed-effects for grid id, for ASAM subregion, and for ASAM region by year by month. All estimates from models with at least one fixed effect are relatively stable, with estimates always showing the same direction and similar magnitude as the preferred specification.

Second, we show robustness to using the total number of encounters occurring in a grid cell over the last 3, 6 and 12 months. We find consistent evidence that additional past pirate encounters result in reduced vessel activity globally and across all three hotspots (Figure S2). Additionally, lengthening the time window for encounters reduces the coefficient estimates because encounters far into the past are not as important as recent events.

Finally, as stated in our Methods, we also estimate dynamic effects in an event-study framework. Here, we use distance traveled (km), normalized distance traveled (km/vessel and km/voyage), occupancy time (hr), and normalized occupancy time (hr/vessel and hr/voyage) as our response variables. This analysis restricts the sample to grid cells with no overlapping attacks five days before or after a given attack date (N = 233). The main results are shown in Figure S3. As before we also test for different fixed-effect specifications (Figure S4) and effects by hotspot (Figure S5). The results are generally consistent and show a decrease in grid-level activity following, but not leading to, an encounter.

table S11: Effect of Piracy on Grid-level Ship Transit For Different Fixed-effects Specifications for a Global Sample.

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| *Panel (A): Total Distance (km)* | | | | |
| Encounters (3 mo) | 484.96* | -14.76 | -14.76 | -4.90 |
| | (284.26) | (12.53) | (12.53) | (11.53) |
| *Panel (B): Occupancy (hr)* | | | | |
| Encounters (3 mo) | 58.73* | 7.75 | 7.75 | 8.42 |
| | (31.50) | (6.86) | (6.86) | (6.73) |
| *Panel (C): Voyages (#)* | | | | |
| Encounters (3 mo) | 10.05* | -0.06 | -0.06 | 0.32 |
| | (5.94) | (0.47) | (0.47) | (0.44) |
| *Panel (D): Vessels (#)* | | | | |
| Encounters (3 mo) | 9.83* | -0.03 | -0.03 | 0.35 |
| | (5.85) | (0.48) | (0.48) | (0.45) |
| Grid ID FE | | X | X | X |
| ASAM Subregion FE | | | X | X |
| ASAM Region-year-month FE | | | | X |

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ The unit of observation is a grid cell (N = 590 unique cells). The sample spans from 2013 to 2021. Each panel examines a measure of grid-level ship transit in terms of total distance in kilometers (km), total occupancy time in hours (hr), and the number of unique voyages or vessels transiting through the grid cell. Each column is a different regression analysis adding fixed-effects by grid ID, then group, and finally time. Every panel-column combination is a different regression analysis. Encounters (3mo) is the count of pirate encounters recorded within the grid cell in the preceding 90 days. Numbers in parentheses are Conley Standard Errors (100 km cutoff). Number of observations: 1,939,330.

table S12: Effect of Piracy on Grid-level Ship Transit For Different Fixed-effects Specifications for the Gulf of Aden.

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| *Panel (A): Total Distance (km)* | | | | |
| Encounters (3 mo) | 58.07 | -30.57** | -30.57** | -26.50* |
| | (105.55) | (14.67) | (14.67) | (13.78) |
| *Panel (B): Occupancy (hr)* | | | | |
| Encounters (3 mo) | 7.91** | -0.89 | -0.89 | -0.70 |
| | (3.84) | (1.05) | (1.05) | (1.20) |
| *Panel (C): Voyages (#)* | | | | |
| Encounters (3 mo) | 0.61 | -1.05** | -1.05** | -0.67** |
| | (1.24) | (0.45) | (0.45) | (0.34) |
| *Panel (D): Vessels (#)* | | | | |
| Encounters (3 mo) | 0.62 | -1.04** | -1.04** | -0.65* |
| | (1.24) | (0.44) | (0.44) | (0.34) |
| Grid ID FE | | X | X | X |
| ASAM Subregion FE | | | X | X |
| ASAM Region-year-month FE | | | | X |

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ The unit of observation is a grid cell (N = 93 unique cells). The sample spans from 2013 to 2021. Each panel examines a measure of grid-level ship transit in terms of total distance in kilometers (km), total occupancy time in hours (hr), and the number of unique voyages or vessels transiting through the grid cell. Each column is a different regression analysis adding fixed-effects by grid ID, then group, and finally time. Encounters (3mo) is the count of pirate encounters recorded within the grid cell in the preceding 90 days. Numbers in parentheses are Conley Standard Errors (100 km cutoff). Number of observations: 305,691.

table S13: Effect of Piracy on Grid-level Ship Transit For Different Fixed-effects Specifications for the Gulf of Guinea.

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| *Panel (A): Total Distance (km)* | | | | |
| Encounters (3 mo) | 28.59 | -4.80*** | -4.80*** | -4.58*** |
| | (23.12) | (1.64) | (1.64) | (1.32) |
| *Panel (B): Occupancy (hr)* | | | | |
| Encounters (3 mo) | 6.84 | -0.33 | -0.33 | -0.26 |
| | (4.69) | (0.63) | (0.63) | (0.62) |
| *Panel (C): Voyages (#)* | | | | |
| Encounters (3 mo) | 0.94 | -0.10*** | -0.10*** | -0.11*** |
| | (0.64) | (0.03) | (0.03) | (0.04) |
| *Panel (D): Vessels (#)* | | | | |
| Encounters (3 mo) | 0.91 | -0.10*** | -0.10*** | -0.10*** |
| | (0.63) | (0.03) | (0.03) | (0.04) |
| Grid ID FE | | X | X | X |
| ASAM Subregion FE | | | X | X |
| ASAM Region-year-month FE | | | | X |

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ The unit of observation is a grid cell (N = 134 unique cells). The sample spans from 2013 to 2021. Each panel examines a measure of grid-level ship transit in terms of total distance in kilometers (km), total occupancy time in hours (hr), and the number of unique voyages or vessels transiting through the grid cell. Each column is a different regression analysis adding fixed-effects by grid ID, then group, and finally time. Encounters (3mo) is the count of pirate encounters recorded within the grid cell in the preceding 90 days. Numbers in parentheses are Conley Standard Errors (100 km cutoff). Number of observations: 440,458.

table S14: Effect of Piracy on Grid-level Ship Transit For Different Fixed-effects Specifications for Southeast Asia.

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| *Panel (A): Total Distance (km)* | | | | |
| Encounters (3 mo) | 773.99*** | -21.09 | -21.09 | -3.69 |
| | (266.27) | (21.06) | (21.06) | (21.18) |
| *Panel (B): Occupancy (hr)* | | | | |
| Encounters (3 mo) | 91.82*** | 14.70 | 14.70 | 15.97 |
| | (34.42) | (10.35) | (10.35) | (9.89) |
| *Panel (C): Voyages (#)* | | | | |
| Encounters (3 mo) | 16.56*** | 0.14 | 0.14 | 0.79 |
| | (5.87) | (0.79) | (0.79) | (0.68) |
| *Panel (D): Vessels (#)* | | | | |
| Encounters (3 mo) | 16.22*** | 0.21 | 0.21 | 0.83 |
| | (5.79) | (0.80) | (0.80) | (0.69) |
| Grid ID FE | | X | X | X |
| ASAM Subregion FE | | | X | X |
| ASAM Region-year-month FE | | | | X |

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ The unit of observation is a grid cell (N = 149 unique cells). The sample spans from 2013 to 2021. Each panel examines a measure of grid-level ship transit in terms of total distance in kilometers (km), total occupancy time in hours (hr), and the number of unique voyages or vessels transiting through the grid cell. Each column is a different regression analysis adding fixed-effects by grid ID, then group, and finally time. Encounters (3mo) is the count of pirate encounters recorded within the grid cell in the preceding 90 days. Numbers in parentheses are Conley Standard Errors (100 km cutoff). Number of observations: 489,763.

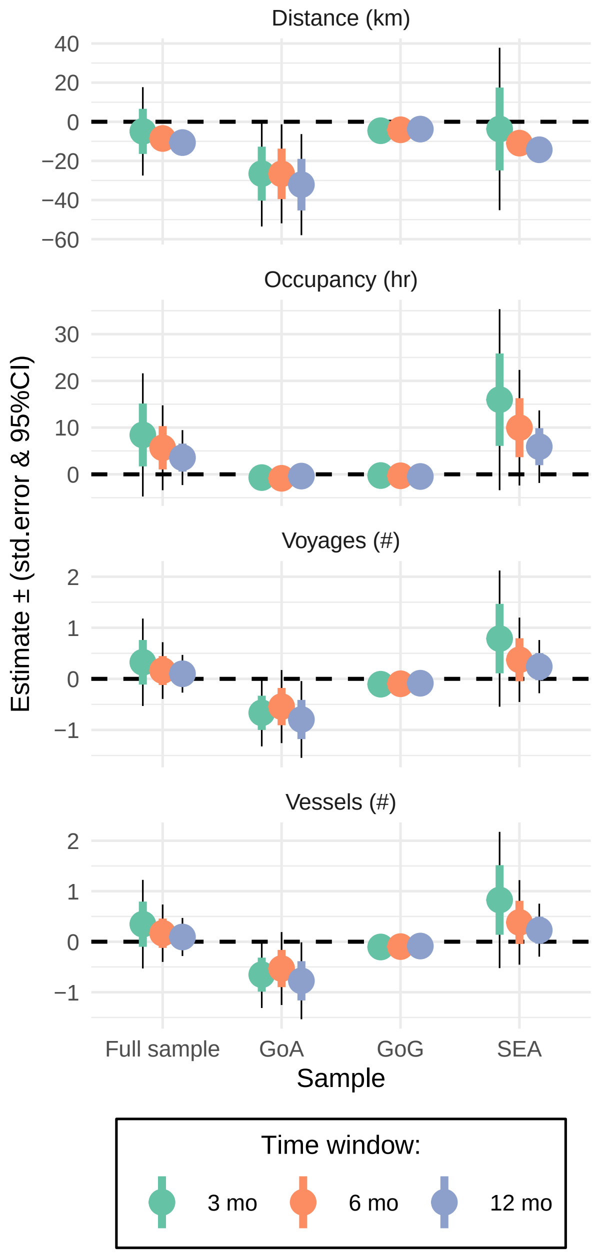


fig S2: **Average piracy effect on grid-level ship transit.** The x-axis shows the sub-sample and the y-axis the estimated effect. Each marker indicates a coefficient estimate for the average effect of the number of attacks over the last 3, 6, or 12 months on the measure of ship transit shown in each panel. The colored portion of error bars show standard errors and the black portion of the error bars shows 95% CIs. Note how increasing the time window results in attenuated coefficients.

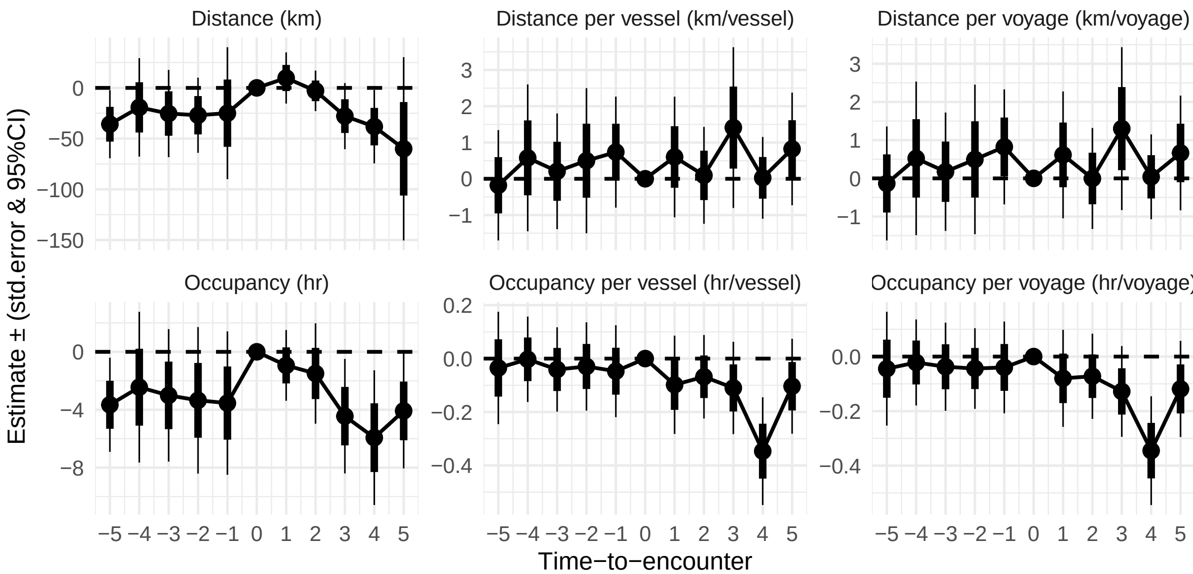


fig S3: **Event-study for the effect of piracy attacks on ship transit.** The top row shows coefficient estimates with distance (km) and normalized distance (km/vessel and km/voyage) as the dependent variable. The bottom row uses occupancy time (hours) and normalized occupancy time (hr/vessel and hr/voyage) as the dependent variable. We estimate a total of 10 coefficients and our sample contains 233 grid cells. Coefficients show the change in transit relative to the day of attack (i.e., Time-to-encounter = 0). The thick portion of error bars are spatial Conley standard errors using a 100 km radius and the thin portion of error bars shows 95%CIs. All estimations include fixed effects by ASAM subregion, Year-by-month-by-ASAM region, and grid-id.

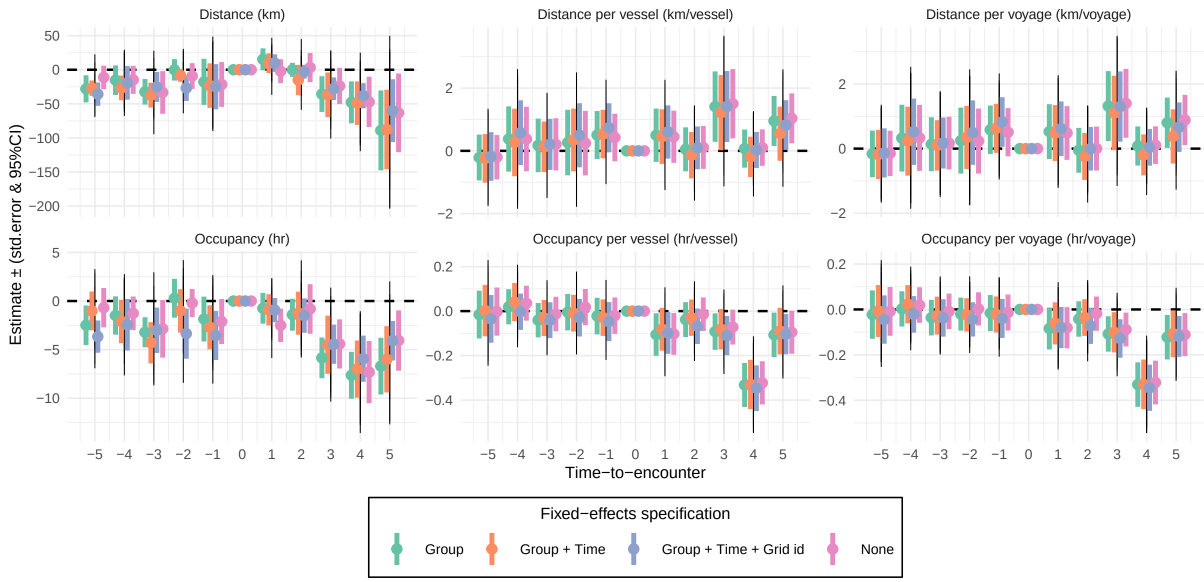


fig S4: **Build-up to a Two-way fixed effects specification.** The top row shows coefficient estimates with distance (km) and normalized distance (km/vessel and km/voyage) as the dependent variable. The bottom row uses occupancy time (hours) and normalized occupancy time (hr/vessel and hr/voyage) as the dependent variable. We estimate a total of 10 coefficients and our sample contains 233 grid cells. Coefficients show the change in transit relative to the day of attack (i.e., Time-to-encounter = 0). Colors indicate different fixed-effects specification. The thick portion of error bars are spatial Conley standard errors using a 100 km radius and the thin portion of error bars shows 95%CIs.The preferred specification contains fixed-effects for group, time, and observational unit and are equivalent to these shown in Figure S3.

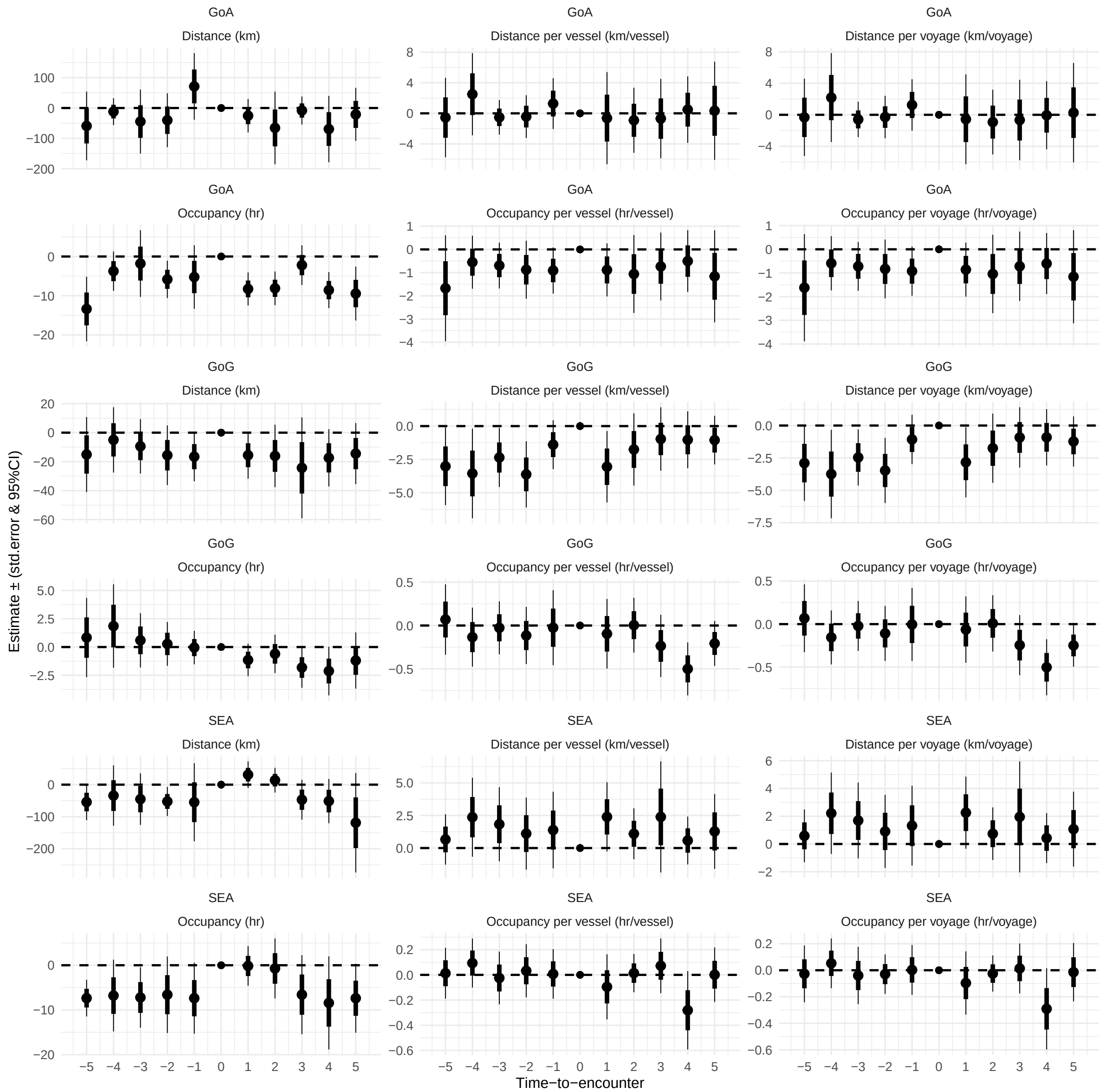


fig S5: **Event-study for the effect of piracy attacks on ship transit by hotspot.** Each row shows a combination of hotspot - measure. We estimate a total of 10 coefficients, which show the change in transit relative to the day of attack (i.e., Time-to-encounter = 0). The thick portion of error bars are spatial Conley standard errors using a 100 km radius and the thin portion of error bars shows 95%CIs. All estimations include fixed effects by ASAM subregion, Year-by-month-by-ASAM region, and grid-id.

### S2.7.2 Voyage-level analysis

Here we present evidence of the robustness of the voyage analysis to several modeling assumptions. First, we show robustness to different sets of fixed effects in tabular form. The estimates are sensitive to the inclusion of country-to-country fixed effects, but this is expected as the length and specific paths of each route are bound to vary widely across combinations. The suite of results are included in Tables S15 to S23. Overall, the results are highly robust to the addition of vessel, hotspot and top route fixed effects. The results are also robust to the inclusion of weather controls in the form of wind speed and wind-resistance index.

Second, we show robustness to i) using a rolling window of 3, 6, and 12 months, as well as the use of a global 3°x3°, 5°x5°, and 7°x7° grid to construct the past encounters variable. This approach allows us to test the temporal and spatial sensitivity of our analysis and the results are shown in Figure S6. The results show that the effect of recent encounters diminishes when longer time windows are considered and that working with larger spatial footprints (i.e., 7°x7°) tends to attenuate results toward zero. For completeness, we will maintain these sensitivities in all of the analyses below.

Third, we show robustness of the results to the categorization of cargo vessels. In the main analysis, we use the best available vessel class for each individual vessel as categorized by Global Fishing Watch. This 'best available' approach uses the vessel class provided by official registries where available, and infers vessel class using a neural network when registries are not available (*9*). As a robustness check, we restrict the analysis to work with: 1) vessels that are always categorized as cargo vessels according to official registries; as well as 2) expand it as those who are categorized in official registries as being cargo vessels at least once. These results are shown in Figure S7 and Figure S8 and are virtually unchanged with respect to the results in the main analysis, though minimal changes around zero are detected for the speed analysis. We reiterate that the magnitudes detected for speed are practically meaningless.

Fourth, we show robustness to the definition of our explanatory variable. For each voyage, we calculate the total number of unique encounters that occurred along all previously traveled paths (i.e., surrogate trips), as well as the chosen path, for each port-to-port route within the preceding months of a voyage's departure. This represents, for any given voyage departure date for any given port-to-port route, the captain's assessment of the prevalence of piracy along the universe of potential paths that have been recently traveled along the route. We call this variable "Total Number of Encounters." The results from this test are shown in Figure S10 and are consistent with the main analysis, though there is considerable attenuation. This is expected, as the marginal impact of an additional pirate encounter diminishes as the potential area of paths along a route increases.

In addition, for each voyage we calculate the average number of unique attacks that occurred along all previously traveled paths (i.e., surrogate trips) for that port-to-port route within a time window. This represents, for any given voyage departure date for any given port-to-port route, the captain's expectation of how many attacks they might expect could occur along the route. We call this variable "Average Number of Encounters." This analysis is presented in Figure S10, and shows considerable attenuation. Positive effects in terms of distance are detected, except in Southeast Asia. Effects in terms of time are mostly dissipated. This result is expected, as it is again easy to see the marginal impact of an additional pirate encounter diminishes further as its effect is now diluted by a considerably increase in the spatial footprint considered, over the number of voyages that took place before.

Finally, we show robustness of the results to the addition of speed and days since the last encounter along a route as *covariates*. The results are shown in Figure S11, and are practically unchanged and provide support that the main adjustments are not polluted by not controlling for voyage speed or other short-term features of risk.

table S15: Effect of Past Pirate Encounters on Voyage Distance.

| | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| Encounters (3 mo) | 146.59*** | 134.88*** | 28.03*** | 27.17*** | 26.94*** | 26.92*** |
| | (15.40) | (14.54) | (3.75) | (3.56) | (3.59) | (3.58) |
| Wind Speed (m/s) | | 305.58*** | 43.21*** | 42.03*** | 31.54*** | 31.29*** |
| | | (24.57) | (4.18) | (3.52) | (4.77) | (4.91) |
| Wind Resistance Index (m/s) (m/s) | | 97.15*** | 11.02*** | −2.10** | −2.19** | −2.78*** |
| | | (7.85) | (1.47) | (0.90) | (0.94) | (0.90) |
| Observations | 19,478,531 | 19,475,535 | 19,475,535 | 19,475,525 | 19,475,525 | 19,475,525 |
| Country Combo. FE | | | X | X | X | X |
| Vessel Type FE | | | | X | X | X |
| Vessel Size FE | | | | X | X | X |
| Hotspot FE | | | | | X | X |
| Top Route FE | | | | | | X |
| Month-by-Year FE | X | X | X | X | X | X |

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ The unit of observation is a voyage. The sample spans from 2013 to 2021. Every column is a different specification. Encounters (3mo) is the count of pirate encounters recorded in the projected path of the vessel in the preceding 90 days from the departure date using a 5 degree spatial footprint. Fixed effects include country-to-country combination, vessel type, vessel size, hotspot, and a battery of month by year and top port-to-port combination for country-to-country combination dummies.

table S16: Effect of Past Pirate Encounters on Voyage Time.

| | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| Encounters (3 mo) | 7.60*** | 7.12*** | 2.29*** | 2.26*** | 2.25*** | 2.25*** |
| | (0.65) | (0.62) | (0.33) | (0.33) | (0.33) | (0.33) |
| Wind Speed (m/s) | | 12.96*** | 1.94*** | 1.91*** | 1.15*** | 1.12*** |
| | | (0.99) | (0.23) | (0.21) | (0.33) | (0.34) |
| Wind Resistance Index (m/s) | | 3.72*** | 0.13** | −0.09* | −0.10* | −0.15*** |
| | | (0.36) | (0.05) | (0.05) | (0.05) | (0.05) |
| Observations | 19,478,531 | 19,475,535 | 19,475,535 | 19,475,525 | 19,475,525 | 19,475,525 |
| Country Combo. FE | | | X | X | X | X |
| Vessel Type FE | | | | X | X | X |
| Vessel Size FE | | | | X | X | X |
| Hotspot FE | | | | | X | X |
| Top Route FE | | | | | | X |
| Month-by-Year FE | X | X | X | X | X | X |

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ The unit of observation is a voyage. The sample spans from 2013 to 2021. Every column is a different specification. Encounters (3mo) is the count of pirate encounters recorded in the projected path of the vessel in the preceding 90 days from the departure date using a 5 degree spatial footprint. Fixed effects include country-to-country combination, vessel type, vessel size, hotspot, and a battery of month by year and top port-to-port combination for country-to-country combination dummies.

table S17: Effect of Past Pirate Encounters on Voyage Speed.

| | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| Encounters (3 mo) | 0.13*** | 0.11*** | 0.01* | −0.01* | −0.01* | −0.01* |
| | (0.02) | (0.02) | (0.01) | (0.01) | (0.01) | (0.01) |
| Wind Speed (m/s) | | 0.43*** | 0.09*** | 0.07*** | 0.06*** | 0.06*** |
| | | (0.05) | (0.02) | (0.01) | (0.01) | (0.01) |
| Wind Resistance Index (m/s) | | 0.55*** | 0.30*** | 0.01 | 0.01 | 0.01 |
| | | (0.03) | (0.02) | (0.01) | (0.01) | (0.01) |
| Observations | 25,641,468 | 25,632,270 | 25,632,270 | 25,632,233 | 25,632,233 | 25,632,233 |
| Country Combo. FE | | | X | X | X | X |
| Vessel Type FE | | | | X | X | X |
| Vessel Size FE | | | | X | X | X |
| Hotspot FE | | | | | X | X |
| Top Route FE | | | | | | X |
| Month-by-Year FE | X | X | X | X | X | X |

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ The unit of observation is a voyage. The sample spans from 2013 to 2021. Every column is a different specification. Encounters (3mo) is the count of pirate encounters recorded in the projected path of the vessel in the preceding 90 days from the departure date using a 5 degree spatial footprint. Fixed effects include country-to-country combination, vessel type, vessel size, hotspot, and a battery of month by year and top port-to-port combination for country-to-country combination dummies.

table S18: Effect of Past Pirate Encounters on Fuel Cost.

| | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| Encounters (3 mo) | 3.07*** | 2.83*** | 0.63*** | 0.58*** | 0.58*** | 0.58*** |
| | (0.28) | (0.27) | (0.09) | (0.08) | (0.08) | (0.08) |
| Wind total (m/s) | | 6.25*** | 0.91*** | 0.80*** | 0.62*** | 0.62*** |
| | | (0.46) | (0.08) | (0.08) | (0.08) | (0.08) |
| Wind Resistance Index (m/s) | | 1.99*** | 0.28*** | −0.08*** | −0.09*** | −0.09*** |
| | | (0.15) | (0.04) | (0.02) | (0.02) | (0.02) |
| Observations | 25,638,777 | 25,629,585 | 25,629,585 | 25,629,585 | 25,629,585 | 25,629,585 |
| Country Combo. FE | | | X | X | X | X |
| Vessel Type FE | | | | X | X | X |
| Vessel Size FE | | | | X | X | X |
| Hotspot FE | | | | | X | X |
| Top Route FE | | | | | | X |
| Month-by-Year FE | X | X | X | X | X | X |

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ The unit of observation is a voyage. The sample spans from 2013 to 2021. Every column is a different specification. Encounters (3mo) is the count of pirate encounters recorded in the projected path of the vessel in the preceding 90 days from the departure date using a 5 degree spatial footprint. Fixed effects include country-to-country combination, vessel type, vessel size, hotspot, and a battery of month by year and top port-to-port combination for country-to-country combination dummies.

table S19: Effect of Past Pirate Encounters on Labor Cost

| | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| Encounters (3 mo) | 0.99*** | 0.92*** | 0.27*** | 0.26*** | 0.26*** | 0.26*** |
| | (0.09) | (0.08) | (0.04) | (0.03) | (0.03) | (0.03) |
| Wind total (m/s) | | 1.77*** | 0.28*** | 0.27*** | 0.20*** | 0.20*** |
| | | (0.13) | (0.03) | (0.02) | (0.03) | (0.03) |
| Wind Resistance Index (m/s) | | 0.61*** | 0.10*** | 0.00 | 0.00 | −0.01 |
| | | (0.04) | (0.01) | (0.01) | (0.01) | (0.01) |
| Observations | 25,638,777 | 25,629,585 | 25,629,585 | 25,629,585 | 25,629,585 | 25,629,585 |
| Country Combo. FE | | | X | X | X | X |
| Vessel Type FE | | | | X | X | X |
| Vessel Size FE | | | | X | X | X |
| Hotspot FE | | | | | X | X |
| Top Route FE | | | | | | X |
| Month-by-Year FE | X | X | X | X | X | X |

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ The unit of observation is a voyage. The sample spans from 2013 to 2021. Every column is a different specification. Encounters (3mo) is the count of pirate encounters recorded in the projected path of the vessel in the preceding 90 days from the departure date using a 5 degree spatial footprint. Fixed effects include country-to-country combination, vessel type, vessel size, hotspot, and a battery of month by year and top port-to-port combination for country-to-country combination dummies.

table S20: Effect of Past Pirate Encounters on Total Cost.

| | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| Encounters (3 mo) | 4.06*** | 3.75*** | 0.89*** | 0.84*** | 0.83*** | 0.83*** |
| | (0.36) | (0.34) | (0.11) | (0.11) | (0.11) | (0.11) |
| Wind total (m/s) | | 8.02*** | 1.18*** | 1.07*** | 0.82*** | 0.82*** |
| | | (0.59) | (0.11) | (0.10) | (0.10) | (0.11) |
| Wind Resistance Index (m/s) | | 2.60*** | 0.38*** | −0.09*** | −0.09*** | −0.09*** |
| | | (0.19) | (0.05) | (0.02) | (0.02) | (0.02) |
| Observations | 25,638,777 | 25,629,585 | 25,629,585 | 25,629,585 | 25,629,585 | 25,629,585 |
| Country Combo. FE | | | X | X | X | X |
| Vessel Type FE | | | | X | X | X |
| Vessel Size FE | | | | X | X | X |
| Hotspot FE | | | | | X | X |
| Top Route FE | | | | | | X |
| Month-by-Year FE | X | X | X | X | X | X |

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ The unit of observation is a voyage. The sample spans from 2013 to 2021. Every column is a different specification. Encounters (3mo) is the count of pirate encounters recorded in the projected path of the vessel in the preceding 90 days from the departure date using a 5 degree spatial footprint. Fixed effects include country-to-country combination, vessel type, vessel size, hotspot, and a battery of month by year and top port-to-port combination for country-to-country combination dummies.

## table S21: Effect of Past Pirate Encounters on $CO_2$ emissions

| | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| Encounters (3 mo) | 22.12*** | 20.39*** | 3.86*** | 3.55*** | 3.50*** | 3.50*** |
| | (1.99) | (1.89) | (0.41) | (0.37) | (0.37) | (0.37) |
| Wind Speed (m/s) | | 45.78*** | 6.52*** | 5.72*** | 4.45*** | 4.46*** |
| | | (3.35) | (0.55) | (0.48) | (0.52) | (0.52) |
| Wind Resistance Index (m/s) | | 14.62*** | 2.16*** | −0.54*** | −0.56*** | −0.55*** |
| | | (1.02) | (0.22) | (0.12) | (0.12) | (0.12) |
| Observations | 25,638,777 | 25,629,585 | 25,629,585 | 25,629,585 | 25,629,585 | 25,629,585 |
| Country Combo. FE | | | X | X | X | X |
| Vessel Type FE | | | | X | X | X |
| Vessel Size FE | | | | X | X | X |
| Hotspot FE | | | | | X | X |
| Top Route FE | | | | | | X |
| Month-by-Year FE | X | X | X | X | X | X |

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ The unit of observation is a voyage. The sample spans from 2013 to 2021. Every column is a different specification. Encounters (3mo) is the count of pirate encounters recorded in the projected path of the vessel in the preceding 90 days from the departure date using a 5 degree spatial footprint. Fixed effects include country-to-country combination, vessel type, vessel size, hotspot, and a battery of month by year and top port-to-port combination for country-to-country combination dummies.

## table S22: Effect of Past Pirate Encounters on $NO_x$ Emissions

| | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| Encounters (3 mo) | 557.07*** | 512.92*** | 94.62*** | 86.75*** | 85.69*** | 85.69*** |
| | (50.38) | (47.69) | (10.08) | (9.27) | (9.28) | (9.29) |
| Wind total (m/s) | | 1,166.35*** | 164.94*** | 144.48*** | 112.84*** | 113.01*** |
| | | (85.33) | (14.01) | (12.34) | (13.10) | (13.05) |
| Wind Resistance Index (m/s) | | 370.58*** | 53.17*** | −15.21*** | −15.75*** | −15.37*** |
| | | (25.88) | (5.80) | (3.25) | (3.28) | (3.28) |
| Observations | 25,638,777 | 25,629,585 | 25,629,585 | 25,629,585 | 25,629,585 | 25,629,585 |
| Country Combo. FE | | | X | X | X | X |
| Vessel Type FE | | | | X | X | X |
| Vessel Size FE | | | | X | X | X |
| Hotspot FE | | | | | X | X |
| Top Route FE | | | | | | X |
| Month-by-Year FE | X | X | X | X | X | X |

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ The unit of observation is a voyage. The sample spans from 2013 to 2021. Every column is a different specification. Encounters (3mo) is the count of pirate encounters recorded in the projected path of the vessel in the preceding 90 days from the departure date using a 5 degree spatial footprint. Fixed effects include country-to-country combination, vessel type, vessel size, hotspot, and a battery of month by year and top port-to-port combination for country-to-country combination dummies.

table S23: Effect of Past Pirate Encounters on $SO_x$ Emissions.

| | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| Encounters (3 mo) | 460.59*** | 424.49*** | 80.34*** | 73.83*** | 72.94*** | 72.94*** |
| | (41.47) | (39.27) | (8.47) | (7.77) | (7.78) | (7.79) |
| Wind total (m/s) | | 953.21*** | 135.73*** | 119.06*** | 92.71*** | 92.79*** |
| | | (69.77) | (11.50) | (10.07) | (10.81) | (10.79) |
| Wind Resistance Index (m/s) | | 304.32*** | 44.97*** | −11.25*** | −11.70*** | −11.51*** |
| | | (21.26) | (4.62) | (2.49) | (2.52) | (2.52) |
| Observations | 25,638,777 | 25,629,585 | 25,629,585 | 25,629,585 | 25,629,585 | 25,629,585 |
| Country Combo. FE | | | X | X | X | X |
| Vessel Type FE | | | | X | X | X |
| Vessel Size FE | | | | X | X | X |
| Hotspot FE | | | | | X | X |
| Top Route FE | | | | | | X |
| Month-by-Year FE | X | X | X | X | X | X |

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ The unit of observation is a voyage. The sample spans from 2013 to 2021. Every column is a different specification. Encounters (3mo) is the count of pirate encounters recorded in the projected path of the vessel in the preceding 90 days from the departure date using a 5 degree spatial footprint. Fixed effects include country-to-country combination, vessel type, vessel size, hotspot, and a battery of month by year and top port-to-port combination for country-to-country combination dummies.

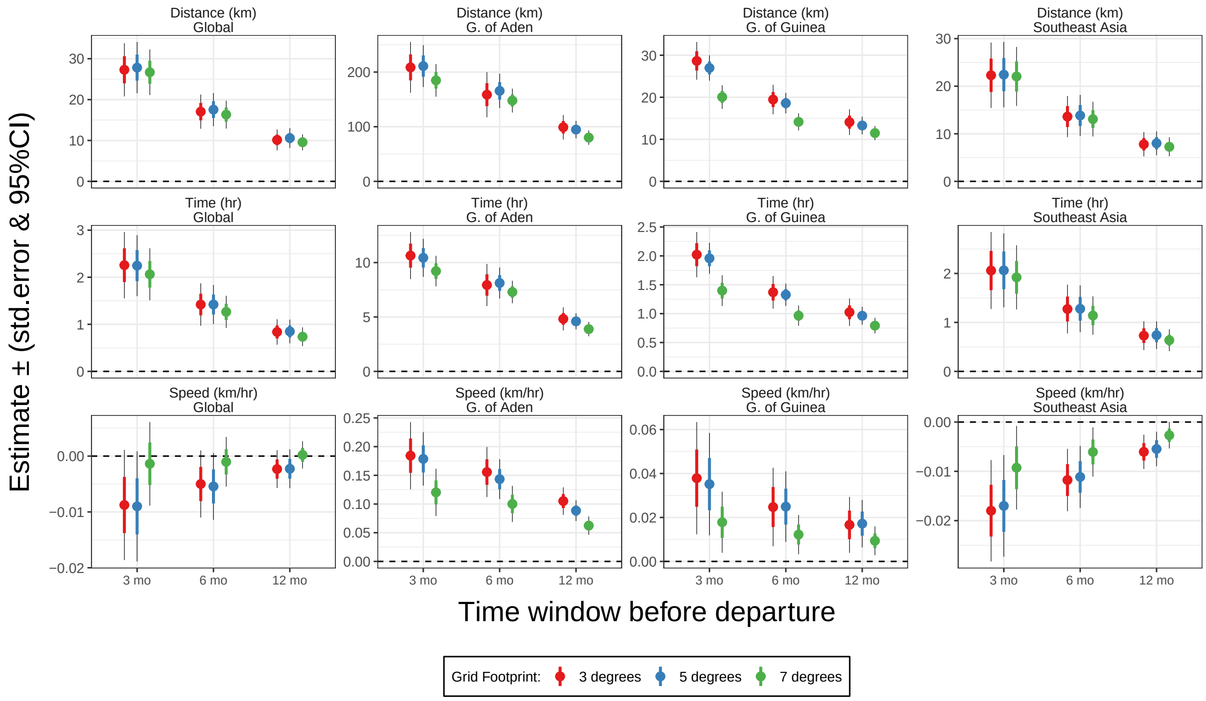


fig S6: **Replication Under Different Time Horizons and Degree Footprints.** Coefficients show the change in voyage features as a function of the number of pirate encounters in the preceding months. The analysis is conducted for all the variables and subsamples reported in the main text. Each plot shows the results for models using time windows of 3, 6, and, 12 months, respectively. Each color shows results for models using a 3, 5, and 7° spatial footprint, respectively. The thick portion of error bars are the clustered standard errors, and the thin portion of error bars shows 95%CIs. Estimation, subsampling, specification, and clustering approach remain identical to those in Table 2.

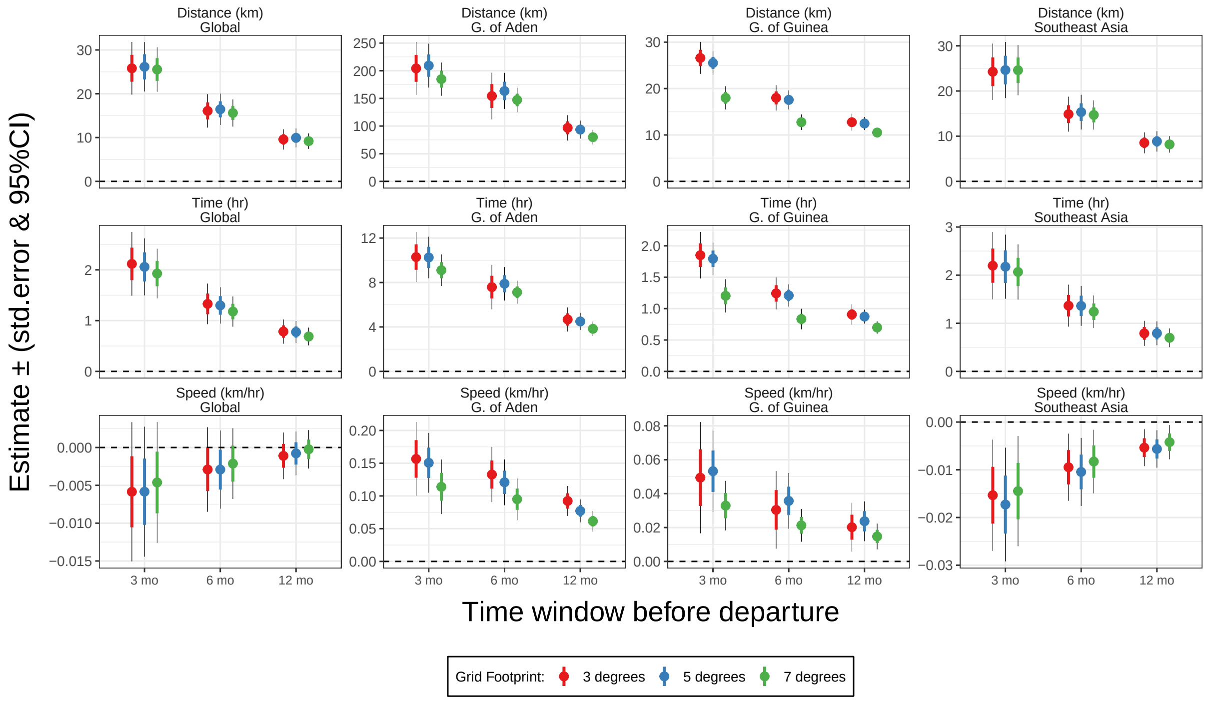


fig S7: **Replication Under Different Time Horizons and Degree Footprints of Vessels Always Classified as Cargo.** Coefficients show the change in voyage features as a function of the number of pirate encounters in the preceding months. The analysis is conducted for all the variables and subsamples reported in the main text. Each plot shows the results for models using time windows of 3, 6, and, 12 months, respectively. Each color shows results for models using a 3, 5, and 7° spatial footprint, respectively. The thick portion of error bars are the clustered standard errors, and the thin portion of error bars shows 95%CIs. Estimation, subsampling, specification, and clustering approach remain identical to those in Table 2.

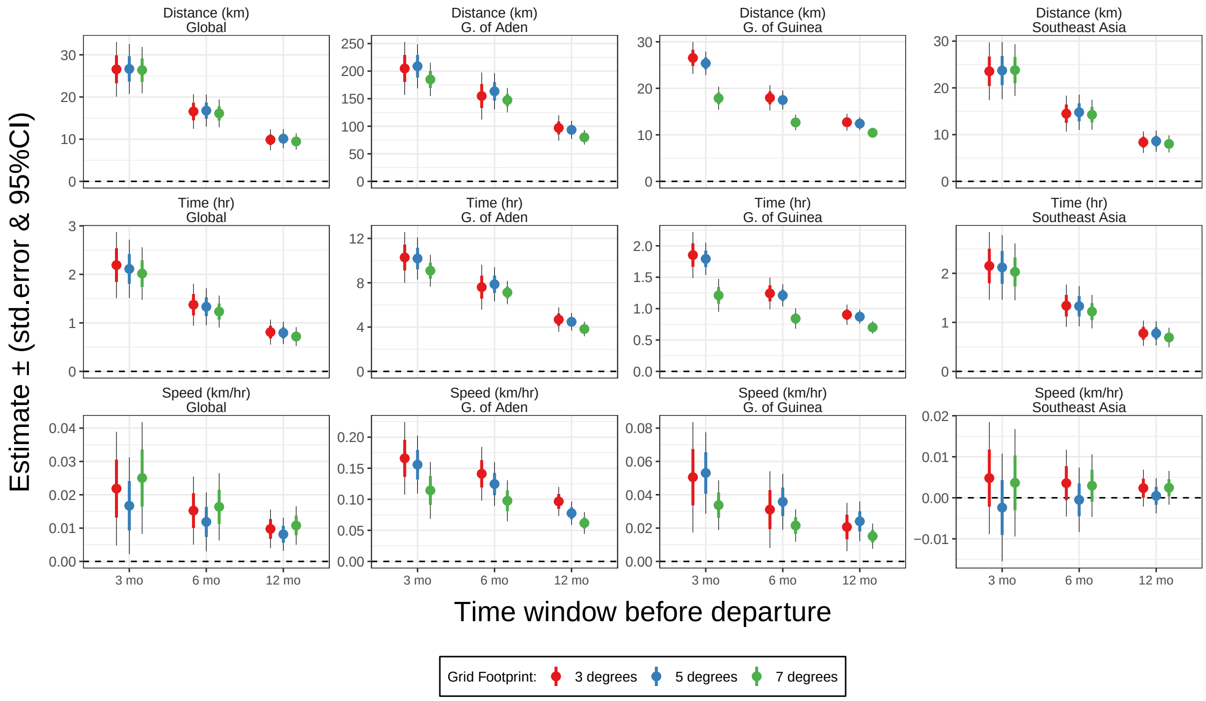


fig S8: **Replication Under Different Time Horizons and Degree Footprints of Vessels at Least Once Classified as Cargo.** Coefficients show the change in voyage features as a function of the number of pirate encounters in the preceding months. The analysis is conducted for all the variables and subsamples reported in the main text. Each plot shows the results for models using time windows of 3, 6, and, 12 months, respectively. Each color shows results for models using a 3, 5, and 7° spatial footprint, respectively. The thick portion of error bars are the clustered standard errors, and the thin portion of error bars shows 95%CIs. Estimation, subsampling, specification, and clustering approach remain identical to those in Table 2.

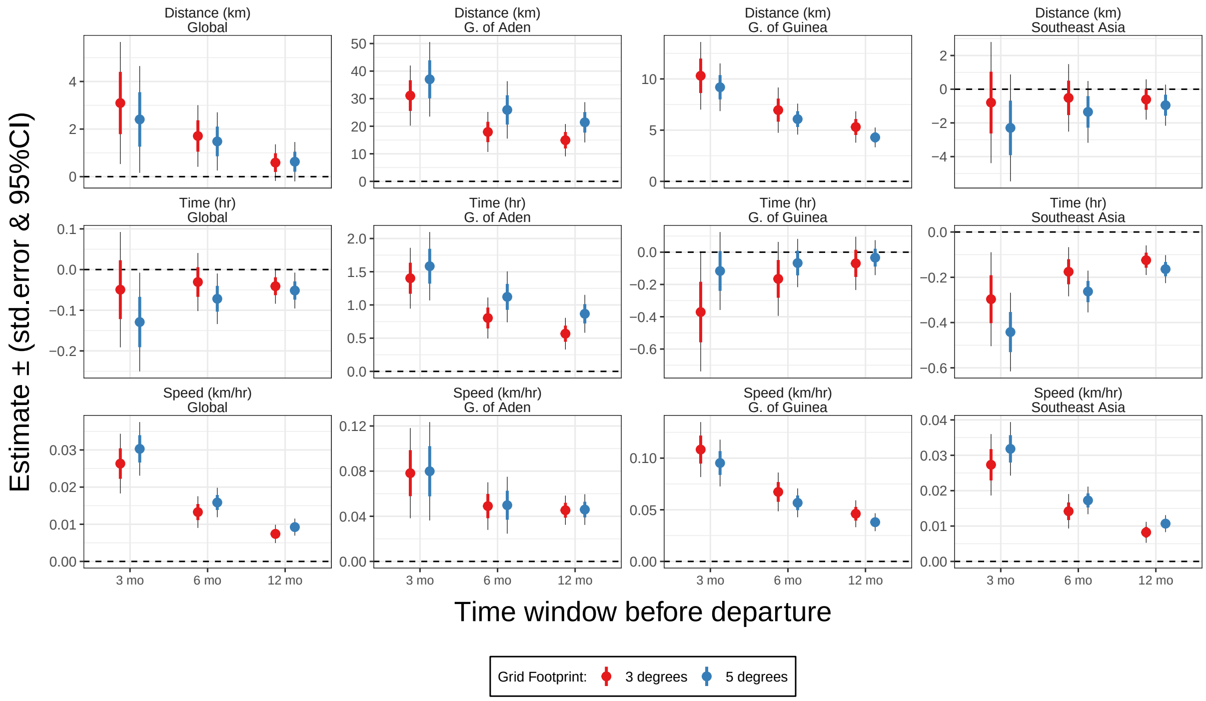


fig S9: **Replication Using Average Number of Encounters Under Different Time Horizons and Degree Footprints.** Coefficients show the change in voyage features as a function of the average number of pirate encounters experienced by other vessels in the preceding months. The analysis is conducted for all the variables and subsamples reported in the main text. Each plot shows the results for models using time windows of 3, 6, and, 12 months, respectively. Each color shows results for models using a 3 and 5° spatial footprint, respectively. The thick portion of error bars are the clustered standard errors, and the thin portion of error bars shows 95%CIs. Other than the explanatory variable, estimation, subsampling, specification, and clustering approach remain identical to those in Table 2.

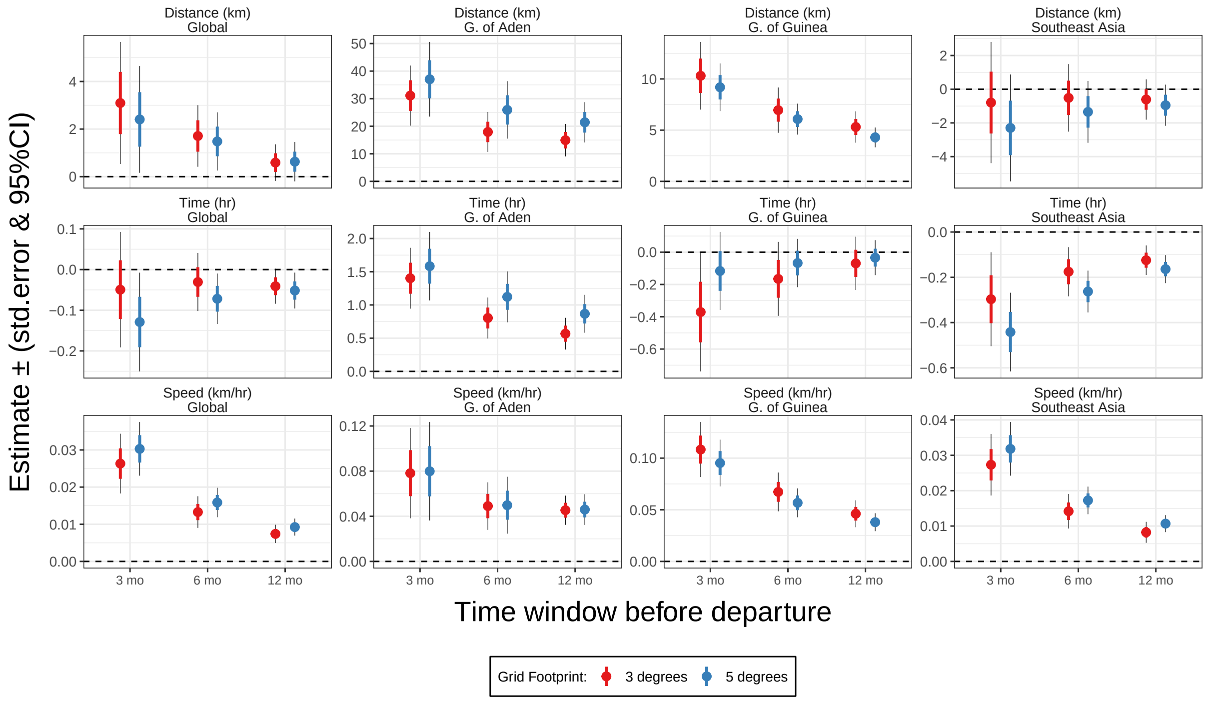


fig S10: **Replication Using Total Number of Encounters Under Different Time Horizons and Degree Footprints.** Coefficients show the change in voyage features as a function of the average number of pirate encounters experienced by other vessels in the preceding months. The analysis is conducted for all the variables and subsamples reported in the main text. Each plot shows the results for models using time windows of 3, 6, and, 12 months, respectively. Each color shows results for models using a 3 and 5° spatial footprint, respectively. The thick portion of error bars are the clustered standard errors, and the thin portion of error bars shows 95%CIs. Other than the explanatory variable, estimation, subsampling, specification, and clustering approach remain identical to those in Table 2.

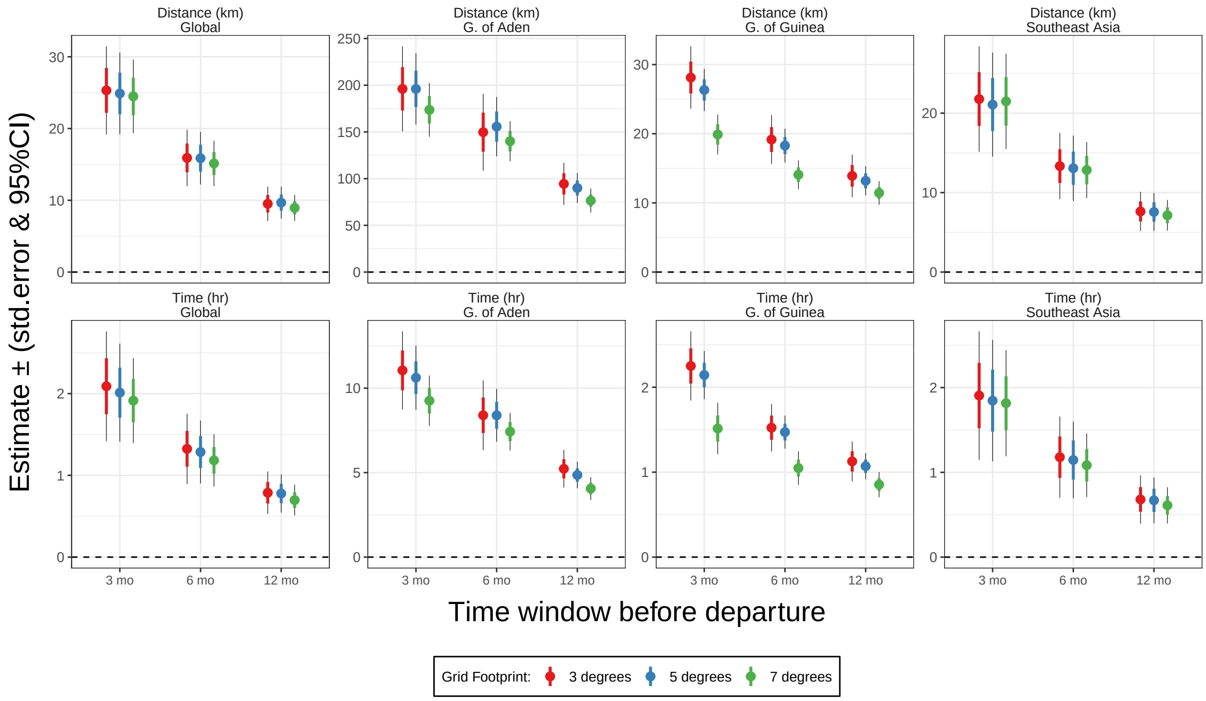


fig S11: **Replication Using Speed and Days Since Last Encounter as Covariates Under Different Time Horizons and Degree Footprints.** Coefficients show the change in voyage features as a function of the average number of pirate encounters experienced by other vessels in the preceding months. The analysis is conducted for all the variables and subsamples reported in the main text. Each plot shows the results for models using time windows of 3, 6, and, 12 months, respectively. Each color shows results for models using a 3 and 5° spatial footprint, respectively. The thick portion of error bars are the clustered standard errors, and the thin portion of error bars shows 95%CIs. Other than the explanatory variables, estimation, subsampling, specification, and clustering approach remain identical to those in Table 2.