Navigating the Waves of Global Shipping: Drivers and Aggregate Implications[1]

Jason Dunn
Boston University

Fernando Leibovici
Federal Reserve Bank of St. Louis

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Abstract

This paper studies the drivers of global shipping dynamics and their aggregate implications. We document novel evidence on the dynamics of global containership shipping supply, demand, and costs. Motivated by this evidence, we set up a dynamic model of international trade with a global shipping market where shipping firms and importers endogenously determine shipping supply and costs. We find the model accounts for the dynamics of global shipping observed in the aftermath of COVID-19, at business cycle frequencies, and following shipping disruptions in the Red Sea. Accounting for global shipping is critical for the dynamics of aggregate economic activity.

[1]Correspondence address: fleibovici@gmail.com. We thank George Alessandria, Roman Merga, and Woan Foong Wong for helpful discussions. We thank comments and feedback from presentations at the Federal Reserve Bank of Atlanta, NBER ITI Spring meetings, SITE, Yale University, Bank of Canada, Inter-American Development Bank, and the Society for Economic Dynamics. The views expressed herein are those of the individual authors and do not necessarily reflect official positions of the Federal Reserve Bank of St. Louis, the Federal Reserve System, or the Board of Governors. First version: February 2023.

1 Introduction

The global shipping industry plays a crucial role in international trade, facilitating the movement of goods across countries. The steady growth of containerships in recent decades has been critical in supporting the growth of the global economy and the increased role of international trade. Yet, this industry is highly cyclical and sensitive to changes in global economic activity, which lead to significant fluctuations of shipping supply, demand, and costs. In this paper, we ask: What accounts for global shipping dynamics and what are their aggregate implications? With shipping disruptions becoming increasingly prevalent, such as following recent attacks to vessels in the Red Sea or due to the impact of COVID-19, the need to better understand global shipping dynamics and their implications is greater than ever.

To answer these questions, we focus on the containership industry, the primary mode in which goods are shipped internationally. We make five key contributions: First, we document novel evidence on the dynamics of global containership supply, demand, and costs. Second, and motivated by this evidence, we develop a dynamic general equilibrium model of international trade with a global shipping market where shipping firms and importers endogenously determine the equilibrium level of shipping capacity and costs. Third, we analytically characterize the key channels through which shocks affect global shipping dynamics. Fourth, we use our model to assess the extent to which it can account for global shipping dynamics following large shipping disruptions as well as at business cycle frequencies. Fifth, we use the model to quantitatively study the implications for aggregate macroeconomic dynamics.

Our findings provide insights to better understand the waves of global shipping: how to interpret fluctuations in shipping costs, evaluating their potential aggregate implications. Building on the evidence from Kalouptsidi (2014) for bulk shipping markets, we document that containership supply is similarly rigid in the short-run, as investments in increased shipping capacity take time and the global containership fleet typically operates close to capacity. We find evidence that suggests these rigidities are likely critical as shipping cost fluctuations are highly correlated with fluctuations of excess demand for shipping capacity relative to a largely predetermined shipping supply. Motivated by these findings, we develop a general equilibrium model of international trade with endogenous shipping supply and a market for global shipping services where shipping costs are endogenous. We find time-intensive shipping investments and high capacity utilization can largely account for the observed dynamics of global shipping supply and costs in an environment where the relation between shipping demand, supply, and cost dynamics arises endogenously. We find that the value of shipping costs relative to imports is critical in accounting for the size of the shipping cost change required to balance shipping demand and supply. Moreover, we find that global shipping dynamics have a significant impact on aggregate outcomes via supply chain linkages, as the constrained short-run access to tradable goods impacts firms that rely on international trade to access intermediate inputs.

We begin the paper by documenting novel features of the dynamics of the global shipping industry. We focus on containerships given their critical role in the international trade of goods.[2] First, we document that international shipping supply has grown steadily in recent decades and that the global fleet is typically used at near-full capacity along both the extensive (ships in operation and their associated capacity) and intensive (degree to which ships are loaded) margins. Second, we observe that, in periods of high shipping costs, shipping companies have higher earnings and place increased orders for containerships. But we show that these investments take time to materialize: We document that the production of new containerships often takes between two to four years. Most importantly, we show that fluctuations of shipping demand relative to a largely predetermined supply of shipping capacity are significantly associated with changes of international shipping costs.

Motivated by these observations, we construct a dynamic general equilibrium model of international trade with input-output linkages and an endogenous demand and supply of global shipping services. Our model features importing firms and a global shipping company. The importing firms buy goods from other countries subject to per-unit international shipping costs in addition to standard ad-valorem iceberg trade costs. The shipping company owns the global stock of shipping capacity and rationally chooses investments to adjust it to maximize profits. Thus, the global shipping company can adjust shipping capacity but, as we observe in the data, doing so takes time. The shipping company can also adjust effective capacity by changing the rate at which the installed capacity is used — but higher utilization increases the rate at which the stock of shipping capacity depreciates. International shipping costs are the equilibrium price that clears the market for global shipping services, equating shipping demand with supply. In contrast to state-of-the-art models of international shipping such as Kalouptsidi (2014) or Brancaccio et al. (2020), we develop a framework that jointly models shipping costs as an endogenous equilibrium outcome along with the endogenous accumulation of global shipping capacity. Critically, this allows us to study the drivers and implications of shipping cost fluctuations in an environment featuring a feedback loop between shipping investment, trade flows, and macroeconomic conditions. In addition, by making global shipping costs endogenous, our model allows us to conduct counter-factuals, where the relation between shipping costs, shipping supply, and shipping demand flexibly

[2]In the Online Appendix, we document summary statistics on the importance of seaborne trade in global trade, as well as on the significance of containerships for global seaborne trade. In addition, we show containership dynamics are similar to those of other significant types of sea shipping such as dry bulk.

adjusts endogenously to structural changes in the environment.

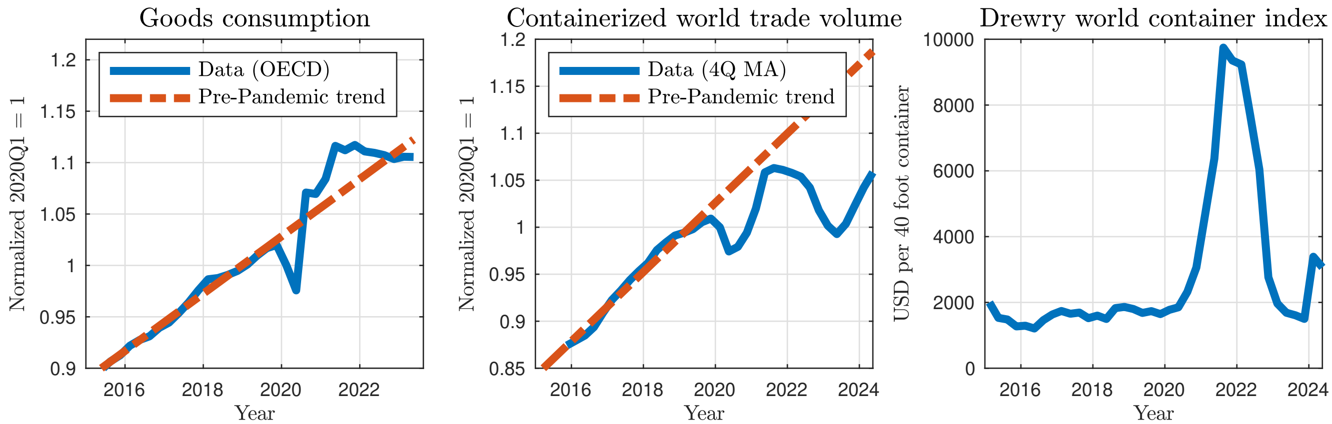
We analytically characterize the key determinants of import demand, shipping costs, capacity utilization, and shipping investment. First, we show that shipping costs affect the demand for imports differently than standard iceberg trade costs given shipping costs are per-unit rather than ad-valorem. Second, we show that the per-unit nature of shipping costs is critical in determining how shipping costs respond to shocks, such as ones that increase the demand for tradable goods. We show analytically that equilibrium shipping costs are determined by the trade elasticity and by the ratio of shipping costs to total import costs. In particular, equilibrium shipping costs are more sensitive to shocks if the trade elasticity or the ratio of shipping costs to imports are low — in such cases, shipping costs need to change relatively more to restore the balance between shipping demand and supply. Third, we characterize how the global shipping firm adjusts capacity utilization and shipping investment following shocks.

We study how well the model accounts for the dynamics of global shipping and quantify their aggregate implications during the aftermath of the COVID-19 recession, at business cycle frequencies, and following shipping disruptions in the Red Sea. We begin by focusing on the unprecedented disruptions of global shipping following COVID-19. During this period, the world economy experienced a sizable increase in the demand for goods relative to the pre-pandemic trend, as shown in the left panel of Figure 1. This resulted from the reallocation of demand from contact-intensive services toward goods and was further amplified by fiscal transfers aimed at mitigating the economic impact of the pandemic. However, despite this unprecedented demand for tradables, the effective supply of shipping capacity contracted sharply, reducing trade volumes as shown in the middle panel of Figure 1. This contraction was driven by operational disruptions that reduced the productivity of the existing shipping fleet, including port closures, labor shortages, delays in ship turnarounds, and widespread congestion at key ports, as further documented in Section 1 of the Online Appendix. We model these disruptions as a shipping efficiency shock. Finally, we observe that global shipping costs experienced an unprecedented increase during this period. For instance, the right panel of Figure 1 shows that the Drewry World Container Index, an index of global shipping costs across major routes, increased from less than $\$2,000$ per 40-foot container to almost $\$10,000$ at the peak.[3]

Motivated by these dynamics, we study the impact of a rapid and sizable increase in the demand for tradable goods along with a contraction of international shipping supply. In addition, we consider a shock to aggregate productivity to capture the dynamics of aggregate

[3] While this series tracks the average containership spot rate, effective shipping rates also increased significantly as we document in Section 2 of the Online Appendix.

Figure 1: Global shipping dynamics following COVID-19



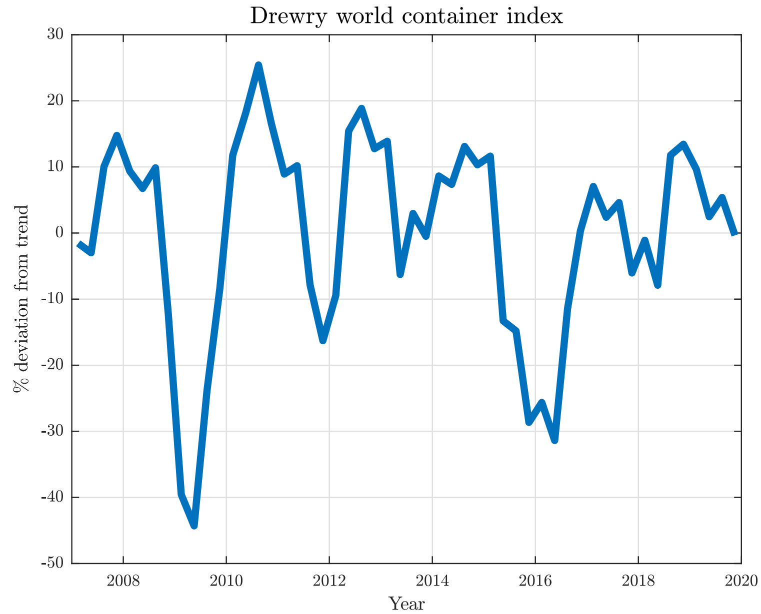
Note: Data from OECDstat, Clarkson's *Shipping Intelligence Network*, and Drewry Supply Chain Advisors.

economic activity. Given the global nature of the pandemic, we study the impact of a global shock affecting all countries. Our estimation approach is designed to capture key cross-sectional features of the data prior to the onset of COVID-19 while also accounting for salient features of the dynamics following the pandemic. We use this experiment to address two key questions. First, we ask: To what extent can our model account for the dynamics of global shipping observed in the aftermath of COVID-19? Second, we ask: To what extent were the macroeconomic dynamics observed during this period accounted for by the dynamics of global shipping?

We find that our model successfully accounts for salient features of the dynamics of global shipping observed in the aftermath of COVID-19. The increased demand for tradables along with the reduced and inelastic supply of shipping services lead to a reduction of international trade along with a sizable increase of shipping costs, as the limited capacity is rationed across the increased demand for shipping. We find that the model accounts for 74% of the peak increase of shipping costs observed in the data while also exhibiting a substantial reversal when the shocks subside. Moreover, we find that the model implies dynamics of shipping investment rates that are in line with the data.

We then investigate the extent to which global shipping affects the aggregate implications of the shocks. To do so, we contrast the implications of our model with those of an otherwise identical counterfactual economy with a perfectly elastic supply of shipping capacity, as implicit in standard models of international trade and international business cycles. We find that the differences in the shipping technology across the two models have important aggregate implications. For instance, real GDP decreases significantly more in the baseline than in the model with perfectly elastic shipping supply — in the baseline model, real GDP is over 3

Figure 2: Global shipping cost fluctuations over the business cycle



Note: Data from Drewry Supply Chain Advisors. Trend is computed via Hodrick-Prescott filter (in logs) with smoothing parameter 1600.

percentage points lower at the trough. Similarly, we find significant quantitative differences in the dynamics of tradable output and international trade flows. We examine how global shipping shocks propagate to trade and macroeconomic outcomes, finding supply rigidities, adjustment costs, and supply chain linkages are key drivers of shipping cost fluctuations.

Given the shocks and dynamics following COVID-19 are rare and unprecedented, we then investigate the implications of our findings for the dynamics of global shipping and macroeconomic aggregates during normal times. We are motivated by the observation that global shipping costs are also very volatile over the business cycle, as illustrated in Figure 2. Thus, we examine whether our model can account for these dynamics and study their aggregate implications. Following a broad literature on international business cycles (Backus et al. 1992), we model business cycle fluctuations as driven by shocks to productivity.

We find that the model implies global shipping costs that are also very volatile over the business cycle, as observed in the data. Moreover, we find these cyclical dynamics of global shipping also have significant implications for aggregate macroeconomic fluctuations. However, in contrast to their implications following COVID-19, we find that shipping *reduces* the volatility of aggregate fluctuations relative to a model with a perfectly elastic supply of shipping services. The key factor that determines if shipping mitigates or amplifies aggregate fluctuations is whether the demand for shipping services increases during periods of expansion (as over the business cycle) or contraction (as in the aftermath of COVID-19). In both cases, the rigid short-run supply of shipping capacity limits the extent to which an increased demand for tradables leads to higher international trade and production of these goods. During an economic expansion, the constrained increase of tradables mitigates the expansion, decreasing aggregate volatility. In contrast, during an economic contraction, the constrained response of tradables amplifies the contraction, as tradables are less able to offset the contraction than in a frictionless model.

To conclude the analysis, we investigate the extent to which our global macroeconomic model can capture the global impact of regional shocks, despite not explicitly featuring spatial granularity. To do so, we quantify the impact of the 2023-2024 attacks on vessels in the Red Sea on global shipping and macro dynamics using our estimated model. Given the extended shipping times, as voyages were largely rerouted away from the Red Sea to the Cape of Good Hope, we interpret this episode as consisting of a contraction of global shipping supply. We find that the model accounts for salient features of global shipping dynamics during this episode. We find that although 15% of global trade is shipped through the Red Sea according to the IMF's Portwatch, the rerouting of vessels due to the attacks has a significant impact on global shipping costs and trade volumes, as observed in the data. The model also implies a significant contraction of global GDP, illustrating how shipping disruptions can propagate through the global economy. We then use the model to evaluate the potential implications of periodic shipping disruptions of this nature on business cycle fluctuations. We show that if disruptions of the size and persistence observed in the Red Sea become a frequent occurrence due to rising geopolitical tensions, they could lead to a significant increase in business cycle volatility.

Our findings point to the importance of improving our understanding of the drivers and implications of global shipping in international trade. Our paper contributes to a growing literature studying the market for global shipping services (Ganapati et al. 2024; Brancaccio et al. 2020; Greenwood and Hanson 2015; Kalouptsidi 2014). In particular, Kalouptsidi (2014) examines how time-to-build constraints in fleet expansion create persistent fluctuations in bulk shipping capacity and freight rates, while Brancaccio et al. (2020) study the role of search frictions in accounting for freight costs across markets.

Our work builds on these and other related studies in two key ways. First, we document novel evidence on the dynamics of container shipping, showing that its supply rigidities and investment patterns closely mirror those observed in bulk shipping markets (as in Kalouptsidi 2014). Second, we develop a dynamic general equilibrium model of international trade consistent with the dynamics of global shipping supply observed in the data, and featuring an endogenous market for global shipping services where shipping costs arise endogenously through the interaction between the demand and supply for shipping goods across countries.

This framework allows us to conduct counter-factual analyses that explicitly consider the impact of changes in the economic environment on both the demand and supply of global shipping services, providing insights into the broader macroeconomic implications of shipping frictions. Moreover, while the parsimonious model that we develop abstracts from many granular aspects of global shipping that are better captured in other state-of-the-art frameworks—such as specific routes, port-level congestion, and the network structure—our highly tractable model captures key macroeconomic dynamics observed in the data and is easy to integrate into broader economic frameworks, allowing it to be used for analyzing a wide range of macroeconomic and trade-related questions.

Our work also belongs to a broader literature that studies the determinants of the level of international shipping costs and their implications for the pattern of trade across countries (Asturias 2020; Coşar and Demir 2018; Wong 2022; Behrens and Picard 2011; Behrens et al. 2006; Hummels et al. 2009). Other related papers study the role of international trade in shipping services in determining the overall extent of international trade costs (Hummels and Skiba 2004; Limao and Venables 2001; Ganapati et al. 2024; Hafner et al. 2022) and the role of policy (Fink et al. 2002). See also Hummels (2007) for an overview of developments in international shipping over recent decades.[4]

Finally, our work also contributes to a growing literature that studies the aggregate implications of supply chain disruptions in the aftermath of COVID-19 (Bai et al. 2024; Comin et al. 2024; Alessandria et al. 2023, among many others).[5] Relative to much of this literature, our key contribution is to investigate the role of global shipping during this period using a model in which both global shipping demand and supply are determined endogenously. A central mechanism in our analysis is the role of supply chain linkages in transmitting shipping disruptions to the broader economy. In contrast to Alessandria et al. 2023 and others, our model abstracts from inventories, which could, in principle, shape firms' responses to shipping disruptions. While inventory-holdings can help smooth shocks, stockpiling in response to disruptions may also amplify their effects by increasing short-run shipping demand. The relative importance of these forces would determine the extent to which inventory dynamics could be a significant additional force. Taken together, our findings provide a complementary perspective to recent empirical studies examining the impact of rising shipping costs on inflation (Isaacson and Rubinton 2023; Carrière-Swallow et al. 2023).

[4]For earlier studies of international trade in shipping services, see Casas (1983), Cassing (1978), and Falvey (1976).

[5]More generally, our work contributes to recent studies that explore the implications of shipping for aggregate dynamics, such as Leibovici and Waugh (2019) and Ravn and Mazzenga (2004).

2 Salient features of global shipping

In this section, we document salient features of the market for global shipping services. The goals of this section are twofold. On the one hand, we identify key features of how this market operates to guide the theoretical analysis of the following sections. On the other hand, the evidence that we document allows us to discipline and evaluate the quantitative analysis of the following sections.

We focus on three key dimensions. First, we examine the level and dynamics of global shipping capacity and the extent of its utilization. Second, we investigate the determinants of investments in shipping capacity and document the time lags involved to expand it. Third, we examine the dynamics of global shipping costs, documenting the extent to which they co-move with fluctuations in global economic activity and shipping supply.

Our analysis focuses on containerships, which account for a substantial share of global trade value and play a central role in facilitating international trade. In Section 3 of the Online Appendix, we provide evidence that the dynamics observed in the containership sector — including investment patterns, capacity utilization, and pricing — are representative of broader seaborne shipping markets, such as bulk shipping. While goods can also be shipped internationally via air, we abstract from this margin given it accounts for less than 1% of global trade volumes both globally and for the U.S.

Our main source of shipping-related data is Clarkson's *Shipping Intelligence Network*, an integrated shipping services data provider that collects a broad range of data on the international shipping industry. This is our source of data on shipping supply, fraction of the fleet in use, new orders of ships, average earnings, and ship build time. For shipping costs, we focus on the Drewry World Container Index, which tracks the average weekly rate of shipping a 40-foot container in U.S. dollars across major world trade routes. For the utilization rate of the fleet in use we rely on data from Alphaliner's July 2022 Monthly Monitor publication. We proxy shipping demand with real aggregate global GDP as collected by OECDstat.[6]

2.1 Shipping capacity

We begin with global shipping capacity. Panel A of Figure 3 reports the evolution of global shipping capacity over time. We focus on two measures: the total number of containerships (orange dashed line) and the corresponding volume that these ships can carry (blue solid line), which is measured in Twenty-Foot Equivalents Units (TEUs), a standard measure of containership volume. We find that the total size of the global containership fleet has grown

[6] For all cross-country data from the OECD throughout the paper, we use information from the following 27 countries: Austria, Bulgaria, Canada, Costa Rica, Croatia, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Iceland, Israel, Italy, Korea, Latvia, Netherlands, Norway, Poland, Portugal, Romania, Slovak Republic, Slovenia, Sweden, United Kingdom, and United States.

steadily over the past 15 years, particularly for the volumetric capacity of the fleet (TEUs). This suggests the growth of global shipping supply is fairly independent of short-run shocks.

Panel B of Figure 3 reports the level and dynamics of the global containership fleet's capacity utilization along both extensive and intensive margins. The extensive margin measures the fraction of the total fleet that is non-idle in a given year, reported both in terms of ship count and total capacity in TEUs. A ship is classified as idle if it has not recorded an average speed > 1 knot for at least seven consecutive days and does not fall under another recorded status such as laid-up, under repair, or in storage.[7] This ensures that fleet capacity utilization measures reflect actively operating vessels. The intensive margin captures the extent to which active containerships are utilized relative to their total container-carrying capacity, measured as the ratio of reported container liftings to total fleet capacity using data from Alphaliner's Monthly Monitor.[8]

We find that the global containership fleet operates close to maximum capacity at all times. Since 2014, the fraction of ships in use, measured in TEUs, has averaged over 96%, meaning that nearly all available fleet capacity is actively deployed. Additionally, reported container liftings consistently exceed 90% of total capacity, indicating that ships are generally filled close to their volumetric limits. These patterns suggest that, in the short run, the containership industry has limited room to expand effective shipping supply in response to demand fluctuations. Consequently, short-run demand surges are likely accommodated through fluctuations in shipping costs rather than increases in capacity.

2.2 Shipping investment

We now turn to investigating the dynamics and determinants of investments in shipping capacity. Panel C of Figure 3 reports new orders of containerships over time (measured in TEUs) alongside the annual growth of average containership earnings.[9] We observe that investments in containerships track average containership earnings closely, with a correlation of 0.79. Thus, in periods in which shipping costs and earnings are relatively higher, shipping companies invest in new ships to take advantage of these higher earnings, placing orders to

[7] Idle ships are also excluded if they subsequently report movement exceeding 20 km over two consecutive days.

[8] Comprehensive data on global shipping capacity utilization along the intensive margin is limited. Thus, we rely on Alphaliner's Monthly Monitor, which reports TEU loadings as a share of trade capacity along the Far East–Europe and Far East–U.S. routes. These major trade lanes may not fully represent global utilization patterns, and they also reflect reallocation dynamics across routes rather than solely capturing aggregate trends.

[9] Clarksons tracks average charter rates across a broad range of containership sizes. Pre June-2017, the series represents the theoretical earnings level of this 'basket' of vessel types, based on trends in the 'Clarksons Containership Earnings Index – Historical Charter Market Basket' timeseries (TSID 542016). The series for average containership earnings is based on average charter rates weighted by the number of ships in the fleet in different size ranges.

Figure 3: Shipping industry dynamics

Note: Data from Clarkson's *Shipping Intelligence Network*, *OECDstat*, and Alphaliner Shipping Solutions

increase future shipping capacity.

But these investments in future shipping capacity take time, as previously documented by Kalouptsidi (2014) for the dry bulk shipping sector. Panel D of Figure 3 shows a histogram with the distribution of ship production times by number of quarters for the set of containerships active in 2023. In particular, for each containership active in 2023, we compute the shipping production time as the difference between the period in which the ship was ordered and when it was delivered. We observe that it typically takes 2-4 years (8-16 quarters) to finish ship construction. Therefore, while these orders are placed contemporaneously to cost changes, the ships take a few years to be built before they become operational.

2.3 Shipping demand, supply, and costs

Finally, we investigate the joint dynamics of global shipping demand, supply, and costs. Panel E of Figure 3 plots the annual growth of real global GDP (a proxy for global shipping demand) alongside the annual growth of global containership supply (in TEUs). As expected, global economic activity fluctuates systematically over time, suggesting there are fluctuations in the extent to which global shipping services are demanded. On the other hand, and as documented in Panel A of Figure 3, we observe that global shipping supply is relatively steady and independent of global demand fluctuations. This implies that there are likely to be systematic fluctuations in the degree of excess demand (the difference between shipping demand and supply) for global shipping services.

Standard demand and supply forces suggest that fluctuations in the degree of excess demand for global shipping services are likely to be positively correlated with shipping costs. That is, in periods in which the growth of demand for global shipping services exceeds the growth of global shipping supply, we are likely to observe a higher increase in global shipping costs in order to ration the relatively scarcer shipping capacity. Panel F of Figure 3 shows that this is indeed the case: Excess demand for shipping tracks closely with shipping costs, with the annual growth of these variables featuring a correlation of 0.67 from 2008 to 2022 using annual data. Note that the link between these variables holds both during periods of excess demand as well as during periods of excess supply of shipping services: in the latter case, we observe declines in global shipping costs.

Next we investigate the drivers and aggregate implications of the evidence documented above through the lens of a general equilibrium model of international trade with an endogenous market for global shipping services.

3 Model

In this section, we set up a model of international trade with an endogenous market for global shipping services to investigate the underlying channels accounting for the dynamics observed in the data and their aggregate implications. Motivated by the evidence documented above, we model global shipping consistent with the following features: (*i*) shipping costs result from the interaction between shipping demand and supply, (*ii*) shipping capacity responds sluggishly to changes in shipping costs since shipping investments take time, and (*iii*) shipping capacity utilization can be adjusted to ease short-run shipping capacity constraints but the potential to do so may be limited.

We study a world economy with two countries: home and foreign. Each country is populated by a representative household, as well as by four types of firms: a producer of domestic tradable varieties, a producer of non-tradable varieties, a producer of a bundle of intermediate inputs, and a producer of a bundle of final goods. Tradable varieties from each country are traded internationally, and there is also trade in financial assets. Finally, the world economy is populated by a global shipping firm that provides shipping services to all countries.

Given that the structure of the two countries is identical, throughout the rest of this section we describe each of these agents focusing on the home country, and refer to variables *chosen* by the foreign country with an asterisk (*). We allow some parameters to be country-specific.

3.1 Household

Each country is populated by a representative household that is infinitely-lived and that discounts the future at rate $\beta < 1$. As in Heathcote and Perri (2002), the household's period utility function is $\frac{\left[c_t^{\mu}(1-n_t)^{1-\mu}\right]^{1-\gamma}}{1-\gamma}$, of the constant relative risk aversion (CRRA) class over a Cobb-Douglas bundle between consumption c_t and leisure $1 - n_t$. Parameter μ controls the contribution of consumption to household utility, and $1/\gamma$ denotes the intertemporal elasticity of substitution.

Households are endowed with a unit of time, which they allocate between work and leisure, and begin each period owning a given amount of physical capital k_t. Households earn labor income from supplying n_t units of labor at wage rate w_t and earn capital rental income r_{Kt} from renting out the physical capital used for production by firms. In addition, households earn dividends from owning the various firms in the economy. In particular, they are sole owners of the various domestic producers, and they own a fraction ψ of the shares of the global shipping firm.[10]

Households accumulate physical capital internally by investing i_t units of final goods subject to a quadratic investment adjustment cost. Given capital depreciates at rate δ, the evolution of the aggregate capital stock consists of $k_{t+1} + \frac{\Phi_k}{2}\left(i_t - \delta\overline{k}\right)^2 = (1-\delta)k_t + i_t$ where Φ_k is a constant that controls the cost of choosing investment levels different from the steady-state. Given this formulation, i_t denotes gross investment used to pay for both the increase in physical capital and the investment adjustment costs.

Households have access to international financial markets, where they can trade a one-

[10]Foreign households own a fraction $1 - \psi$ of these shares.

period risk-free bond vis-a-vis households in the other country subject to bond-holding costs. The bond is denominated in units of home final goods and trades at interest rate r_t. Following Schmitt-Grohé and Uribe (2003), households' bond-holding choices b_{t+1} in period t are subject to a quadratic bond-holding cost given by $\frac{\Phi_b}{2}\left(b_{t+1}-\overline{b}\right)^2$, where Φ_b controls the cost of holding bond levels different from steady-state bond-holdings $\overline{b}$.

The household's budget constraint in period t is then given by:

$$p_t c_t + p_t i_t + \frac{p_t b_{t+1}}{1+r_t} + p_t \frac{\Phi_b}{2}\left(b_{t+1}-\overline{b}\right)^2 = w_t n_t + r_{Kt} k_t + p_t b_t + \Pi_t + \psi \Theta_t,$$

where p_t denotes the price of final goods, Π_t denotes the combined profits from ownership of all domestic firms, and Θ_t denotes the profits of the global shipping firm.

The household's problem is then given by:

$$\max_{\{c_t, i_t, k_{t+1}, b_{t+1}, n_t\}} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \frac{\left[c_t^{\mu}(1-n_t)^{1-\mu}\right]^{1-\gamma}}{1-\gamma}$$

subject to

$$p_t c_t + p_t i_t + \frac{p_t b_{t+1}}{1+r_t} + p_t \frac{\Phi_b}{2}\left(b_{t+1}-\overline{b}\right)^2 = w_t n_t + r_{Kt} k_t + p_t b_t + \Pi_t + \psi \Theta_t \quad \forall t = 0, \ldots \infty$$

$$k_{t+1} + \frac{\Phi_k}{2}\left(i_t - \delta \overline{k}\right)^2 = (1-\delta) k_t + i_t \quad \forall t = 0, \ldots \infty$$

k_0 and b_0 given,

where the expectation operator is conditional on the information set in period $t=0$, and the initial capital stock k_0 and bond holdings b_0 are given.

3.2 Producers of domestic tradable varieties

A representative firm produces domestic tradable varieties with a constant returns-to-scale Cobb-Douglas technology using capital k_{Tt}, labor n_{Tt}, and intermediate inputs m_{Tt}, with time-invariant sector-specific productivity a_T and time-varying aggregate productivity z_t. The production function is then given by $y_{Tt} = z_t a_T \left(k_{Tt}^{\theta} n_{Tt}^{1-\theta}\right)^{\varphi} m_{Tt}^{1-\varphi}$, where y_{Tt} denotes the amount of domestic tradable varieties produced, θ controls the capital share, and φ controls the contribution of intermediates to gross output.

Domestic tradable varieties are sold domestically and internationally to producers of intermediate and final goods at a common price p_{Tt} denominated in units of the numeraire. The producer of these goods takes their price and the cost of factor inputs as given and chooses k_{Tt}, n_{Tt}, and m_{Tt} to maximize profits π_{Tt}. The firm's problem is given by:

$$\max_{k_{Tt}, n_{Tt}, m_{Tt}} \pi_{Tt} = p_{Tt} y_{Tt} - w_t n_{Tt} - r_{Kt} k_{Tt} - p_{Mt} m_{Tt}$$

$$\text{subject to} \quad y_{Tt} = z_t a_T \left(k_{Tt}^{\theta} n_{Tt}^{1-\theta}\right)^{\varphi} m_{Tt}^{1-\varphi},$$

where p_{Mt} denotes the price of intermediate inputs.

3.3 Producers of non-tradable varieties

A representative firm produces non-tradable varieties by operating a linear technology using labor n_{Nt} with time-invariant sector-specific productivity a_N and time-varying aggregate productivity z_t. The production function is then given by $y_{Nt} = z_t a_N n_{Nt}$, where y_{Nt} denotes the amount of non-tradables produced.

Non-tradable goods are only sold to domestic producers of final goods at price p_{Nt}, denominated in units of the numeraire. The producer of these goods takes their price and the cost of labor as given and chooses n_{Nt} to maximize profits π_{Nt}. The firm's problem is given by:

$$\max_{n_{Nt}} \pi_{Nt} = p_{Nt} y_{Nt} - w_t n_{Nt} \quad \text{subject to} \quad y_{Nt} = z_t a_N n_{Nt}.$$

3.4 Producers of intermediate goods

A representative firm produces intermediate goods m_t by combining tradable varieties produced domestically (m_t^h) and abroad (m_t^f). To do so, the firm operates a constant elasticity of substitution technology given by:

$$m_t = \left[\zeta m_t^{h\frac{\nu-1}{\nu}} + (1-\zeta) m_t^{f\frac{\nu-1}{\nu}} \right]^{\frac{\nu}{\nu-1}},$$

where the parameter ζ controls the relative importance of domestic and foreign intermediates, and the elasticity of substitution between these two types of tradable varieties is given by $\nu > 0$.[11]

The problem of the firm consists of choosing the amounts m_t^h and m_t^f to purchase in order to maximize profits. The prices of the domestic and imported varieties are given by p_{Tt} and p_{Tt}^*, respectively. Imports are subject to two types of trade costs. In addition to proportional ad-valorem iceberg trade costs τ, importing requires payment of shipping costs h_t per *unit* shipped. Then, the firm's problem consists of choosing purchases from each source to maximize profits π_{Mt}:

$$\max_{m_t, m_t^h, m_t^f} \pi_{Mt} = p_{Mt} m_t - p_{Tt} m_t^h - (\tau p_{Tt}^* + h_t) m_t^f$$

$$\text{subject to} \quad m_t = \left[\zeta m_t^{h\frac{\nu-1}{\nu}} + (1-\zeta) m_t^{f\frac{\nu-1}{\nu}} \right]^{\frac{\nu}{\nu-1}}.$$

[11] If the elasticity of substitution ν is equal to one, then the production technology is Cobb-Douglas, with exponents given by ζ and $1-\zeta$. The same applies analogously to the technology operated by producers of final goods.

3.5 Producers of final goods

A representative firm produces final goods y_t combining tradable varieties from each source and non-tradable varieties. To produce final goods, the firm operates a nested technology.

In the outer nest, the firm produces final goods y_t by aggregating a bundle of tradable goods q_{Tt} with non-tradable varieties q_{Nt}. To do so, the firm operates a constant elasticity of substitution technology given by:

$$y_t = \left[\chi q_{Tt}^{\frac{\eta-1}{\eta}} + (1-\chi) q_{Nt}^{\frac{\eta-1}{\eta}}\right]^{\frac{\eta}{\eta-1}},$$

where the parameter χ controls the relative importance of the two goods for the aggregate absorption bundle, and η denotes the elasticity of substitution between tradable and non-tradable goods.

In the inner nest, the firm produces bundles of tradable goods q_{Tt} by combining tradable varieties produced domestically (q^h_{Tt}) and abroad (q^f_{Tt}). To do so, the firm operates a constant elasticity of substitution technology given by:

$$q_{Tt} = \left[{q^h_{Tt}}^{\frac{\rho-1}{\rho}} + {q^f_{Tt}}^{\frac{\rho-1}{\rho}}\right]^{\frac{\rho}{\rho-1}},$$

where q^h_{Tt} and q^f_{Tt} denote domestic and foreign purchases of tradable varieties, respectively. The elasticity of substitution between these two types of tradable varieties is given by $\rho > 0$.

Final goods are sold only to domestic households, who use them for consumption and for investment in physical capital. The producer of these goods takes their price and the price of tradable and non-tradable varieties as given and chooses their amount to maximize profits π_t. As above, imports are subject to two types of trade costs: In addition to proportional ad-valorem iceberg trade costs τ, importing requires payment of shipping costs h_t per unit shipped. The firm's problem is given by:

$$\max_{y_t, q^h_{Tt}, q^f_{Tt}, q_{Tt}, q_{Nt}} \quad \pi_t = p_t y_t - p_{Tt} q^h_{Tt} - (\tau p^*_{Tt} + h_t) q^f_{Tt} - p_{Nt} q_{Nt}$$

subject to

$$y_t = \left[\chi q_{Tt}^{\frac{\eta-1}{\eta}} + (1-\chi) q_{Nt}^{\frac{\eta-1}{\eta}}\right]^{\frac{\eta}{\eta-1}}$$

$$q_{Tt} = \left[{q^h_{Tt}}^{\frac{\rho-1}{\rho}} + {q^f_{Tt}}^{\frac{\rho-1}{\rho}}\right]^{\frac{\rho}{\rho-1}}.$$

3.6 Global shipping firm

Finally, we describe the global shipping firm, which supplies shipping services to producers of intermediates and final goods when purchasing goods across countries.

Consider the start of some given time period t. The global shipping firm begins the period owning shipping capacity g_t. Each unit of shipping capacity allows the global shipping firm to ship a unit of tradable varieties either from the home country to the foreign country or vice-versa. Shipments depart and arrive in the same time period.

The global shipping firm sells global shipping services at cost h_t per unit shipped. That is, importers need to pay shipping cost h_t per unit of tradable variety purchased internationally, on top of the underlying price of these goods and iceberg trade costs.[12]

The extent to which installed shipping capacity g_t is used depends on exogenous and endogenous factors. First, we assume exogenous factors imply that a given installed shipping capacity g_t effectively supplies $\overline{g}g_t$ units of shipping services, where $\overline{g} > 0$. In the following section we use these to model the contraction of shipping capacity following COVID-19. Second, we assume that the global shipping firm can endogenously choose the degree to which it uses the installed shipping capacity g_t. In particular, it chooses the degree of shipping capacity utilization $\upsilon_t \in [0, 1]$, which determines the total amount of shipping capacity supplied to ship goods internationally. By construction, shipping utilization can range from 0 to 1. As in Baxter and Farr (2005), while higher shipping capacity utilization increases the firm's revenues, using the installed shipping capacity intensively increases the rate at which it depreciates due to greater mechanical strain, hull fatigue, and the potential costs of deferring maintenance.[13] Following their work, we assume the rate of shipping capacity depreciation is given by $\delta_G(\upsilon_t) = \overline{\delta}_G + \frac{\xi}{2}\left(\frac{\upsilon_t}{1-\upsilon_t}\right)^2$, where $\xi > 0$.

Then, we have that the global shipping firm is a necessary intermediary between producers of tradable varieties and their international buyers. Thus, utilized shipping capacity acts as an upper bound to the amount of international trade that the world economy can support. That is, total demand for shipping services in a given period has to be less or equal than the utilized shipping capacity available in that period:

$$\left(q_{Tt}^{f} + {q_{Tt}^{h}}^{*}\right) + \left(m_t^f + m_t^{h*}\right) \leq \upsilon_t \overline{g} g_t,$$

where the first term denotes imports of varieties to produce final goods by the home and foreign country, while the second term denotes the analogous variables for producing intermediate goods.

While installed shipping capacity g_t cannot be adjusted within a given period, the global shipping firm can invest to adjust shipping capacity in the future. However, producing new ships takes time, as documented in Section 2. Thus, we assume that investments in new

[12]Shipping costs that scale up with value, like insurance or security measures for containers, are captured by the iceberg trade cost.

[13]Idle ships also require maintenance to prevent degradation, such as barnacle growth and engine upkeep, but these costs are largely mitigated through standard industry practices, including anti-fouling coatings and periodic hull cleaning.

ships i_{Gt} in period t increase shipping capacity by $a_G i_{Gt}$ units in period $t+J$, where $J \geq 1$ denotes the shipping production lag and a_G controls the productivity of shipping investments. Shipping capacity depreciates at rate $\delta_G(\upsilon_t)$, as described above. Thus, shipping capacity evolves according to the following law of motion:

$$g_{t+1} = [1 - \delta_G(\upsilon_t)]\, g_t + a_G i_{Gt-J+1}.$$

In addition to the shipping production lag, we assume that shipping investments are subject to quadratic investment adjustment costs.[14] In particular, the choice of shipping investment i_{Gt} in period t also requires the global shipping firm to pay $\frac{\Phi_G}{2}\left(\frac{i_{Gt}}{i_{Gt-1}} - 1\right)^2$, where Φ_G controls the magnitude of the adjustment costs. We assume that both shipping investments and adjustment costs consist of final goods from each of the countries, with the relative weights given by each country's respective ownership shares.

Finally, the global shipping firm is owned by households in each of the countries. We assume that households in the home country own fraction ψ of the shares in this firm, while households in the foreign country own the rest.

The problem of the global shipping firm consists of choosing shipping investments and capacity utilization to maximize the lifetime discounted sum of period profits Θ_t:

$$\max_{\{g_{t+1}, \upsilon_t \in [0,1], i_{Gt}\}} \mathbb{E}_0 \sum_{t=0}^{\infty} \Lambda_t \left\{ h_t \upsilon_t \bar{g} g_t - p_{Gt} i_{Gt} - p_{Gt} \frac{\Phi_G}{2} \left(\frac{i_{Gt}}{i_{Gt-1}} - 1 \right)^2 \right\}$$

subject to

$$g_{t+1} = [1 - \delta_G(\upsilon_t)]\, g_t + a_G i_{Gt-J+1}$$

$$g_{t+1} \geq 0$$

$$g_0 \text{ given,}$$

where Λ_t denotes the stochastic discount factor of the owners of the global shipping firm, $p_{Gt} \equiv [p_t \psi + (1-\psi) p_t^*]$ denotes the price of shipping investments and adjustment costs, g_0 denotes the initial level of shipping capacity, and the second constraint requires shipping capacity to be positive.[15]

While the containership sector is highly concentrated, with the top 10 firms controlling a significant share of global capacity, the dynamics of investment and pricing in this sector closely resemble those of the bulk shipping sector, which operates under more competitive conditions (Brancaccio et al. 2020; Kalouptsidi 2014). Despite these differences in market

[14] In our quantification, this allows us to match the gradual response of shipping investment to shocks. Consistent with the evidence we document in the Online Appendix, shipping adjustment costs can also be interpreted to generate time-varying shipping production lags.

[15] In particular, we define $\Lambda_t = \beta^t \frac{\psi \lambda_t + (1-\psi)\lambda_t^*}{\psi \lambda_0 + (1-\psi)\lambda_0^*}$, where ψ capture ownership shares, and λ denotes the Lagrange multiplier on the household's budget constraint, capturing the marginal utility of relaxing it.

structure, the observed dynamics across both subsectors—such as fleet growth, capacity utilization, and investment responses to earnings—are remarkably similar, as documented in Section 3 of the Online Appendix. This suggests that the shipping dynamics we observe are unlikely to be driven primarily by differences in market structure. Instead, they appear to reflect broader economic forces that are common across different types of sea shipping, providing support for our modeling approach that treats the industry as competitive despite its concentration.

3.7 Equilibrium

We let the price of final goods in the home country p_t be the numeraire. We provide a formal definition of the equilibrium in Section 6 of the Online Appendix. An equilibrium consists of prices and allocations such that, in each country: (*i*) households and firms solve their problem taking prices as given; (*ii*) profits from firms are rebated to households; (*iii*) labor markets clear; (*iv*) the capital market clears; (*v*) the market for tradable varieties clears; and (*vi*) the market for non-tradable varieties clears. In addition, we have that (*vii*) given prices, allocations solve the global shipping firm's problem; (*viii*) the market for shipping services clears, $q^f_{Tt} + q^{h*}_{Tt} + m^f_t + m^{h*}_t = \upsilon_t \bar{g} g_t$; and (*ix*) the financial market clears.

4 Mechanism: How shipping affects equilibrium outcomes

In this section, we study the key channels through which shipping affects equilibrium outcomes in our model. We first show how shipping affects the demand for imports. Then, we study how shocks affect equilibrium imports and shipping costs, as well as global shipping dynamics. As in the previous section, while we focus our discussions on the home country, the analyses and forces are symmetric for the foreign country.

4.1 Import demand

The demand for imports in our model is given by the following equation:

$$\text{Imports}_t = \underbrace{\left(\frac{\tau p^*_{Tt} + h_t}{\widetilde{p_{Tt}}}\right)^{-\rho} q_{Tt}}_{\text{Final goods}} + \underbrace{\left(\frac{\tau p^*_{Tt} + h_t}{p_{Mt}}\right)^{-\nu} m_t}_{\text{Intermediate goods}}, \tag{1}$$

where Imports_t denotes the home country's total imports of tradable varieties purchased in period t (that is, $q^f_{Tt} + m^f_t$), and $\widetilde{p_{Tt}}$ denotes the implicit ideal price index for tradable goods.[16] The first term denotes imports used to produce final goods, while the second term denotes imports used to produce intermediate goods. As in standard models of international trade with a constant elasticity of substitution demand for imports, we observe that imports are

[16] In our model, the ideal price index for tradable goods can be computed as the total cost of producing one unit of the tradable good q_{Tt}.

increasing in total demand for both final goods and intermediates, and decreasing in both the price of imports and the value of iceberg trade costs.

While shipping costs h_t also decrease the demand for imports, we find that they affect imports differently than standard iceberg trade costs τ: Shipping costs are per-unit costs rather than ad-valorem. That is, shipping costs h_t are paid per unit shipped, regardless of the value of the goods shipped — in contrast, in an environment with ad-valorem iceberg trade costs, higher-value goods require payment of higher trade costs. As we show in the rest of this section, this difference critically affects the determinants and dynamics of shipping costs, and thus, of global shipping dynamics. See Hummels and Skiba (2004) for detailed evidence on the per-unit nature of shipping costs.

4.2 Increase in demand for tradables

To sharpen the exposition of how shipping costs, imports, and global shipping dynamics respond to shocks, we frame our discussion around one specific shock: An increase in χ, which increases the demand for tradable final goods q_{Tt}. This is a key force in two of the quantitative exercises that we study in the following sections.[17] However, the forces and channels that we study are more generally at play in response to other types of shocks.

An increase in the demand for tradable final goods increases the demand for imports through two channels. First, there is a direct impact on imports, captured by the first term of Equation 1: Higher demand for tradable final goods increases the demand for both domestic and imported tradable varieties used in the production of tradable final goods. Second, there is an indirect impact on imports, captured by the second term of 1: As the demand for tradable varieties increases, there is an increase in the demand for intermediate inputs, and thus, for the tradable varieties required to produce them.

Effect on shipping costs To study the impact of the increased demand for imports on shipping costs, we examine the potential of shipping supply to adjust and meet the increase in demand. In the short run, however, the increase of import demand cannot be fully accommodated by expanding the supply of shipping services. The effective supply of shipping capacity is relatively inelastic in the short-run, given utilization is typically high and costly to increase, and expanding the shipping fleet is time-intensive. Instead, shipping costs h_t must rise to restore equilibrium in the market for shipping services, discouraging import demand until it equals effective shipping supply.

To analytically characterize the determinants of shipping cost changes in response to the

[17]In Section 5, we characterize the aftermath of COVID-19 in part through a shock that increases the demand for q_{Tt}. Moreover, cyclical fluctuations in the demand for tradable final goods are a standard feature of business cycle fluctuations, as we study in Section 6.

higher demand for tradable goods, we consider the following special version of our model: A symmetric world economy subject to a symmetric shock, we abstract from changes in capacity utilization, we let the change in the demand for intermediates be proportional to the change in the demand for tradable final goods ($m_t \propto q_{Tt}$), and we assume the elasticities of final and tradables are identical ($\sigma \equiv \nu = \rho$). Then, we find the elasticity of shipping costs to changes in the demand for tradable final goods is given by:

$$\frac{\partial \log h_t}{\partial \log q_{Tt}} = \frac{1}{\sigma} \times \left(\frac{h_t}{\tau p_{Tt} + h_t} \right)^{-1}. \tag{2}$$

This equation implies that the increase of shipping costs is determined by two factors. The first is the elasticity of substitution σ. A lower elasticity σ implies that shipping costs need to increase relatively more to reduce import demand and restore equilibrium. Intuitively, if import demand is relatively insensitive to shipping costs, then a larger cost increase is required to induce the necessary reduction in demand.

The second factor is the inverse of the ratio of shipping costs to total import costs. Intuitively, if shipping costs are a small share of total import costs, then h_t must increase relatively more in percentage terms to induce a given change in total import costs and quantities. In contrast, if shipping costs are a high fraction of total import costs, then given changes of shipping costs have a larger impact on import demand.

It is instructive to contrast these determinants with those that control the response of shipping costs when these are modeled as ad-valorem rather than per-unit. In such an environment, we find that the elasticity of shipping costs to changes in the demand for tradable final goods is given by:

$$\frac{\partial \log h_t}{\partial \log q_{Tt}} = \frac{1}{\sigma}.$$

This expression shows that the per-unit nature of shipping costs accounts for the second term of Equation 2. That is, we find that if shipping costs are modeled as ad-valorem, their response to changes in the economic environment are solely determined by the elasticity of substitution.

Effect on capacity utilization Faced with the increase in shipping demand and costs, the global shipping firm must choose how much to increase its capacity utilization rate υ_t, which is the intensity at which the fleet is operated. Increasing utilization means the existing shipping capacity can be used to carry more goods today, but at the cost of higher depreciation and a smaller effective fleet size in the future. The optimality condition for the capacity utilization choice can be expressed as:

$$\underbrace{h_t}_{\text{Return from increasing utilization}} = \underbrace{\frac{\delta'_G(\upsilon_t)}{(1-\upsilon_t)^2}\mathbb{E}_t\left\{\sum_{k=1}^{\infty}\Lambda_{t,t+k}h_{t+k}\prod_{j=1}^{k}\left[1-\delta_G(\upsilon_{t+j})\right]^{\mathbb{I}_{\{k>1\}}}\right\}}_{\text{Cost of reducing shipping capacity}}$$

The left-hand side is the marginal return to increasing shipping utilization today — earning price h_t on the marginal unit of shipping capacity. The right-hand side is the marginal cost — a higher shipping capacity depreciation rate, which reduces it from next period onwards. Given shipping capacity is durable, the reduced shipping capacity affects earnings in every subsequent period. The present value of these costs is computed using the stochastic discount factor $\Lambda_{t,t+k}$.

Thus, an increase in h_t today increases the return to utilization, as the firm earns more for each unit of capacity. But this is at the expense of having less capacity to earn revenue with in the future. If the increase in h_t is transitory, the firm finds it relatively more attractive to increase current returns by increasing utilization at the expense of future shipping capacity.

Effect on shipping investment While utilization can be used to adjust the effective capacity at which the fleet is used in the short-run, persistently increasing total shipping supply ultimately requires investments in shipping capacity. The optimality condition for investing in shipping capacity is given by:

$$\underbrace{\mathbb{E}_t\sum_{k=J}^{\infty}\left[\Lambda_{t,t+k}a_G\left[1-\delta_G(\upsilon_{t+k})\right]^{k-J}h_{t+k}\upsilon_{t+k}\right]}_{\text{Returns from selling shipping services}} = \underbrace{p_{Gt}}_{\text{Investment cost}},$$

where we abstract from shipping investment adjustment costs to simplify the exposition. The left-hand side is the lifetime expected stream of discounted marginal revenue products from investing in a marginal unit of capacity today. In period $t+J$, J periods after the investment is undertaken, the increased shipping capacity begins to operate, earning a per-period rate of $h_{t+J}\upsilon_{t+J}$, which is the shipping cost h_{t+J} adjusted by the prevailing utilization rate. In each subsequent period, per unit revenues are reduced by depreciation. The right-hand side is the marginal cost of investing in shipping capacity today, which depends on the price of shipping investment as well as on the shipping adjustment costs.

This equation reveals that the response of shipping investment to a demand shock critically depends on the expected path of discounted marginal products from period $t+J$ onwards. If the elevated demand and shipping costs are expected to be short-lived, dissipating before the J-period time-to-build lag, then there is little incentive to invest, because the increased capacity starts to operate in an environment where the marginal product has returned to normal. Instead, persistent increases in demand lead to higher shipping investments to earn the elevated returns.

4.3 Aggregate implications

The combination of the inelastic short-run shipping supply with imperfect substitution across the various goods can have significant aggregate implications following shocks. Larger, more persistent shocks are likely to induce more sizable responses in shipping costs, trade, and output. Lower elasticities of substitution, either between domestic and foreign inputs (ν and ρ) or between tradables and non-tradables (η), amplify the costs by limiting the economy's flexibility to adjust absorption patterns to overcome rigidities in shipping supply.

The following sections quantitatively investigate these mechanisms to evaluate their role in explaining recent global shipping and macroeconomic dynamics.

5 Quantitative analysis: Dynamics following COVID-19

In this section, we use the model to study the drivers and aggregate implications of the global shipping dynamics observed in the aftermath of COVID-19, as documented in Sections 1 and 2. To do so, we consider an experiment designed to capture three key features of the post-pandemic dynamics: (*i*) the rapid increase in the demand and absorption of tradable goods, (*ii*) the contraction of global shipping supply, and (*iii*) the contraction of aggregate economic activity.

We use this framework to address two key questions. First: To what extent can the model account for the dynamics of global shipping observed in the aftermath of COVID-19? Second: What are the implications of shipping dynamics for aggregate outcomes?

We begin by estimating the model to capture key features of the data prior to the onset of COVID-19. We then estimate the remaining parameters to match salient features of the dynamics observed following the onset of COVID-19. Given the global nature of the pandemic, we focus on a world economy populated with symmetric countries that are subject to identical aggregate shocks. We pin down the parameters of the model by targeting global moments on trade, production, and shipping. We interpret a period in the model as a quarter in the data.

Our analysis focuses on the containership industry, which handles a substantial share of global trade by value and serves as a backbone of international commerce. As documented in Section 3 of the Online Appendix, key dynamics in containership markets—such as investment responses, capacity utilization, and pricing behavior—closely resemble those observed in other shipping sectors, including bulk shipping. These similarities suggest that the mechanisms captured by our model are not unique to containerships but instead reflect broader structural patterns across global shipping markets.

5.1 Experiment

To study the dynamics following COVID-19, we consider the following experiment. We assume the economy is in its steady state prior to the pandemic and is hit by three unexpected shocks in the third quarter of 2020.[18] On the one hand, the economy experiences an increase in the demand for tradable goods — we model it as an increase in the share χ of tradables in the production of final goods. This shock captures the reallocation of demand towards goods and away from services during this period.

On the other hand, the economy experiences a contraction of effective shipping capacity — we model it as a negative shipping efficiency shock $\overline{g}$ that reduces effective shipping capacity $\upsilon_t \overline{g} g_t$. We measure $\overline{g}$ using the ratio of global containerized trade volume to total fleet capacity: $\frac{q^f_{Tt}+q^{h*}_{Tt}+m^f_t+m^{h*}_t}{g_t} = \frac{\upsilon_t \overline{g} g_t}{g_t} = \upsilon_t \overline{g}$. Then, we back out $\overline{g}$ by assuming utilization was at capacity ($\upsilon_t = 1$) during COVID-19 given the unprecedented level of shipping costs and documented capacity constraints. Specifically, we estimate $\overline{g}$ to match the observed decline in the trade-to-capacity ratio relative to its pre-pandemic level.

We acknowledge this approach has limitations, as low trade-to-fleet ratios could reflect either a contraction of effective fleet capacity or reduced shipping demand. However, several pieces of evidence support the former interpretation particularly during COVID-19. First, the decline coincides with widespread operational disruptions in the shipping industry – including port closures, labor shortages, delays in ship turnarounds, and logistical bottlenecks – that directly reduced the productivity of the existing fleet. Second, the reduction in trade volumes occurred despite historically high shipping costs and a documented surge in demand for tradable goods, suggesting binding supply constraints rather than demand deficiency. These COVID-19 containment measures and logistical challenges reduced the speed and reliability of global shipping services, lowering the effective capacity of the existing fleet to meet the surge in demand for goods. In Section 1 of the Online Appendix, we show the dynamics of $\overline{g}$ are highly correlated with other contemporaneous measures of shipping disruptions.

A key feature of our identification strategy is that we do not rely on shipping costs to disentangle shocks to the demand and supply of shipping services. Instead, we identify the demand shock through changes in global tradable consumption, which capture the shift in expenditure patterns toward goods during the pandemic. The supply shock, on the other hand, is inferred from the trade-to-capacity ratio, which reflects constraints on effective shipping supply. This approach ensures that the two shocks are separately identified based on their distinct effects on trade and capacity rather than on price movements. Importantly,

[18] We focus on the dynamics of the economy from 2020Q3 onward relative to the pre-pandemic trend to abstract from the extremely sharp and transitory decline of economic activity in 2020Q2 at the onset of COVID-19.

while shipping utilization remained high throughout the period, this does not undermine our identification strategy, as utilization is explicitly accounted for in the construction of the supply shock measure. By isolating the shocks through their direct impact on quantities rather than prices, we ensure that our framework robustly distinguishes the role of demand from supply in driving post-COVID shipping dynamics.

In addition, the economy experiences shocks to aggregate productivity z_t that affect the dynamics of aggregate economic activity. These productivity shocks capture broader changes in economic performance that are independent of the demand and shipping disruptions, allowing us to isolate the contribution of each channel to the observed dynamics.

These shocks are time-varying and chosen to match the dynamics of their empirical counterparts. We let period 0 denote the initial steady state and assume that the full path of shocks—both their initial values and future trajectories—is observed in period 1. For the tradable demand and aggregate productivity shocks, we target data over the period 2020Q3–2023Q2, while for the shipping efficiency shock, we target data through 2023Q3. These shocks gradually revert to zero, reaching their pre-pandemic levels by 2024Q2.

5.2 Parameterization

To parametrize the model, we partition the parameter space into three sets of parameters: predetermined parameters, parameters estimated to match moments prior to the onset of COVID-19, and parameters estimated to match the dynamics following the onset of COVID-19. All parameters are identical across countries.

Predetermined parameters Predetermined parameters are set to standard values from the literature and consist of the discount factor β, the intertemporal elasticity of substitution $1/\gamma$, the consumption share μ in the household utility function, the capital depreciation rate δ, the share of capital θ in the production of tradable varieties, the share of intermediate inputs φ in the production of tradable varieties, the elasticity of substitution ν between domestic and imported tradable varieties used for producing intermediates, the elasticity of substitution η between tradable and non-tradable goods, the elasticity of substitution ρ between domestic and imported tradable varieties used for producing final goods, the share of tradables in final goods χ, and the shipping production lag J (the time lag between shipping investment and the realization of increased shipping capacity).

Table 1 reports the parameter values used throughout. Unless otherwise specified, our parameter choices follow Backus et al. (1995). We set β to 0.99, which implies an annual interest rate of 4%. We set the risk aversion parameter $1/\gamma$ to 0.5, the share of consumption μ in household period utility to 0.34, and the capital share θ to 0.36. We set the quarterly capital depreciation rate δ to 0.025%, implying an annual capital depreciation rate $\approx$ 10%, consistent with equipment depreciation estimates in U.S. manufactures (Albonico et al. 2014). We set the elasticity ρ between domestic and imported varieties in final goods to 1.50. Consistent with previous studies, we set η and ν to unity, letting tradables and non-tradables, as well as domestic and imported tradable intermediates, be complementary.[19]

To parametrize the share of tradables χ in the production of final goods and the share of intermediate inputs φ in the production of tradable goods, we begin by classifying goods as tradable and non-tradable. Using data from OECDstat, we define tradable goods to consist of consumption of durable, semi-durable, and non-durable goods, along with investment in machinery and equipment and weapons systems. Given this classification, we compute the share of aggregate absorption accounted by tradables and set χ to 0.29. Similarly, we use data from OECDstat to compute the share of intermediate inputs in gross output of manufactures and set φ to 0.63.

Based on data from Clarkson's *Shipping Intelligence Network*, we set the shipping production lag J to 6, which implies that investments in shipping capacity become operational after a year and a half. Along with the shipping adjustment cost that we estimate below, we show that investments in shipping increase capacity consistent with the dynamics observed in the data.

Finally, we normalize the productivity of producers of tradable varieties a_T and the productivity of producers of non-tradable goods a_N to unity. We focus on an economy with integrated financial markets, where bond-holding costs Φ_b are set to a small value to ensure stationarity. We set $\overline{g}$ to unity, and given our focus on symmetric countries, we set the share of the shipping firm ψ owned by households in the home country to 0.50.

Parameters estimated to match targets prior to COVID-19 The set of parameters estimated to match moments of the data prior to the pandemic consists of the iceberg trade cost τ, the weight on domestic intermediates ζ, and shipping investment productivity a_G.

We choose these parameters to ensure that the steady state of our model captures the following features of the global economy in 2019, prior to the onset of COVID-19: (*i*) the imports-to-absorption ratio in tradable goods, (*ii*) the imports-to-absorption ratio in tradable intermediates, and (*iii*) the shipping costs-to-imports ratio.[20] We compute empirical counterparts to moment (*i*) using data from OECDstat on the imports of goods. For (*ii*), we use data from OECDstat to target the share of intermediate inputs that are imported across manufacturing industries. For (*iii*), we target the ratio of shipping costs to imports

[19]For instance, see Stockman and Tesar (1995) and Caliendo and Parro (2015).

[20]These moments are robust to being calculated over a longer time span prior to COVID-19. The imports-to-absorption ratio measures the share of imports in total purchases, where absorption is defined as the sum of domestic and imported purchases of the respective type of goods.

Table 1: Predetermined parameters

Parameter	Value	Description
β	0.99	Discount factor
$1/\gamma$	0.5	Intertemporal elasticity of substitution
μ	0.34	Consumption share in household utility
δ	0.025	Capital depreciation rate
θ	0.36	Tradable varieties: Share of capital in gross output
φ	0.63	Tradable varieties: Share of intermediates in gross output
ν	1	Intermediates: Elasticity between domestic and imported
η	1	Final goods: Elasticity tradable and non-tradables
ρ	1.50	Final goods: Elasticity between domestic and imported
χ	0.29	Final goods: Share of tradables
J	6	Shipping production lag

that we estimate using UNCTAD's Trade-and-Transport Dataset, which back it out from CIF-to-FOB import ratios.[21] In particular, we target a value of shipping costs to imports equal to 6.4% which falls well in the range of previous estimates from the literature (Anderson and van Wincoop 2004; Hummels 2007).

The estimated parameters as well as the empirical targets and their model counterparts are reported in Table 2. The three estimated parameters can be chosen to exactly match the three targets. Trade costs τ determine the extent to which tradable final goods are imported.[22] Similarly, the weight ζ on imports of tradable intermediates determines the share of imported intermediate inputs. Finally, the magnitude of shipping costs in imports in the steady-state is determined by shipping investment productivity a_G.

Parameters estimated to match dynamics following COVID-19 We estimate the remaining parameters to match salient features of the dynamics following the onset of COVID-19: the investment adjustment cost Φ_k, the shipping adjustment cost Φ_G, the shipping utilization cost ξ, and the shipping capacity depreciation parameter $\overline{\delta}_G$.[23]

We estimate the first three parameters to match the following features of the data after the onset of COVID-19 relative to pre-pandemic levels: (*i*) the global growth of capital investment, (*ii*) the global change in the shipping investment rate, and (*iii*) the average

[21] For further information, see `https://unctadstat.unctad.org/datacentre/dataviewer/US.TransportCosts`.

[22] We use UNCTAD data to discipline shipping costs by targeting the observed share of shipping costs in total imports. The trade cost parameter τ is then inferred as a residual to match observed import shares.

[23] While we estimate shipping capacity depreciation to capture salient features of the data prior to the pandemic, we do so jointly with the dynamic targets given its implications are jointly determined with ξ.

Table 2: Estimated parameters

Steady-State Parameter	Value	Description	
τ	2.99	Iceberg trade cost	
ζ	0.45	CES weight on domestic intermediates	
a_G	0.36	Shipping investment productivity	
Steady-State Moment		**Data**	**Model**
Tradables: Imports/Absorption, 2019		0.224	0.224
Intermediates: Imports/Absorption, 2019		0.280	0.280
Shipping costs/Imports, 2019		0.064	0.064
Dynamic Parameter	**Value**	**Description**	
Φ_k	10.88	Investment adjustment cost	
Φ_G	0.35	Shipping adjustment cost	
ξ	0.001	Shipping utilization cost	
$\overline{\delta}_G$	0.029	Shipping depreciation shifter	
Dynamic Moment		**Data**	**Model**
Real investment, avg. log-change 2020Q3-2022Q2		-0.041	-0.041
Shipping investment/Shipping fleet, avg. change 2020Q3-2022Q2		0.027	0.027
Trade (TEU)/Shipping capacity (TEU), avg. 2019		0.74	0.74
Shipping depreciation rate, avg. 1996-2022		0.030	0.035

shipping capacity utilization rate. We measure utilization as the ratio between trade volume and shipping capacity. This statistic allows us to capture the various potential margins of capacity utilization, including those documented in Section 2. In addition, we target the (*iv*) the average shipping depreciation rate over the period 1996 to 2022, which we back out using the law of motion for global shipping capacity in the steady-state, where depreciation is equal to the long-run average shipping investment rate.[24]

We compute empirical counterparts for these moments as follows. We compute moment (*i*) using investment data from OECDstat. For moment (*ii*), we use data on new ship orders and total fleet capacity from Clarksons *Shipping Intelligence Network*. For moment (*iii*) we use Clarksons data on total containership trade and fleet capacity, both expressed in TEUs. Finally, we estimate shipping depreciation (*iv*) from Clarksons. To isolate the impact of the increased demand for tradables, we let period 1 be 2020Q3. Then, target (*i*) is expressed relative to a pre-2020 linear trend and target (*ii*) is expressed relative to a 2019 average. Targets (*iii*) and (*iv*) are computed as averages for the periods 2019 and 1996-2022, respectively.

Finally, we estimate the shocks to the demand for tradables, effective shipping supply, and aggregate productivity by targeting the dynamics of the following series: (*i*) global tradable consumption, (*ii*) the ratio of international trade flows to shipping capacity, and (*iii*) global

[24] We estimate the depreciation rate using data from Clarkson's on new shipping orders and fleet size. We target a quarterly depreciation rate of 0.03, implying that ships become largely obsolete within 10 years without maintenance. In practice, regular upkeep and reinvestment extend operational lifespans well beyond this, offsetting depreciation and sustaining shipping capacity over time.

real GDP. We measure series (*i*) and (*iii*) using a global aggregate computed using data from OECDstat, expressed as log-deviations from the 2015–2019 trend. Series (*i*) is weighted using country-level exports (excluding intra-Europe trade) to capture the increased demand for shipping capacity.[25] Series (*iii*) is weighted using country-level GDP. Finally, series (*ii*) is measured using Clarksons data on total containership trade and fleet capacity, both expressed in TEUs, examining changes relative to the 2015–2019 average.

We estimate the model through a simulated method of moments (SMM) algorithm, designed to minimize the sum of absolute deviations between the empirical moments and their model counterparts, assigning equal weight to each of the moments. Table 2 reports the estimated parameters as well as the empirical targets and their model counterparts. We find that the four estimated parameters match the target moments almost exactly.

Figure 4 plots the estimated shocks along with the dynamics of tradable absorption, effective shipping supply, and real GDP in both the model and the data. We find that the estimated shocks account well for the increase of tradable absorption, for the decline in effective shipping capacity, and for the dynamics of real GDP.[26]

5.3 Aggregate dynamics

We begin by examining the dynamics of key aggregate variables following the shocks presented in Figure 4. We plot the dynamics of key variables in Figure 5, expressed as log-deviations from their steady-state values. We restrict attention to the dynamics over the five years (20 periods) following the onset of the pandemic.

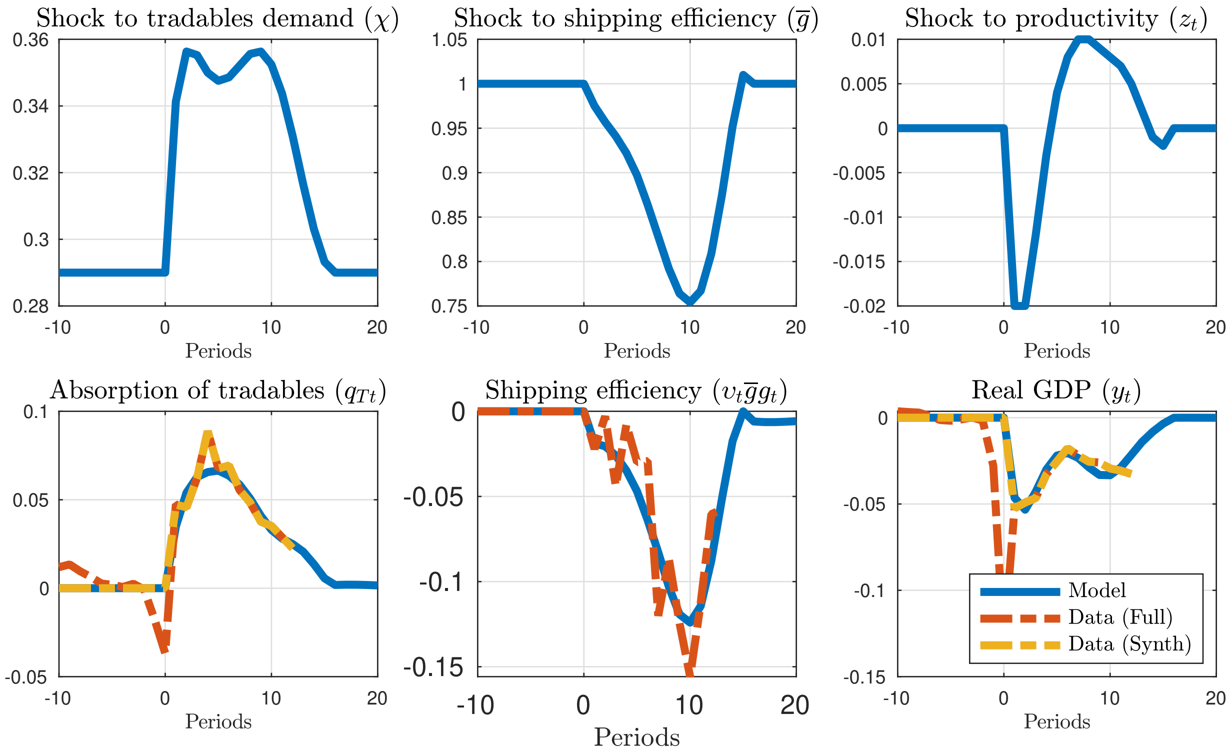
The increase of χ increases the relative contribution of tradables to the production of final goods. Thus, final good producers now demand more tradable goods and less non-tradables, leading to an increase in the aggregate absorption of tradable goods (q_{Tt}) and to a decline in the aggregate absorption of non-tradables (q_{Nt}). Tradable output, however, decreases as a result of the reduced effective shipping efficiency, which lowers the amount of tradables that countries are able to export. The increase in the relative demand for tradable and non-tradable goods, along with the decline of their relative supply, leads to an increase in the relative price between these goods (p_{Tt}/p_{Nt}).[27] In Section 5 of the Online Appendix we show that the relative price dynamics implied by the model are largely aligned with their empirical

[25] Moreover, to better capture pressures on shipping capacity that may differ across routes, we construct a bilateral shares matrix across the countries under consideration. For each bilateral country pair, we take the larger of the two changes in tradable consumption, treating it as the binding constraint for that route. We then average these changes across all pairs, weighting by bilateral trade volume.

[26] In addition, in Section 7.1 of the Online Appendix, we contrast the dynamics of capital investment between the model and the data. We observe that the model accounts well for these dynamics throughout the episode.

[27] We compute the price of tradable final goods as the cost of producing one unit of the tradable good q_{Tt}.

Figure 4: Shocks and implied dynamics



Note: The top panels report the level of the shocks throughout the experiment. The bottom panels report impulse response functions expressed as log-deviations from their respective steady-state values. "Data (Full)" reports the raw data while "Data (Synth)" excludes the sharp and transitory decline in 2020Q2 by setting its value to zero.

counterpart.

In the aggregate, we find that aggregate absorption of final goods and real GDP both decline.[28] In Section 7.2 of the Online Appendix we show that both aggregate consumption and investment decline, with consumption declining more than investment, as the reallocation of demand toward the capital-intensive tradable sector increases the demand for investments relative to consumption.

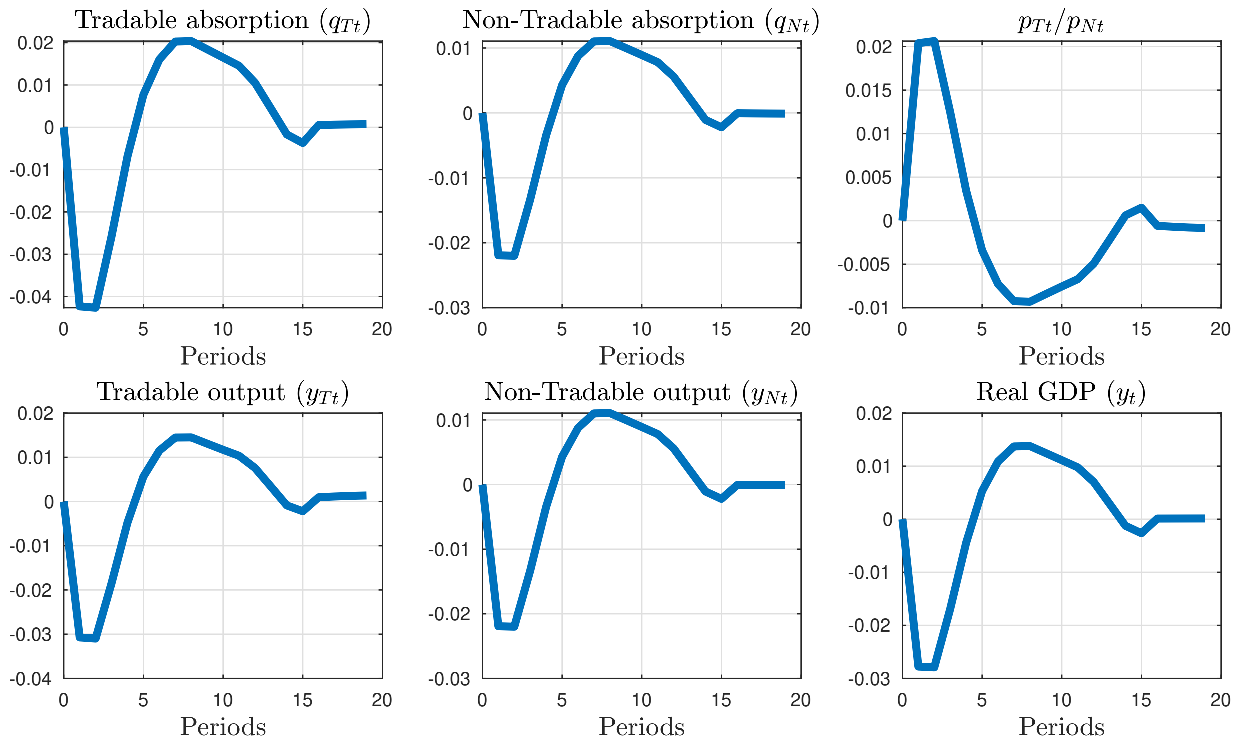
5.4 Shipping dynamics

We now investigate the implications of our model for the dynamics of shipping and trade. We report these dynamics in Figure 6. We ask: To what extent can the model account for the dynamics of global shipping observed in the aftermath of COVID-19?

We begin by observing that effective shipping capacity (bottom-right panel) declines as soon as the shocks hit. Thereafter, while effective capacity reverts back gradually, it remains below its pre-pandemic level for the duration of the shocks. The dynamics of effective

[28]Here and throughout the rest of the paper we compute real GDP as total value added with all prices kept fixed at their steady-state values.

Figure 5: Aggregate dynamics



Note: All impulse-response functions are expressed as log-deviations from their respective steady-state values.

shipping capacity result from the combination of three factors, shown in the bottom-left panel: the efficiency shock to shipping capacity ($\overline{g}$), the endogenous response of shipping capacity utilization (υ_t), and the installed shipping capacity (g_t). The efficiency shock to shipping capacity depresses effective shipping capacity through the duration of the shock. In response, firms increase the level of shipping capacity utilization for over 3 years. This increased utilization, however, comes at the cost of accelerated shipping depreciation, which reduces installed shipping capacity during the first six periods. Subsequently, increased shipping investments begin to raise installed capacity.

The reduced effective shipping capacity implies that real exports (q^*_{Tt}) and imports (q^f_{Tt}) need to contract in order to clear the market for shipping services. Equilibrium between demand and supply of shipping services is restored through a substantial increase of shipping costs (h_t), as observed in the upper-right panel, which reduces demand for trade and shipping services, while increasing supply of shipping services via higher utilization. The relatively small value of shipping costs in total imports (6.4% in the pre-pandemic steady-state, as observed in Table 2) implies shipping costs need to increase considerably to induce a significant reduction of trade.

The higher shipping costs raise the returns to investments in shipping capacity, leading to an increase in the shipping investment rate over the first few periods after the shock is realized. The lengthy shipping production lag along with the transitory nature of the shocks imply that shipping investments increase only over the first few periods, reverting thereafter, as observed in the top-right panel. There are declining incentives to investing after these first periods, since later investments would become operational once the shocks largely subside. As a result, both the model and the data exhibit a front-loaded investment response, with a sharp increase in shipping investment early on, followed by a decline as anticipated future shipping returns decrease. This pattern reflects strong incentives to expand capacity before demand pressures ease, consistent with forward-looking investment behavior in a market with production lags.

As investments in shipping capacity become operational in period 7 (that is, 6 periods after the investments are made) and the negative shipping efficiency shock begins reverting in period 11, we observe that real exports and real imports increase in tandem, and shipping costs begin to decline. Note, however, that this is a gradual process, as shipping investments are also subject to adjustment costs that prevent the global shipping firm from concentrating all investments in a single period. Thus, both production lags and quadratic adjustment costs are critical to account for the dynamics of shipping investment, with the model capturing the interplay between forward-looking investment decisions and time-to-build constraints that shape the observed dynamics.[29]

Model vs. data We now contrast the implied shipping and GDP dynamics vis-a-vis evidence from the data. In particular, Figure 6 plots the dynamics of shipping costs and shipping investment for both the model and the data in the aftermath of COVID-19.

The top left panel contrasts the dynamics of shipping costs (h_t) in the model with their empirical counterpart. To do so, we plot the dynamics implied by the model along with the Drewry World Container Index reported in Figure 1, which we compute as the log deviation from 2020Q3 onward relative to the 2017Q1-2020Q1 average.[30] We find that the implications of the model mirror the dynamics observed in the data, accounting for around 74% of the peak increase in shipping costs.

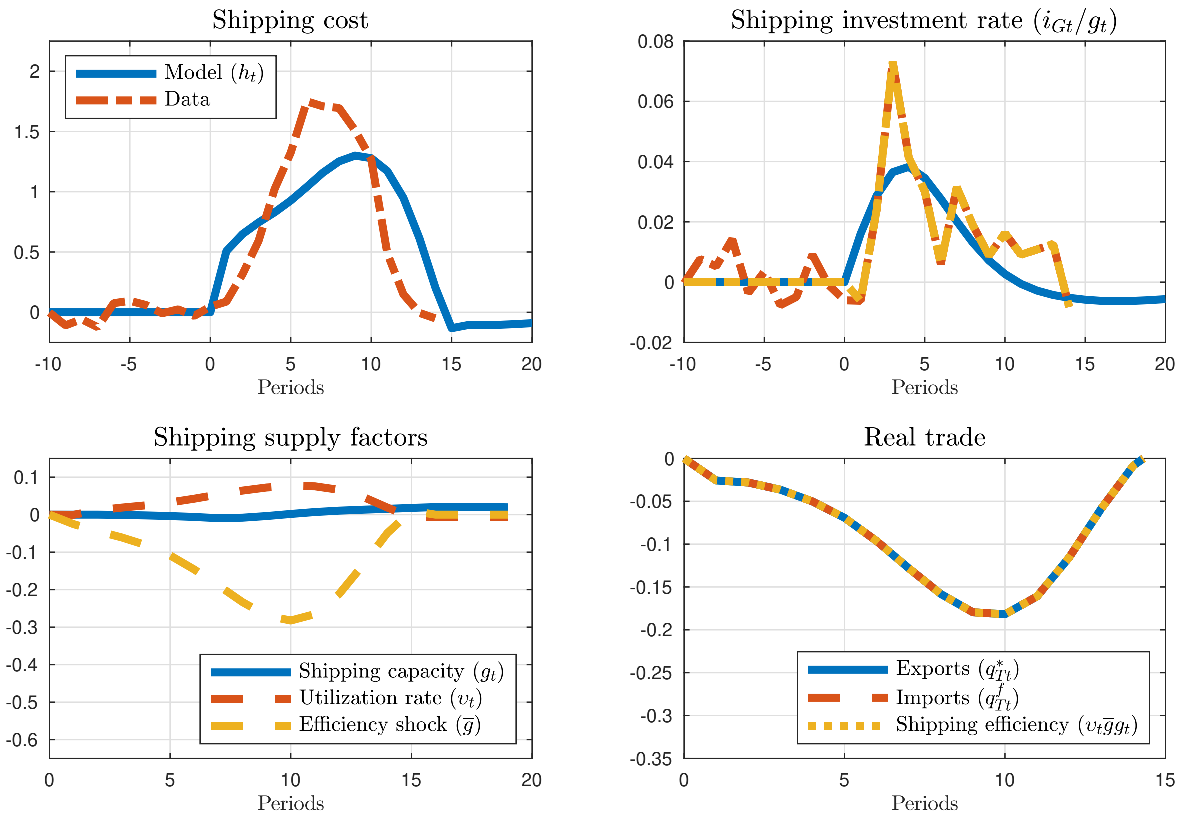
The top right contrasts the dynamics of the shipping investment rate in the model and data. In the data, we report the quarterly difference (in levels) from the 2019 investment rate.[31] We find that the model implies dynamics of shipping investment that are in line with

[29]See also Section 7.3 of the Online Appendix for results under alternative time lags and adjustment costs.

[30]In the model, shipping costs are contracted contemporaneously to the period in which goods are delivered. However, in the data shipping costs are measured prior to delivery. Thus, we account for the lag introduced by delivery lags by plotting the model's shipping costs shifted by a quarter when contrasting them with the data. We contrast shipping costs in the model vs. spot rates in the data given data availability across countries – in Section 2 of the Online Appendix we show that effective shipping costs in the U.S. also increased significantly and similarly during this period.

[31]The shipping investment rate is measured as new orders of ships relative to the fleet size, measured in

Figure 6: Shipping and international trade dynamics



Note: All impulse-response functions (except net exports and the shipping utilization rate) are expressed as log-deviations from their respective steady-state values. The shipping utilization rate is expressed as the percentage point deviation from its steady-state value.

the data.

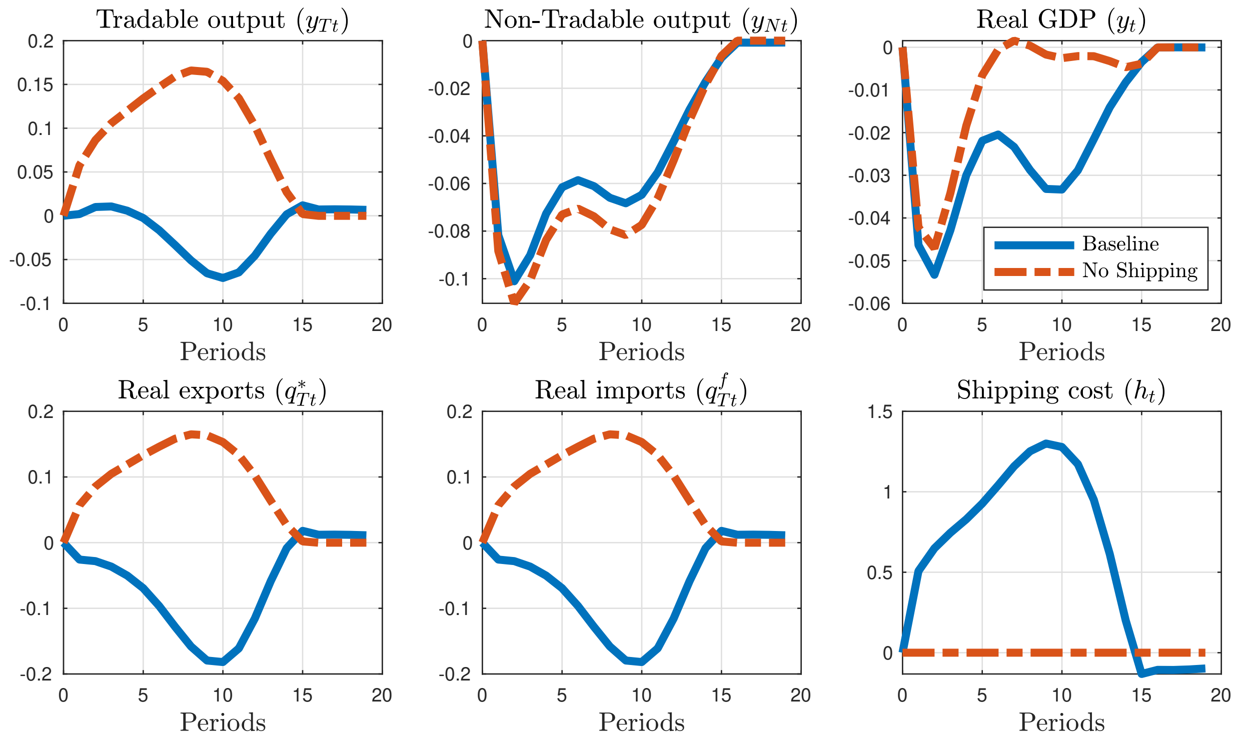
5.5 Aggregate implications of global shipping dynamics

The previous findings show that the model implies realistic shipping dynamics. In particular, these findings show that the low elasticity of shipping capacity in the short run significantly limited the adjustment of international trade flows, leading to a sharp increase of shipping costs.

We now investigate the extent to which the rigid short-run supply of shipping capacity affects the dynamics of key aggregate outcomes of the model. To do so, we contrast the implications of our model with those of a counterfactual economy with a perfectly elastic and costless supply of shipping capacity. This is implicitly the assumption in standard models of international trade and international business cycles (Backus et al. 1995; Heathcote and Perri 2002). That is, we consider an identical model but without the endogenous global shipping firm, where international purchases are only subject to the iceberg trade cost τ. We

TEUs.

Figure 7: Aggregate implications of shipping capacity



Note: All impulse-response functions are expressed as log-deviations from their respective steady-state values. "Baseline" denotes the dynamics implied by the model with endogenous shipping capacity, while "No shipping" denotes the dynamics implied by a model with perfectly elastic shipping supply.

recalibrate the steady-state parameters in the top panel of Table 2 to ensure both economies look identical in the pre-pandemic steady state. But we keep all other estimated parameters (bottom panel of Table 2) and shocks unchanged at their baseline values, avoiding differences in these from driving differences in the implied dynamics.

Figure 7 contrasts the dynamics of key aggregate variables between the two economies in response to these shocks. We refer to the model with endogenous shipping as "baseline" and to the model with perfectly elastic and costless supply of shipping capacity as "no shipping." We interpret differences in the implied dynamics as accounted for by the different shipping technologies across the two models. In contrast to our baseline, we find that tradable output (y^h_{Tt}) increases in the economy with perfectly elastic shipping supply. In the baseline, while demand for domestic and imported tradables increases, production contracts given the reduced availability of imported intermediates as shipping supply contracts. Production is also reduced since increased shipping costs reduce foreign demand and, thus, the returns to exporting. In contrast, access to imported intermediates is not constrained in the model with perfectly elastic shipping capacity. Thus, production of tradables increases given that imports and exports of these goods can increase more easily than in the baseline.

These differences in the dynamics of tradable output have important implications in the aggregate. For instance, real GDP decreases significantly more in the baseline than in the model with perfectly elastic shipping supply — real GDP is over 3 percentage points lower at the trough in the former than in the latter. Notice that these significant aggregate implications are despite the offsetting dynamics of non-tradable output, which decline relatively less in our baseline as final goods producers are unable to reallocate toward tradables as much as desired. Thus, we conclude that the dynamics of global shipping have significant aggregate effects despite only directly affecting the tradable goods sector, which is just a fraction of aggregate economic activity.

5.6 Shock decomposition: Tradable demand, Shipping capacity, Productivity

We now investigate the relative importance of the various shocks in accounting for the key findings documented above. To do so, we restrict attention to the model's implications for shipping costs and real GDP dynamics, and we compute three additional versions of the model. Each of these is identical to the baseline but features only one shock at a time. In particular, we keep all parameters as in the baseline. We interpret differences in the dynamics implied by these models as informative about the relative contribution of the respective shocks to the aggregate dynamics of the baseline model.

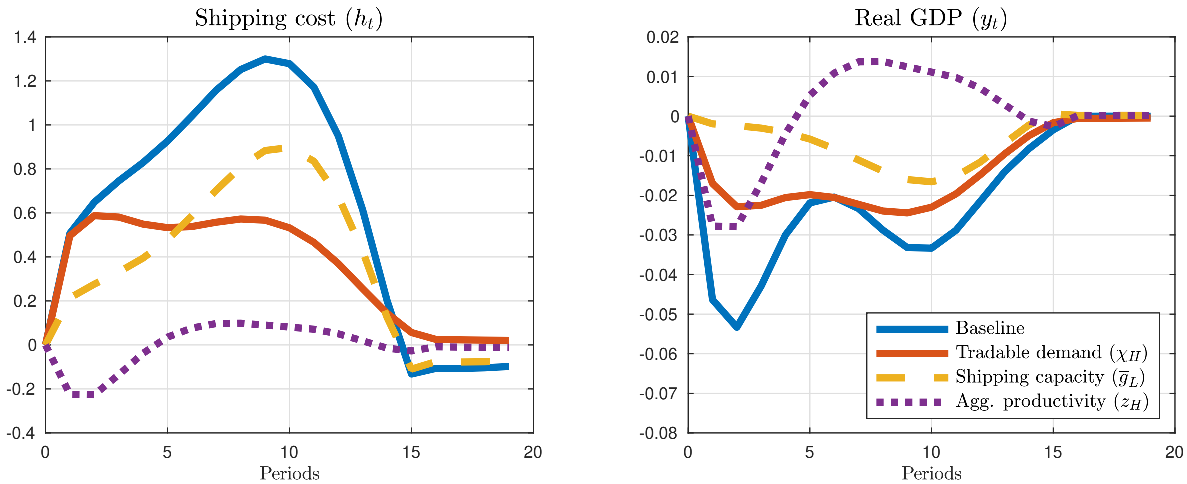
Figure 8 reports our findings. We observe that both the shipping efficiency shock and the shock to the demand for tradable goods are quantitatively significant drivers of shipping cost dynamics. In contrast, the productivity shock has a minimal impact on shipping costs. On the other hand, we find the tradable demand shock has a significantly larger effect on real GDP over the first few periods than the contraction of shipping supply. Aggregate productivity leads to a transitory decline of real GDP, reverting back and leading to an economic expansion starting in period 5.

5.7 Key channels accounting for quantitative results

In Section 7.3 of the Online Appendix we investigate the relative importance of alternative channels in accounting for the implications of the model. To sharpen the contrast between the different specifications, we study an alternative experiment where each of the shocks takes a constant value over 8 periods, estimated to target the average of the respective series, and reverting back gradually thereafter. We summarize our findings here, see the Online Appendix for further details.

First, we examine the role of alternative aspects of how shipping is modeled and parameterized. In particular, we examine the role of the shipping production lag (J), shipping investment adjustment costs (Φ_G), and the productivity of shipping investments (a_G). For

Figure 8: Shock decomposition



Note: All impulse-response functions are expressed as log-deviations from their respective steady-state values.

each of these dimensions, we re-estimate the steady-state but keep all other parameters unchanged at their baseline values. We report our findings in Figure 12 of the Online Appendix. We find that the shipping production lag along with shipping adjustment costs are jointly critical in determining the persistence of shipping cost and trade changes. Moreover, we find that neither the shipping production lag nor the adjustment costs affect the change of shipping costs on impact. Instead, what is key for this effect is the productivity of shipping investments, which pins down the value of shipping costs relative to the value of imports. As we describe in Section 4, in an economy where shipping costs are a higher fraction of the total import costs, a lower increase of shipping costs is required to reduce import demand such that it is in line with effective shipping capacity.

Second, we examine the role of alternative aspects of our setup in accounting for our findings. In particular, we examine the role of input-output linkages (φ) and the degree of complementarity or substitutability between domestic and imported varieties for both consumption-capital goods (ρ) and intermediates (ν). Given the importance of these features for the implications of the model, we sharpen the contrast with the baseline by re-estimating all parameters for each alternative following the same approach as the baseline. For each version, we restrict attention to the effect of shipping on real GDP dynamics, which we report in Figure 13. We find that input-output linkages are critical in accounting for the effect of shipping on real GDP dynamics — in an economy without input-output linkages, real GDP dynamics are much more similar with and without shipping. We observe a similar effect in the economy where domestic and imported varieties are more substitutable in the final good or intermediate input bundles. These findings show that a key channel accounting for the effect of shipping on real GDP dynamics is the rationing of intermediate inputs that are critical for production and which are hard to substitute with domestic alternatives.

6 Quantitative analysis: Business cycle dynamics

The previous section shows that our model accounts for a significant fraction of the increase in international shipping costs in the aftermath of COVID-19. Given the significant volatility of international shipping costs during normal times, as documented in Figure 2, we now ask: To what extent can our model account for cyclical fluctuations of international shipping costs, and what are their aggregate implications? To answer these questions, we extend the model such that aggregate country-level productivities z_t and z_t^* follow a joint vector autoregressive process of order 1.[32] While the post-COVID period was characterized by a reallocation of demand toward tradables and a contraction of shipping efficiency—two atypical but well-documented features of the pandemic—international business cycles are generally modeled as driven by country-specific productivity shocks. Accordingly, we restrict attention to productivity shocks for studying cyclical fluctuations in shipping costs, allowing us to assess the implications of our model in a manner consistent with the broader business cycle literature (Backus et al. 1995; Heathcote and Perri 2002).

Then, our approach to evaluating the drivers and implications of cyclical shipping cost fluctuations is the following: First, we estimate the parameters controlling the productivity process described above. Second, we simulate the model to compute moments characterizing the typical business cycle dynamics implied by the model. In particular, we examine the implied dynamics of international shipping costs, which are not targeted in the estimation. Finally, we evaluate how global shipping affects international business cycles by contrasting the dynamics implied by our model to those implied by a model with a perfectly elastic supply of shipping capacity.

We begin by re-estimating the model to capture salient features of international business cycles. We parametrize the productivity process by setting the persistence (ρ_z) and spillover (ρ_{zz}) coefficients as estimated by Backus et al. (1995), but we set productivity shocks to be uncorrelated across countries and re-estimate their volatility (σ_z) to ensure the model reproduces the volatility of real GDP observed in the data. In addition, we re-estimate the capital adjustment cost to capture the volatility of investment relative to GDP. Both empirical business cycle moments, the volatility of real GDP and investment, are from Backus et al. (1995). All other parameters are kept unchanged at the values described in the previous section. Model moments are based on 100 simulations of 120 periods.

Table 3 reports the implications of the model (second column) for a broader set of mo-

[32] In particular, z_t is given by $\log z_{t+1} = (1 - \rho_z - \rho_{zz}) \log \overline{z} + \rho_z \log z_t + \rho_{zz} \log z_t^* + \varepsilon_{zt+1}$ and z_t^* is given by $\log z_{t+1}^* = (1 - \rho_z - \rho_{zz}) \log \overline{z} + \rho_z \log z_t^* + \rho_{zz} \log z_t + \varepsilon_{zt+1}^*$, where $\overline{z}$ denotes the steady-state productivity level and $\{\varepsilon_{zt+1}, \varepsilon_{zt+1}^*\}$ are uncorrelated zero mean innovations with std. dev. σ_z.

Table 3: **Business cycle fluctuations**

	Data	**Baseline**	**No Shipping**
Std. dev. real GDP	1.92	1.92	2.19
Std. dev. relative to real GDP:			
Consumption	0.75	0.65	0.65
Investment	3.27	3.27	3.25
Tradable absorption	1.26	0.97	1.22
Std. dev. relative to GDP			
Shipping costs	7.70	7.08	–
Shipping capacity	0.92	0.63	–
Correlation w/real GDP			
Shipping costs	0.49	0.62	–
Shipping capacity	0.13	-0.21	–

ments beyond those targeted in the estimation, along with their empirical counterparts (first column). We find the model with endogenous shipping can account for standard features of business cycle dynamics beyond those targeted directly in the estimation. For instance, the model implies a volatility of consumption and a cyclicality of tradable absorption similar to the data.

6.1 Global shipping cost fluctuations

We now examine the implications of the model for global shipping cost fluctuations. To do so, Table 3 reports its volatility and cyclicality in our baseline model relative to the data.

We find that our model implies shipping costs that are 7.08 times more volatile than real GDP, largely accounting for the significant volatility of shipping costs observed in the data. Our model implies that these costs are more correlated with GDP than we see in the data, but this is to be expected given our model features only two countries, whereas in the data no individual country is sufficiently large to be so tightly correlated with global shipping fluctuations. In contrast, we find global shipping capacity is less volatile than GDP and largely uncorrelated with it.

6.2 Global shipping and aggregate fluctuations

We now evaluate the impact of global shipping on international business cycle fluctuations. Our goal is to quantify the extent to which observed aggregate fluctuations are accounted for by global shipping. We do so by contrasting the cyclical fluctuations implied by our model vis-a-vis a counter-factual economy with a perfectly elastic and costless supply of shipping services. As in the previous section, we keep all parameters unchanged across the two models except for those estimated to match steady-state targets. Table 3 reports our findings — the second column reports the moments implied by our baseline, while the third column reports those in the economy with perfectly elastic shipping capacity. We interpret differences between the models as the impact of shipping on business cycle fluctuations.

In contrast to our findings in the aftermath of COVID-19, we find that global shipping *reduces* the volatility of aggregate fluctuations at business cycle frequencies. In the absence of global shipping rigidities, we find that the volatility of real GDP and tradable absorption would be 14.1% and 25.8% higher, respectively. These estimates reflect an extreme counterfactual where shipping supply is perfectly elastic. Rather than aiming to capture a realistic change in the environment, the exercise isolates the role of shipping rigidities relative to standard models with perfectly elastic shipping supply, highlighting the significance of shipping as an adjustment margin in shaping macroeconomic fluctuations.

To understand these findings, consider the impact of a positive productivity shock in our model. This shock increases the production possibility frontier of the economy while reducing international trade costs. Thus, the demand for tradable goods increases during booms, leading to a higher demand for shipping services. But given shipping supply is inelastic in the short run, international shipping costs increase to ration the increased demand for trade, reducing the extent to which producers of tradable goods scale up production. In contrast, the economy with perfectly elastic shipping supply does not respond by rationing international shipping supply during booms, featuring a greater increase of trade and absorption during economic expansions. Thus, global shipping mitigates aggregate fluctuations at business cycle frequencies.[33]

These effects differ markedly from those implied by the shocks experienced by the global economy in the aftermath of COVID-19, as we show in the previous section. The key difference is that, in the aftermath of COVID-19, the demand for tradables increased during a period of aggregate economic contraction rather than expansion, as is typically observed at business cycle frequencies. In this context, the higher demand for tradables acts as a mitigating force to the contraction of aggregate GDP. But with short-run rigidities in shipping supply, demand and production of tradables are able to increase relatively less than in a model with elastic shipping supply. Therefore, aggregate GDP declines relatively more in our baseline than in the economy with perfectly elastic shipping capacity. These findings show that the nature of the shocks at play are critical in determining whether global shipping amplifies or mitigates macroeconomic fluctuations.[34]

[33]Brancaccio et al. (2020) also find that endogenous shipping costs dampen the response of trade to shocks, but through a complementary mechanism. In their model, overall shipping capacity is fixed, and trade imbalances and search frictions determine how it is spatially allocated, muting demand fluctuations. In contrast, our framework highlights how investment decisions and production lags in shipping create rigidities in the adjustment of total shipping capacity, shaping the response of trade and economic activity to shocks.

[34]In Section 8.1 of the Online Appendix we additionally show that the local vs. global nature of the shocks can also be important for global shipping dynamics and their aggregate implications.

Our findings relate closely to a growing literature on the macroeconomic implications of shipping supply rigidities. For instance, Kalouptsidi (2014) examines how investment lags influence shipping prices and finds that in the absence of time-to-build constraints, shipping price volatility would be 14% lower. Our analysis builds on this insight by embedding these frictions into a general equilibrium framework and exploring their broader macroeconomic implications. In Section 8.2 of the Online Appendix, we show that reducing the shipping production lag and the associated adjustment costs lowers the volatility of shipping costs relative to GDP by approximately 30%. While differences in other modeling assumptions may also contribute to this gap, our results suggest that general equilibrium interactions between shipping supply adjustments and macroeconomic conditions are important in amplifying shipping price volatility beyond what is observed in partial equilibrium settings.

7 Quantitative analysis: Shipping disruptions in the Red Sea and beyond

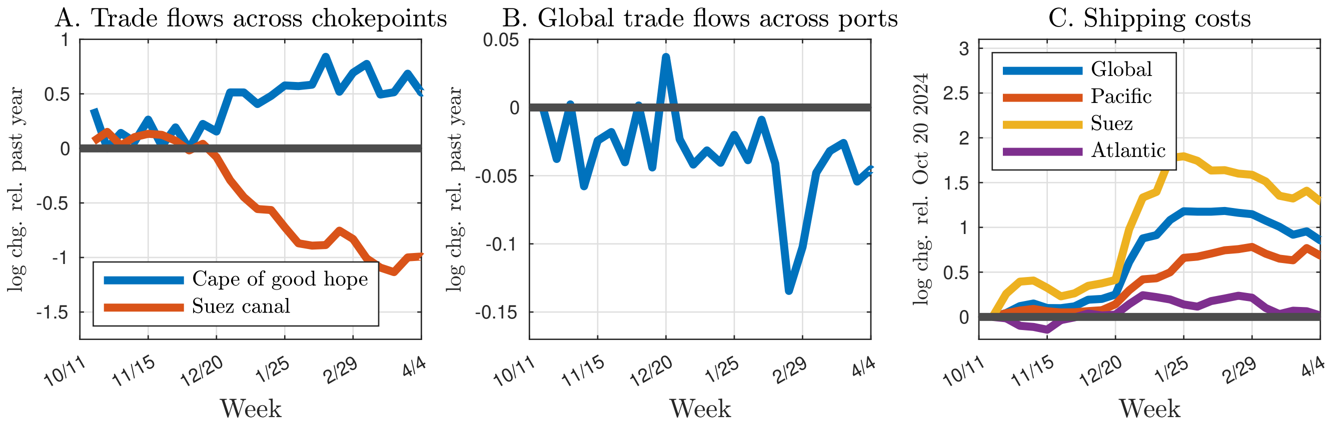
The previous sections analyzed the role of demand, productivity, and shipping supply shocks in shaping global trade and shipping dynamics, first in the context of COVID-19 and then for global business cycles. We now examine whether a global macroeconomic model, despite not explicitly modeling granular regional disruptions, can still capture the broader global impact of localized shocks. Specifically, we study the Red Sea shipping disruptions which began in late 2023 as a case study of how regional shocks propagate through global markets. This exercise allows us to assess the extent to which the mechanisms identified in prior sections remain relevant in a setting where shipping constraints originate from localized disruptions that contract global shipping capacity. We conclude by examining the potential implications of recurring shipping disruptions for business cycle volatility amid rising geopolitical tensions.

7.1 Shipping disruptions in the Red Sea

In late 2023, attacks to ships navigating the Red Sea led vessels to reroute through the Cape of Good Hope, increasing shipping times by at least 14 days. Panel A of Figure 9 shows that trade flows around the Cape of Good Hope have increased in tandem with the rerouting from the Suez Canal, confirming that this has been the primary alternative route for much of the trade initially intended to ship through the Red Sea.

Despite only 15% of global trade moving through the Suez Canal, this regional shock has impacted global shipping, reducing trade flows and increasing costs. Panel B of Figure 9 plots weekly estimates of global exports based on IMF's Portwatch data across 1,378 major ports. We observe that global exports have declined systematically (relative to the same week the year prior) since mid-December 2023, when major shipping companies began rerouting their voyages away from the Red Sea. Panel C of Figure 9 plots the dynamics of global and

Figure 9: Impact of attacks on Red Sea vessels on global shipping



Note: Data from IMF PortWatch's daily chokepoint transit calls and trade volume estimates, IMF PortWatch's daily port activity data and trade estimates, and Freightos price indexes.

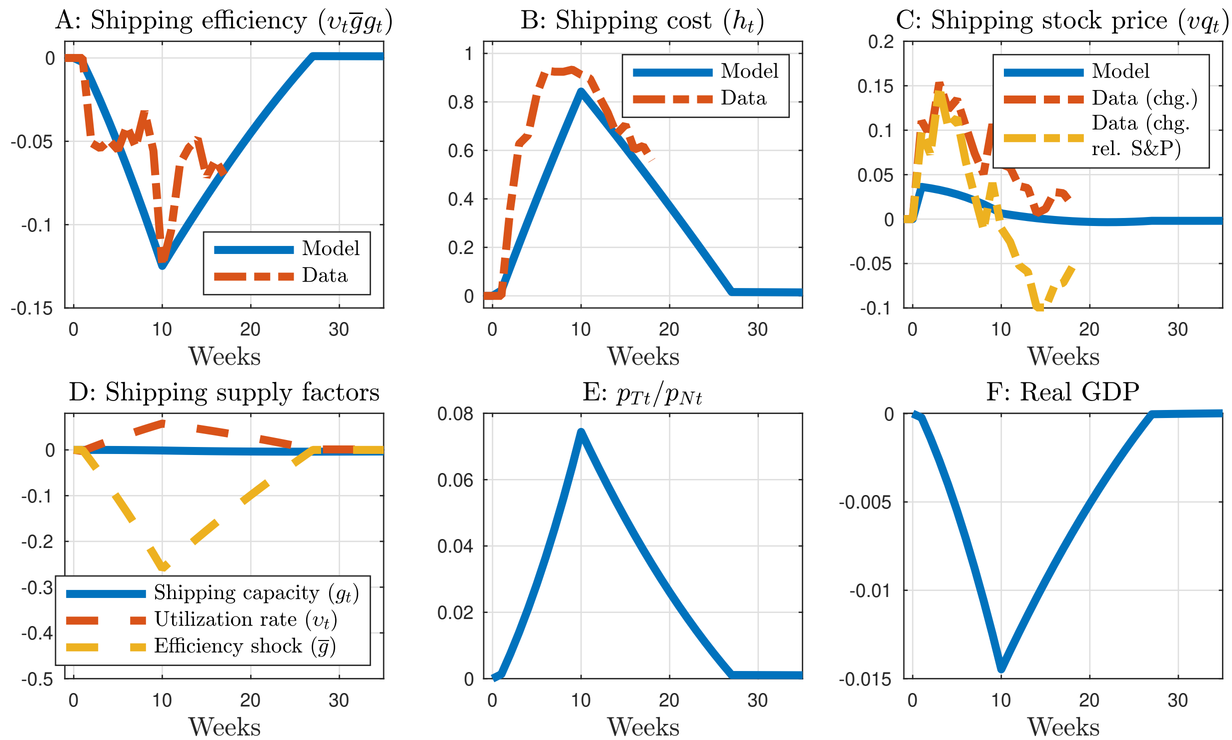
regional shipping costs, using data from Freightos. As expected, we observe that shipping prices for routes around the Suez Canal have increased substantially over this period. More surprisingly, we observe that global shipping costs have also increased substantially despite the regional nature of the shock.

To investigate the channels accounting for the global impact of shipping disruptions and their implications, we use our model to study the effect of shipping capacity shocks designed to mimic the reduction of global trade flows observed in the data. Specifically, we study a weekly version of the model, estimated using data prior to the Red Sea disruptions, and assume the economy is in steady state before the disruptions start in mid-December 2023.[35] Information about the shocks is revealed in the week of December 17-23, 2023, with negative shipping supply shocks starting the following week, chosen to track the observed global trade flows. Panel A of Figure 10 plots the dynamics of global effective shipping supply in the model and the data. The shocks are assumed to revert gradually to the steady state over the next four months.

The top row of Figure 10 compares the model's implications for global shipping dynamics with their empirical counterparts. Panel B shows that the model generates a substantial increase of global shipping costs. In the model, the rigid short-run supply of shipping capacity due to high utilization and time-to-build in shipping investment implies that reductions in effective capacity can only be partially offset in the short run. This leads to higher shipping costs to bring imports in line with the reduced shipping supply. Panel C shows that the model

[35]First, we adjust the following parameters to be as in our baseline, but expressed at a weekly frequency: $\beta = 0.999228$, $\delta = 0.001901$, $\overline{\delta}_G = 0.00217$, and $J = 72$. Given these parameters, we re-estimate the model to target the steady-state moments. Then, we re-estimate Φ_k, Φ_G, and ξ as in our baseline along with one-time shocks that reproduce the average dynamics following COVID-19. The estimated values of these parameters are 12.65, 1.50, and 0.0001, respectively.

Figure 10: Shipping and aggregate dynamics following Red Sea disruptions



Note: All impulse-response functions are expressed as log-deviations from their respective steady-state values.

also accounts for the observed increase in the value of shipping firms, as captured by their stock prices.[36] In the model, these effects are accounted by the combination of rigid shipping supply and inelastic imports demand, which allows for higher prices and profits despite the disruptions.

Although the model does not explicitly incorporate regional shocks, it captures their global effects through the contraction of shipping efficiency, which translates into higher shipping costs, stock prices, and broader macroeconomic adjustments. The reduced shipping efficiency constrains the ability of countries to trade, leading to a decline in both exports and imports. The resulting reduction in access to tradable goods causes their relative price to increase, inducing a partial reallocation of consumption and investment towards nontradables. However, the overall effect is contractionary, with declines in aggregate trade, investment, and production. These findings provide a lens through which to interpret the potential implications of shipping disruptions in the Red Sea for the global economy.

[36] We report the simple average of stock price changes relative to the week of 12/10-12/16 for all publicly traded shipping companies. In particular, we focus on Antong Holdings, Evergreen Marine Corporation, Yang Ming Marine Transport Corporation, Wan Hai Lines, Maersk, COSCO Shipping Lines, Hapag-Lloyd, HMM Co. LTD, Korea Marine Transport Corporation, Matson, Ningbo Ocean Shipping Company, Zhonggu Logistics Corporation, Swire Shipping, and Zim Integrated Shipping Services. These firms account for around 50% of the market share of the global containership industry.

Table 4: Business cycles with shipping disruptions

	Std. dev. Real GDP	*Std. dev. relative to GDP* Shipping cost	*Avg.* Shipping capacity
A. No shipping disruptions			
Data	1.92	7.70	—
Baseline	1.92	7.08	1.00
No shipping	2.19	—	—
B. Shipping disruptions			
std. dev. = 1X Red Sea, half-life = 1Q	2.01	19.69	1.02
std. dev. = 2X Red Sea, half-life = 1Q	2.29	33.73	1.07
std. dev. = 1X Red Sea, half-life = 2Q	2.04	21.67	1.03
std. dev. = 2X Red Sea, half-life = 2Q	2.44	36.50	1.11

7.2 Business cycle implications of periodic shipping disruptions

To conclude our analysis, we examine the impact that periodic shipping disruptions can have on business cycle dynamics. To do so, we extend the model to feature stochastic shocks to shipping efficiency, following an AR(1) process.[37] We consider the model as estimated in Section 6 and examine its implications for the volatility of shipping costs and aggregate economic activity. We study shipping disruptions with standard deviation equal to 1 and 2 times the magnitude of the Red Sea shock, with half-lives of 1 and 2 quarters. Table 4 reports our findings.

To put our findings in context, in Panel A we reproduce the findings reported in Section 6, which show the effect of shipping on business cycle fluctuations without periodic shipping disruptions. In Panel B, we report the business cycle implications of periodic shipping disruptions. We find that larger and more persistent disruptions lead to a significant increase in the volatility of shipping costs and aggregate economic activity. For instance, with disruptions that are twice as large as the Red Sea shock and a half-life of 2 quarters, the standard deviation of real GDP rises from 1.92% to 2.44% and the volatility of shipping costs relative to GDP rises from 7.08 to 36.5.

However, for disruptions of the magnitude and persistence observed in the Red Sea, the impact on aggregate volatility is more modest. With a shock of that size and a half-life of 1 quarter, real GDP volatility increases from 1.92% to 2.01%. This suggests that while large and persistent shipping disruptions can significantly amplify business cycles, more transitory shocks do not have a major impact on aggregate fluctuations. Thus, our findings point to the importance of the magnitude and persistence of shipping disruptions in determining their ultimate impact on aggregate volatility.

[37] We assume the shocks to shipping efficiency are orthogonal to country-specific productivity shocks.

Finally, the third column of the table shows how shipping disruptions affect overall shipping capacity. The results show that as the volatility and persistence of the disruptions increase, average shipping capacity also increases. For example, with a disruption twice the size of the Red Sea shock and a half-life of 2 quarters, the average shipping capacity rises by 11 percent. These effects capture the precautionary increase of global shipping capacity in the face of growing risks.

8 Concluding remarks

This paper studies the drivers and aggregate implications of global shipping dynamics. Motivated by salient features of global container shipping that we document, we develop a dynamic model of international trade with an endogenous market for global shipping services. We find that the model successfully accounts for shipping cost fluctuations in the aftermath of COVID-19, over the business cycle, and following shipping disruptions in the Red Sea, with significant implications for aggregate economic activity. Our findings highlight the critical role of global shipping as the backbone of the global trading system and the importance of accounting for its endogenous dynamics when evaluating the economy's response to shocks. As shipping disruptions become increasingly prevalent, our results point to the need for models that explicitly incorporate the endogenous adjustment of global shipping capacity and costs to assess the implications of future developments and policies.

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Online Appendix — Not for Publication

Navigating the Waves of Global Shipping: Drivers and Aggregate Implications[1]

Jason Dunn (Boston University), Fernando Leibovici (FRB St. Louis)

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[1] Correspondence address: fleibovici@gmail.com. The views expressed herein are those of the individual authors and do not necessarily reflect official positions of the Federal Reserve Bank of St. Louis, the Federal Reserve System, or the Board of Governors.

Part I

Data

1 Shipping disruptions during COVID-19

The COVID-19 pandemic caused significant disruptions to global shipping, leading to a contraction in effective shipping capacity. This section provides additional context on the shipping efficiency shock modeled in our quantitative exercise. We present both empirical evidence from key shipping indicators and anecdotal reports from major ports to highlight the nature and extent of these disruptions.

1.1 Quantitative evidence

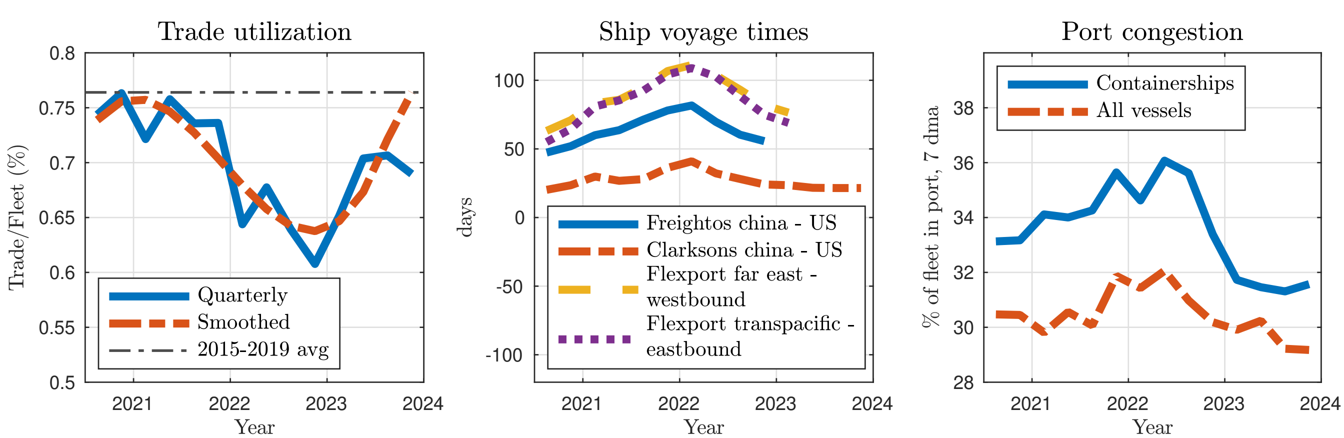
Figure 1 presents three key indicators of shipping disruptions during the pandemic: trade utilization, voyage times, and port congestion.

The left panel shows trade utilization, calculated as the ratio of global trade volume to total fleet capacity. This measure proxies the effective use of global shipping capacity. The observed decline in trade utilization during COVID-19, despite higher demand for tradable goods, reflects widespread reduced effective shipping capacity caused by port congestion, shipping delays, and labor shortages. This is the variable we use in the paper to back out the productivity shock $\bar{g}$ to shipping efficiency.

The middle panel shows average voyage times across major shipping routes, illustrating a significant increase during the pandemic. Ships were delayed at ports due to health restrictions, crew shortages, and longer turnaround times, reducing the availability of shipping services and contributing to the decline in effective capacity.

The right panel displays port congestion data for containerships and all vessel types. Ports around the world experienced unprecedented delays, with ships waiting offshore for extended periods before being processed. This congestion further constrained the shipping industry's ability to meet rising demand and drove up shipping costs.

Figure 1: Shipping disruptions during COVID-19



Data details

Data from Clarkson's *Shipping Intelligence Network*, Flexport, and Freightos. **Trade utilization** is measured using Clarksons data on total containership trade and fleet capacity, both expressed in TEUs, examining changes relative to the 2015–2019 average. **Clarksons China to US** West Coast Containership Voyage - Average Duration (Beta) Basis data derived from AIS vessel movements data. **Flexport**'s Ocean Timeliness Indicator measures the amount of time taken to ship freight from the point at which cargo is ready to leave the exporter to when it is collected from its destination port. Measures are shown for Far East Westbound (e.g., China-to-Europe) and Transpacific Eastbound (e.g., China-to-US) routes. **Freightos**: Door to Door shipping from China to U.S. Clarksons **Port Congestion** Index - % fleet capacity, 7dma Data based on the proportion of vessels (in terms of TEU) in the fleet in a defined port or anchorage location based on vessel's closest to midday AIS signal on the date specified.

1.2 Anecdotal evidence of port restrictions and crew shortages

Anecdotal evidence from major ports provides further insight into the specific disruptions that reduced shipping capacity. For example, Chinese ports implemented stringent quarantine measures for incoming vessels. The port of Fuzhou, for instance, imposed a requirement for ships arriving from certain countries to wait up to 14 days before docking, significantly delaying ship processing.[2] In the United States, the ports of Los Angeles and Long Beach faced significant operational challenges due to labor shortages and increased cargo volumes. COVID-19 infections among dockworkers led to slowdowns in operations, with dozens of cargo ships anchored offshore and waiting to be offloaded.[3]

Additionally, the pandemic caused a global crew change crisis, with an estimated 400,000 seafarers stranded on vessels due to international travel restrictions. In China, for example, returning seafarers were subjected to mandatory quarantine periods of up to seven weeks, further delaying shipping operations.[4]

The combination of quantitative indicators and anecdotal evidence provides broad support for our interpretation of the shipping efficiency shock that we consider in the paper. The disruptions observed during the pandemic played a crucial role in driving the supply chain bottlenecks and trade slowdowns that significantly impacted global shipping capacity.

2 Shipping costs: Spot vs. effective rates

In this section, we contrast the shipping cost measure that we use throughout the paper relative to other ways of measuring shipping costs. The benchmark series we use for comparison and analysis is the Global Drewry average spot rate for 20-foot TEU containers. It is important to note that while spot rates are

[2] TTNews, "Chinese Port Restricts Ships From Virus-Hit Nations for 14 Days," available at `https://www.ttnews.com/articles/chinese-port-restricts-ships-virus-hit-nations-14-days`

[3] NewsNation, "COVID-19 Infections Among Hundreds of Workers Lead to Cargo Ship Traffic Jam," available at `https://www.newsnationnow.com/business/covid-19-infections-among-hundreds-of-workers-lead-to-cargo-ship-traffic-jam`

[4] Supply Chain Digital, "7-Week Quarantine for Ship Crew in China Hits Supply Chain," available at `https://supplychaindigital.com/logistics/7-week-quarantine-ship-crew-china-hit-supply-chain`

among the most cited measures of shipping costs, they may not be representative of overall effective shipping costs given that some carriers engage in longer-term contracts that do not adjust immediately in response to shocks.

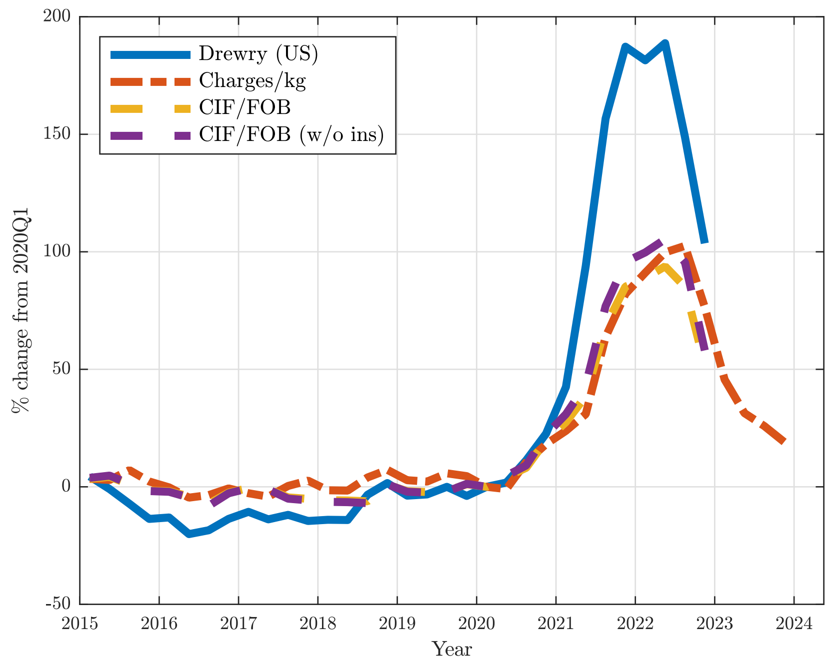
To evaluate whether spot rates reflect effective shipping costs, we compare the Drewry spot rates to U.S. trade cost data from the U.S. Census. Specifically, Figure 2 shows four series: the Drewry container index for U.S. ports, the U.S. Census measure of freight and insurance charges per kilogram of trade, and the ratio of CIF (cost, insurance, and freight) to FOB (free on board) values, with and without insurance.[5] Critically, these alternative measures of shipping costs capture the effective shipping cost paid, combining both spot rates and long-term contracts. Each series is expressed as a percentage change relative to 2020Q1. We restrict attention to U.S. imports given that data limitations prevent us from computing these variables systematically across countries — this is why we focus on global spot rates in the paper.

The comparison suggests that the effective shipping costs measured using U.S. Census data and the CIF/FOB ratio exhibit similar trends as the Drewry spot rates during the pandemic, albeit with less pronounced fluctuations. The freight and insurance charges per kilogram and the CIF/FOB ratio (with and without insurance) both increased significantly during the pandemic, but their increases were milder in magnitude than spot rates. This difference is consistent with the notion that spot rates are more sensitive to immediate supply and demand shocks, whereas aggregate shipping costs capture a broader set of shipping arrangements, including longer-term contracts.

Overall, the comparison indicates that the Drewry spot rates capture the direction and timing of changes in shipping costs observed in aggregate trade data. While the lack of data availability on effective shipping costs across countries prevents us from comparing spot vs. effective rates across countries, the findings reported in this section suggest the spot rates used in our model reflect broader shipping cost trends, making them a suitable proxy for the purpose of this study.

[5] To calculate the CIF/FOB rate without insurance, we remove 0.5% from the CIF before calculating percent changes. The 0.5% insurance estimate is taken from Freightos: `https://www.freightos.com/freight-resources/freight-insurance`.

Figure 2: Shipping costs, spot vs. effective rates



Note: Data from Drewry Supply Chain Advisors and US Trade Census.

3 Containers and global shipping

Understanding the role of container shipping in global trade is crucial to assessing the broader impact of shipping disruptions on economic fluctuations. While the paper focuses on container shipping, this section provides additional context by examining the value and volume of goods transported by different shipping modes, comparing industry dynamics across container and bulk shipping, and analyzing trade fluctuations following the COVID-19 pandemic. The evidence presented here highlights that container shipping accounts for a significant share of global trade value, exhibits dynamics similar to other important seaborne shipping markets, and experienced trade fluctuations comparable to bulk shipping during COVID-19.

3.1 Containers: Value and volume of goods shipped

To assess the significance of container shipping within global trade, it is useful to examine the breakdown of trade by different shipping modes. Tables 1 and 2 present the distribution of trade shares across sea, air, and land, both globally and for the United States. These tables highlight the dominant role of maritime shipping in international trade and the substantial contribution of containerships.

Table 1 shows that sea shipping accounts for a significant share of global trade, both in value and volume. Globally, around 42.6% of trade value is transported by sea, while in the U.S., sea shipping represents 41.3% of trade value. In terms of volume, sea shipping dominates air: relative to air shipping, more than 99% of the volume of goods transported in the U.S. and globally are moved by sea.[6] Air freight trade values are higher given the prevalence of high-value goods.

These patterns highlight the limited scope for mitigating COVID-19-related shipping disruptions through a reallocation from sea shipments to air or land transport. First, air shipping capacity is minimal compared to sea shipping capacity. Second, land-based reallocation is only feasible for shipments between geographically proximate and connected locations.

Table 2 provides a breakdown of sea transport by shipping type. Containerships account for a substantial portion of sea trade by value, representing 58.1% and 55.5% of U.S. and global sea trade value, respectively. In terms of volume, containerships represent about 13.9% of U.S. sea shipping volume and approximately 15% globally. The remainder of sea trade volume is primarily carried by bulk shipping.

These figures underscore that container shipping accounts for a significant portion of global trade value and plays a key role in maritime transport worldwide, making it central to understanding global shipping dynamics.

3.2 Industry dynamics: Containers vs. bulk

Given that container and bulk shipping together account for the majority of sea trade, it is useful to examine whether the dynamics observed in the containership sector extend to bulk shipping as well. Figure 3 shows these subsectors exhibit similar patterns across fleet growth, capacity utilization, new orders relative to

[6] Data limitations prevent us from comparing trade volumes relative to land.

Table 1: Total trade shares

Mode	Value share US	Value share Global	Volume share US	Volume share Global
Sea	41.3%	42.6%	99.4%	> 99%
Air	28.1%	15.4%	0.6%	< 1%
Land	30.6%	38.1%	-	-
Other	-	4.0%	-	-

Notes: Columns 1 and 3 are 2015 - 2023 averages from the US Trade Census for both exports and imports. Column 2 is the 2017 - 2023 average from a sample of 46 countries from Comtrade. Column 4 is a 2021 value reported in Boeing World Air Cargo Forecast 2022 - 2041. In columns where the "Land" and/or "Other" categories are omitted, it is because those categories are not included in that data.

Table 2: Sea trade shares

Mode	Value share US	Value share Global	Volume share US	Volume share Global
Containerships	58.1%	55.5%	13.9%	15.0%
Dry Bulk	8.3%	10.3%	34.9%	52.5%
Other	33.6%	34.2%	51.2%	32.5%

Notes: Columns 1 and 3 correspond to those in Table 1. To classify the goods shipped between containerships and dry bulk, we consider the following HS commodities as containership goods: 7-9, 16, 19-22, 39-40, 50-63, 68-70, 73-74, 76, 78-79, 84-88, 90-91, 94-96. We consider the following commodities as dry bulk goods: 10, 12, 23, 25-26, 28, 31, 44, 47-48, 2701-2704, 2713. Column 4 is the 2015 - 2023 average from Clarkson's *Shipping Intelligence Network*. The dry bulk category here includes grain, iron ore, minor bulk, coal, and other dry bulk. The "Other" category includes crude oil, oil products, gas, and chemicals.

earnings, and the relationship between earnings and excess demand. The observed similarities suggest that the key economic forces driving shipping dynamics are common across shipping modes and not unique to containerships.

The top left panel of Figure 3 shows that fleet sizes for both container and bulk shipping have grown steadily over time, reflecting consistent investment in shipping capacity across both markets. The top right panel illustrates capacity utilization rates for these subsectors, which have remained high and stable, indicating a persistent balance between supply and demand in both the containership and bulk shipping markets.

The middle panels of Figure 3 show new orders and average earnings for both subsectors. In both cases, we observe a positive relationship between earnings and new orders, indicating that periods of higher earnings are also ones featuring increases in new ship orders. This similarity suggests that investment decisions are driven by comparable incentives across both subsectors.

The bottom panels of Figure 3 illustrate the relation between earnings and excess demand for both container and bulk shipping. The positive correlation observed in both markets further demonstrates that pricing and investment dynamics are driven by similar economic forces, regardless of subsector.

Lastly, Figure 4 shows that spot rates for containers (Drewry World Container Index) and dry bulk (Baltic Dry Index) have followed similar trends over the past 20 years. However, the Great Recession had a more pronounced impact on dry bulk rates, while the effects of COVID-19 were slightly more significant for containerships.

These similarities are particularly noteworthy given the differences in market structure between the two subsectors. The containership sector is dominated by a few large firms, with the top 10 companies controlling approximately 80% of the market. These firms often operate through strategic alliances to coordinate capacity and routes. In contrast, bulk shipping is much more fragmented and competitive, with a large number of smaller operators. The bulk shipping market, as studied by Kalouptsidi (2014) and Brancaccio et al. (2020), is generally considered a benchmark for competitive behavior in shipping markets.

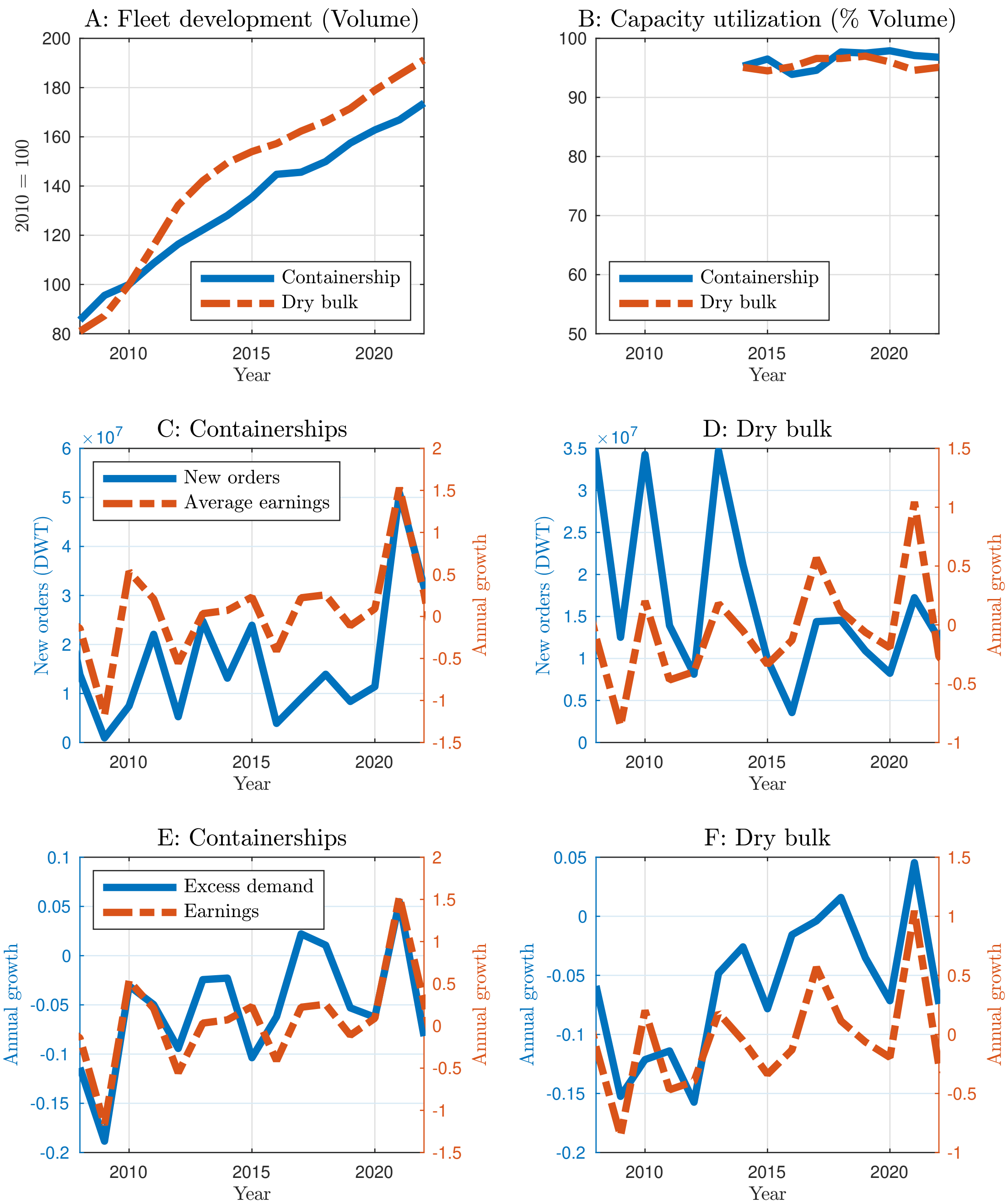
Despite these differences in market structure, the observed dynamics across both subsectors—such as fleet growth, capacity utilization, investment responses to earnings, and spot rates—are remarkably similar. This suggests that the shipping dynamics we observe are unlikely to be driven primarily by differences in market structure. Instead, they appear to reflect broader economic forces that are common across different types of sea shipping. The fact that containerships, despite their more concentrated market structure, exhibit similar investment and price patterns to bulk shipping supports the relevance of using container shipping as a representative case for modeling broader shipping dynamics.

3.3 Trade dynamics following COVID-19: Containers vs. bulk

The dynamics of global trade following the COVID-19 pandemic further support the relevance of our focus on container shipping. Figure 5 compares trade dynamics for containers and dry bulk shipping, showing the detrended world trade volume relative to 2020Q1 for both segments. We observe that both container and dry bulk shipping experienced a similar percentage decline in the aftermath of the pandemic.

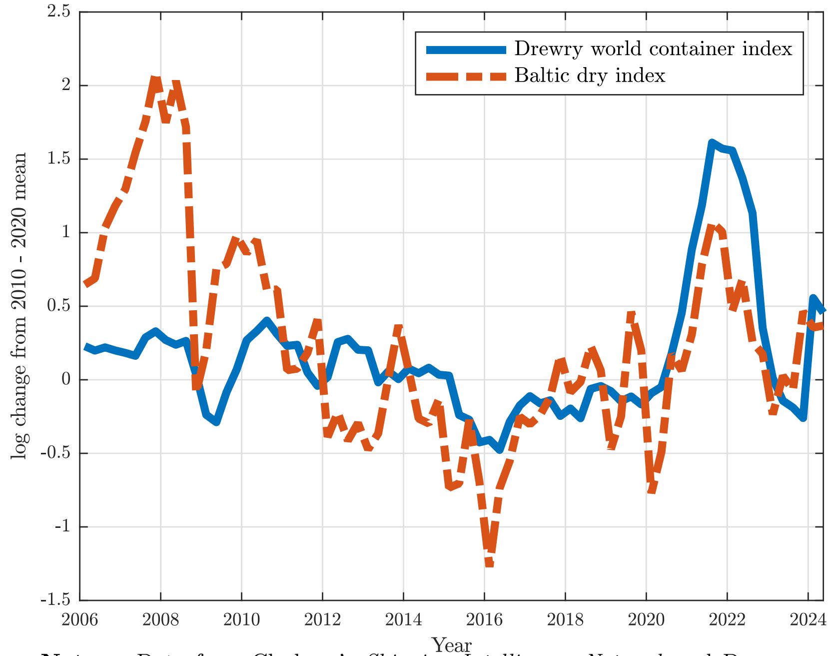
These above comparisons suggest that, although our analysis focuses on container shipping, many of the key dynamics in our model also apply to other forms of sea shipping. The similarities in trade and investment patterns between container and bulk shipping highlight the broader relevance of our findings to global shipping markets.

Figure 3: Shipping industry dynamics, containers vs. dry bulk



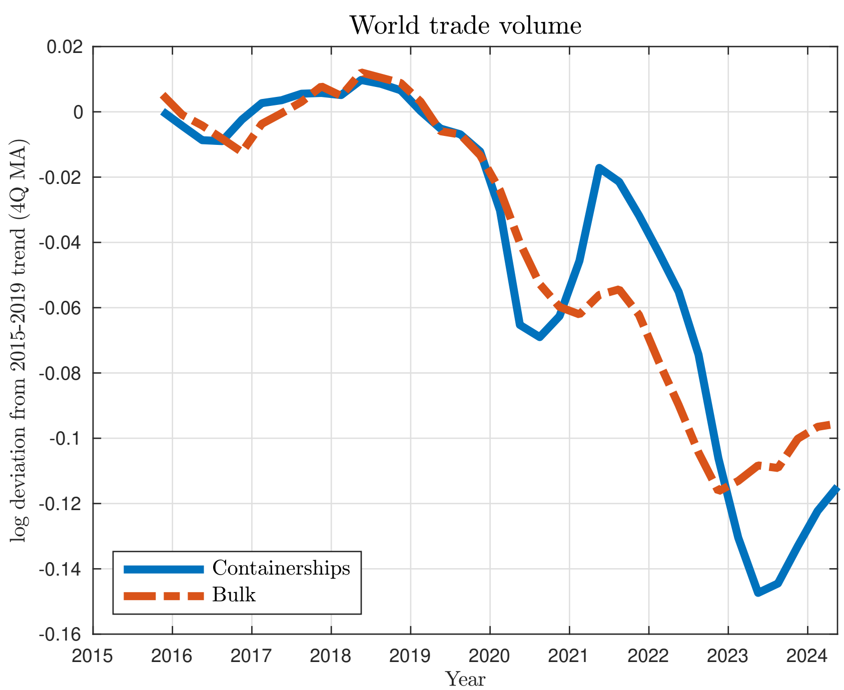
Note: Data from Clarkson's *Shipping Intelligence Network* and *OECDstat*.

Figure 4: Shipping prices, containers vs. dry bulk



Note: Data from Clarkson's *Shipping Intelligence Network* and Drewry Supply Chain Advisors.

Figure 5: Global trade dynamics following COVID-19



Note: Data from Clarkson's *Shipping Intelligence Network*.

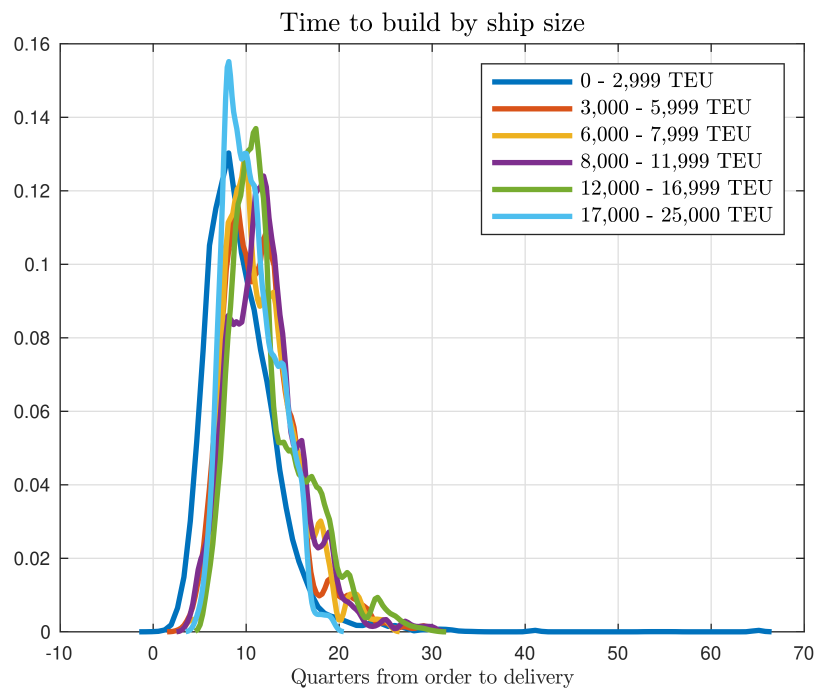
4 Containership time-to-build

Understanding the time it takes to build new containerships is essential for assessing the dynamics of shipping capacity. In this section, we examine how the time-to-build varies both by ship size and across different time periods. While our model abstracts from explicit time variation in production lags, the shipping adjustment cost can generate similar effects, particularly by limiting the speed of capacity expansion during periods of high ordering activity.

4.1 By ship size

Figure 6 presents the distribution of time-to-build by ship size, measured in quarters, using data from Clarkson's Shipping Intelligence Network. The figure shows that construction times remain relatively uniform across different ship sizes, suggesting that production lags are not significantly affected by vessel size. This indicates that shipyards can maintain similar timelines regardless of the ships' dimensions.

Figure 6: Containership time-to-build by ship size

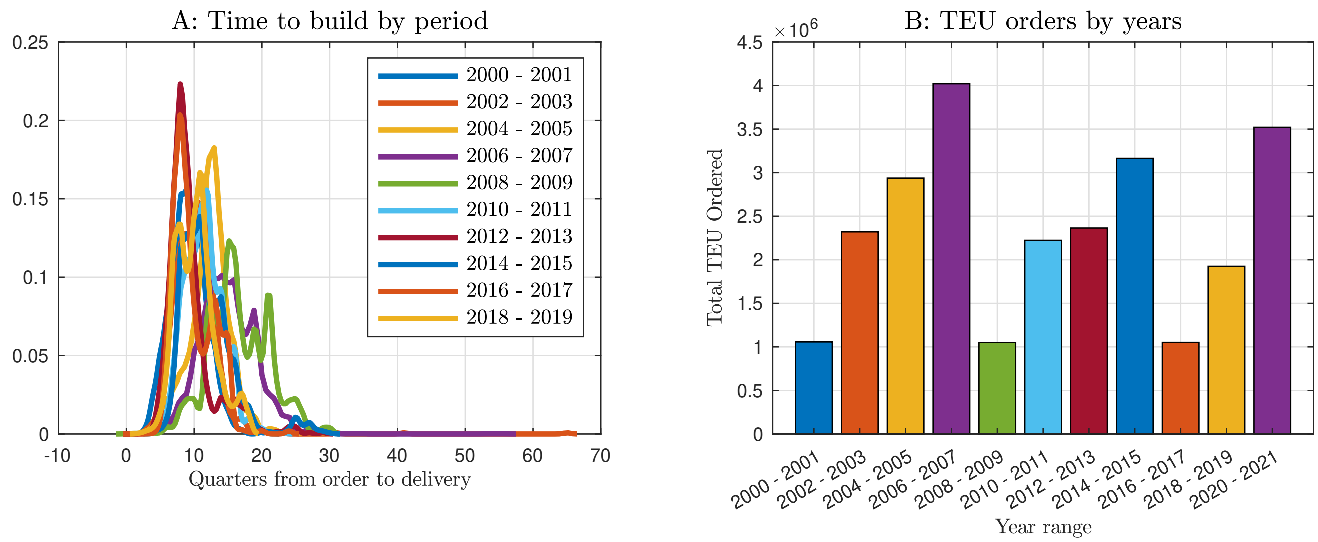


Note: Data from Clarkson's *Shipping Intelligence Network*.

4.2 By time period

Next, we examine how time-to-build varies over time, particularly between periods of high and low total demand for new ships. Figure 7 presents the distribution of time-to-build by time period, using data from Clarkson's *Shipping Intelligence Network*. The left panel shows how time-to-build fluctuates across different periods, while the right panel plots the volume of ship orders in twenty-foot equivalent units (TEUs) over time. The left panel indicates that time-to-build extends during periods of heightened ordering activity, consistent with the idea that increased demand strains shipyard capacity and leads to longer production timelines.

Figure 7: Containership time-to-build by time period



Note: Data from Clarkson's *Shipping Intelligence Network*.

Table 3 provides a summary of shipbuilding activity by time period. For each period, we report the total TEUs ordered, the number of ships ordered, and the mean and median time-to-build. The table confirms that both the mean and median time-to-build increase during periods of high ordering activity, suggesting that shipyard capacity constraints become more binding during shipping booms.

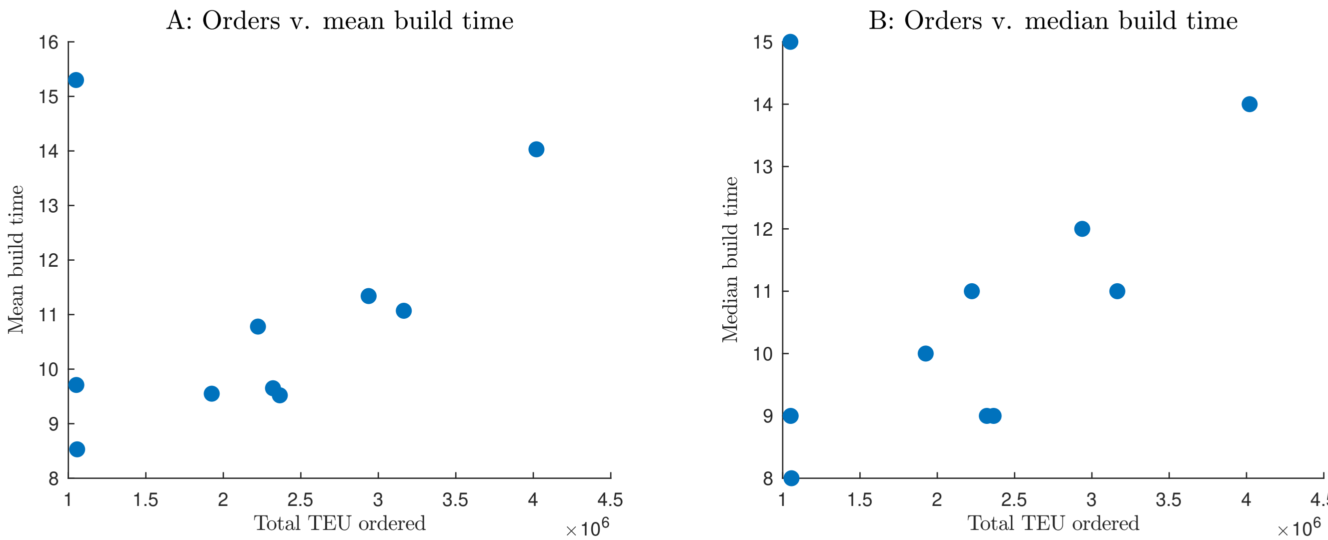
Table 3: Containership time-to-build by time period

Period	Orders (TEU)	Orders (Ships)	Mean time	Median time
2000 - 2001	1,056,841	332	8.53	8
2002 - 2003	2,320,349	535	9.65	9
2004 - 2005	2,937,581	790	11.34	12
2006 - 2007	4,020,397	706	14.03	14
2008 - 2009	1,049,622	169	15.30	15
2010 - 2011	2,223,460	302	10.78	11
2012 - 2013	2,364,439	304	9.52	9
2014 - 2015	3,164,462	323	11.07	11
2016 - 2017	1,051,611	188	9.71	9
2018 - 2019	1,925,130	284	9.55	10
2020 - 2021	3,520,884	501	8.76	9

Figure 8 further illustrates this relationship. The scatterplot shows the relationship between the size of ship orders (in TEUs) and the time-to-build. The left panel presents the mean time-to-build, while the right panel presents the median time-to-build, with each point representing a two-year period from 2000 to 2019. Both panels indicate a positive relationship between the volume of orders and the time-to-build, reinforcing the notion that production lags increase during periods of high demand.

The empirical evidence documented in this section shows that time-to-build varies across periods of high and low ship orders, reflecting shipyard capacity constraints. While our model assumes a fixed production lag, the shipping adjustment cost can partially capture these dynamics by limiting the speed at which new capacity enters the market. In periods of high demand, the adjustment cost slows capacity expansion, mirroring the observed lengthening of time-to-build when shipyard constraints become more binding. As a result, the model leads to a gradual adjustment of shipping capacity that echoes the delays observed during boom periods.

Figure 8: Containership time-to-build, amount ordered vs. build time



Note: Data from Clarkson's *Shipping Intelligence Network*. Each point represents a two year period from 2000 - 2019.

5 Prices following COVID-19: Tradables vs. non-tradables

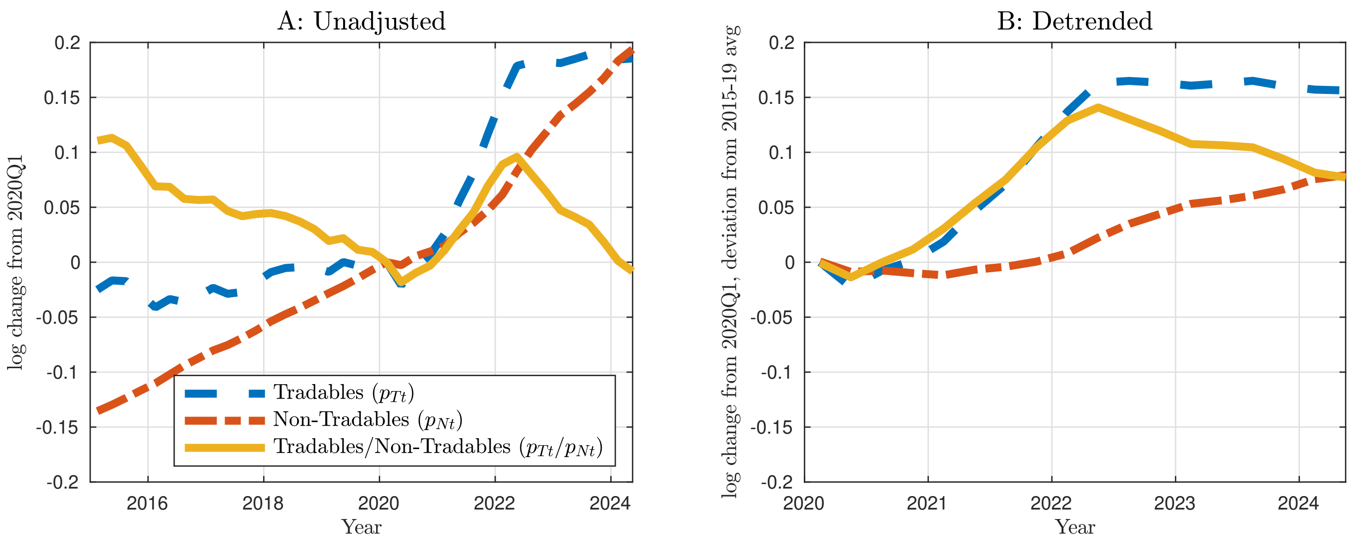
The model's implications for relative prices exhibit qualitative similarities with observed trends in U.S. data. To evaluate the extent to which this is the case, we obtained series for the prices of tradable goods (commodities) and non-tradable goods (services) from the Consumer Price Index for All Urban Consumers (CPI-U) produced by the U.S. Bureau of Labor Statistics. Figure 9 presents the log-changes in these prices relative to Q1 2020, as well as the relative price of tradables to non-tradables. The left panel (A) shows the raw data, while the right panel (B) presents the same data after removing a linear trend over 2015-2019.

The raw data in panel (A) show that prices for tradable goods rose considerably more than those for non-tradable goods following the onset of the COVID-19 pandemic. The relative price of tradables to non-tradables increased by about 10% by early to mid-2022, before gradually reverting as non-tradable prices began to catch up. Our model captures this pattern, as shown in the top right panel of Figure 5 of the paper, exhibiting an increase in the relative price of tradables by approximately 15% before gradually declining after peaking at around 20%. While the increase in the model is somewhat larger than in the raw data, the overall magnitude and both the timing and direction of the relative price movements align.

Panel (B) presents the detrended series, which isolate cyclical movements in relative prices by removing long-term trends. This adjustment provides a more appropriate comparison with the model, as the model does not feature secular long-term trends. Once detrended, the increase in the relative price of tradables to non-tradables is more pronounced, bringing it closer in magnitude to the response implied by the model.

These findings show that the model captures key features of the relative price movements, particularly the initial surge in tradable prices and their subsequent reversion. These results reinforce the model's ability to explain short-run price dynamics during the pandemic, driven by disruptions in global shipping and supply chains.

Figure 9: Prices following COVID-19, tradables vs. non-tradables



Note: Data from the *U.S. Bureau of Labor Statistics.*

Part II

Model and Quantitative Results

6 Equilibrium

A *competitive equilibrium of the world economy* described in Section 3 of the paper consists of prices, home allocations, foreign allocations, and global shipping allocations such that the following conditions hold in every period t:

- Home country:

  1. Given prices, allocations solve household problem
  2. Given prices, allocations solve problem of producers of tradable varieties
  3. Given prices, allocations solve problem of producers of non-tradable varieties
  4. Given prices, allocations solve problem of producers of intermediate goods
  5. Given prices, allocations solve problem of producers of final goods
  6. Profits from producers rebated to households: $\Pi_t = \pi_t + \pi_{Mt} + \pi_{Tt} + \pi_{Nt}$
  7. Labor market clears: $n_{Tt} + n_{Nt} = n_t$
  8. Capital market clears: $k_{Tt} = k_t$
  9. Tradable varieties clear: $y_{Tt} = q^h_{Tt} + \tau {q^h_{Tt}}^* + m^h_t + \tau m^{h*}_t$
  10. Non-tradable varieties clear: $y_{Nt} = q_{Nt}$
  11. Intermediate goods clear: $m_{Tt} = m_t$
  12. Final goods clear:

$$y_t = c_t + i_t + \psi i_{Gt} + \frac{\Phi_b}{2}\left(b_{t+1} - \bar{b}\right)^2 + \psi \frac{\Phi_G}{2}\left(\frac{i_{Gt}}{i_{Gt-1}} - 1\right)^2$$

- Foreign country:

  1. Given prices, allocations solve household problem
  2. Given prices, allocations solve problem of producers of tradable varieties
  3. Given prices, allocations solve problem of producers of non-tradable varieties
  4. Given prices, allocations solve problem of producers of intermediate goods
  5. Given prices, allocations solve problem of producers of final goods
  6. Profits from producers rebated to households: $\Pi^*_t = \pi^*_t + \pi^*_{Mt} + \pi^*_{Tt} + \pi^*_{Nt}$
  7. Labor market clears: $n^*_{Tt} + n^*_{Nt} = n^*_t$

8. Capital market clears: $k_{Tt}^* = k_t^*$

9. Tradable varieties clear: $y_{Tt}{}^* = \tau q_{Tt}^f + q_{Tt}^{f*} + \tau m_t^f + m_t^{f*}$

10. Non-tradable varieties clear: $y_{Nt}^* = q_{Nt}^*$

11. Intermediate goods clear: $m_{Tt}^* = m_t^*$

12. Final goods clear:

$$y_t^* = c_t^* + i_t^* + (1-\psi)i_{Gt} + \frac{\Phi_b}{2}\left(b_{t+1}^* - \overline{b}^*\right)^2 + (1-\psi)\frac{\Phi_G}{2}\left(\frac{i_{Gt}}{i_{Gt-1}} - 1\right)^2$$

- Global shipping:

1. Given prices, allocations solve problem of global shipping firm

2. Shipping services clear: $q_{Tt}^f + q_{Tt}^{h*} + m_t^f + m_t^{h*} = \upsilon_t \overline{g} g_t$

- Financial market clears: $b_{t+1} + b_{t+1}^* = 0$

7 Dynamics following COVID-19

7.1 Investment dynamics: Model vs. data

Figure 10 compares the model's implications for aggregate investment dynamics following COVID-19 with their empirical counterparts. This comparison allows us to assess how well the model captures key features of investment behavior, including its responsiveness to economic conditions. We find that the model broadly captures the observed investment dynamics.

7.2 Additional variables

Figure 11 reports the dynamics of additional variables of the model in the aftermath of COVID-19.

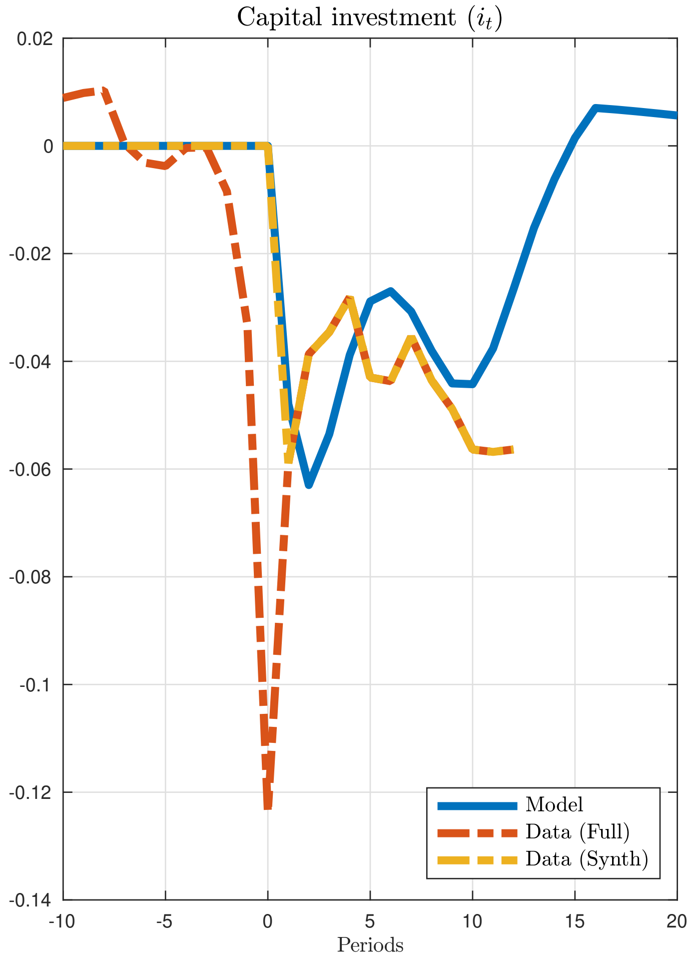
7.3 Key channels

In this section, we investigate the relative importance of alternative channels in accounting for the findings reported in Section 5 of the paper.

Shipping investment technology

First, in Figure 12, we examine the role of the shipping production lag (J), shipping investment adjustment costs (Φ_G), and the productivity of shipping investments (a_G). To do so, we start with the baseline and change one parameter (or set of parameters) while keeping all other parameters at their baseline values. We consider 4 alternative versions of the model: (i) lower shipping investment productivity $a_G = 0.15$, which implies a steady-state ratio of shipping costs to imports equal to 17.2% (vis-a-vis $a_G = 0.36$ in the baseline which implies a value of the ratio equal to 6.4%), (ii) lower shipping adjustment cost $\Phi_G = 0.001$

Figure 10: Capital investment dynamics



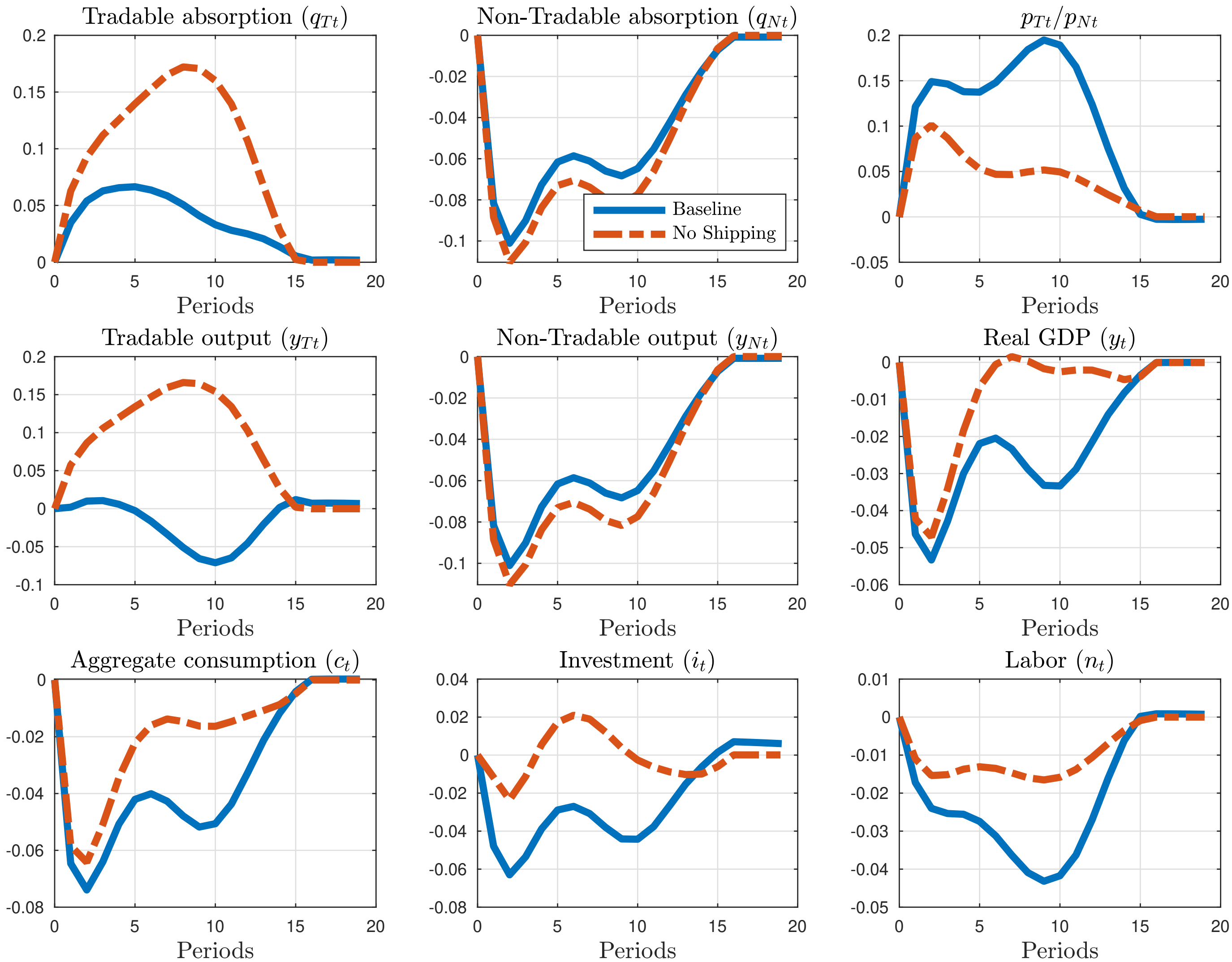
Note: Capital investment is expressed as the log-deviation from its respective steady-state value. The shipping investment and shipping utilization rates are expressed as a percentage point deviation from the steady-state value. "Data (Full)" reports the raw data while "Data (Synth)" excludes the sharp and transitory decline in 2020Q2 by setting its value to zero.

(vis-a-vis 0.35 in the baseline), (*iii*) a one-period shipping production lag ($J = 1$, vis-a-vis $J = 6$ in the baseline), and (*iv*) the combination of (*ii*) and (*iii*).

Input-output linkages and trade elasticity

Second, in Figure 13, we examine the role of input-output linkages and the degree of complementarity or substitutability between domestic and imported varieties in final goods (ρ) and intermediates (ν). To do so, we start with the baseline and fully re-estimate the model under alternative values of the relevant parameters. We consider 3 alternative versions of the model: (*i*) low intermediate inputs ($\varphi = 0.05$, vis-a-vis $\varphi = 0.63$ in the baseline), (*ii*) higher elasticity between tradable domestic and imported varieties in the production of final goods ($\rho = 2.50$, vis-a-vis $\rho = 1.50$ in the baseline), and (*iii*) higher elasticity between tradable domestic and imported varieties in the production of intermediates ($\nu = 4$, vis-a-vis $\nu = 1$ in the baseline).

Figure 11: Additional aggregate implications



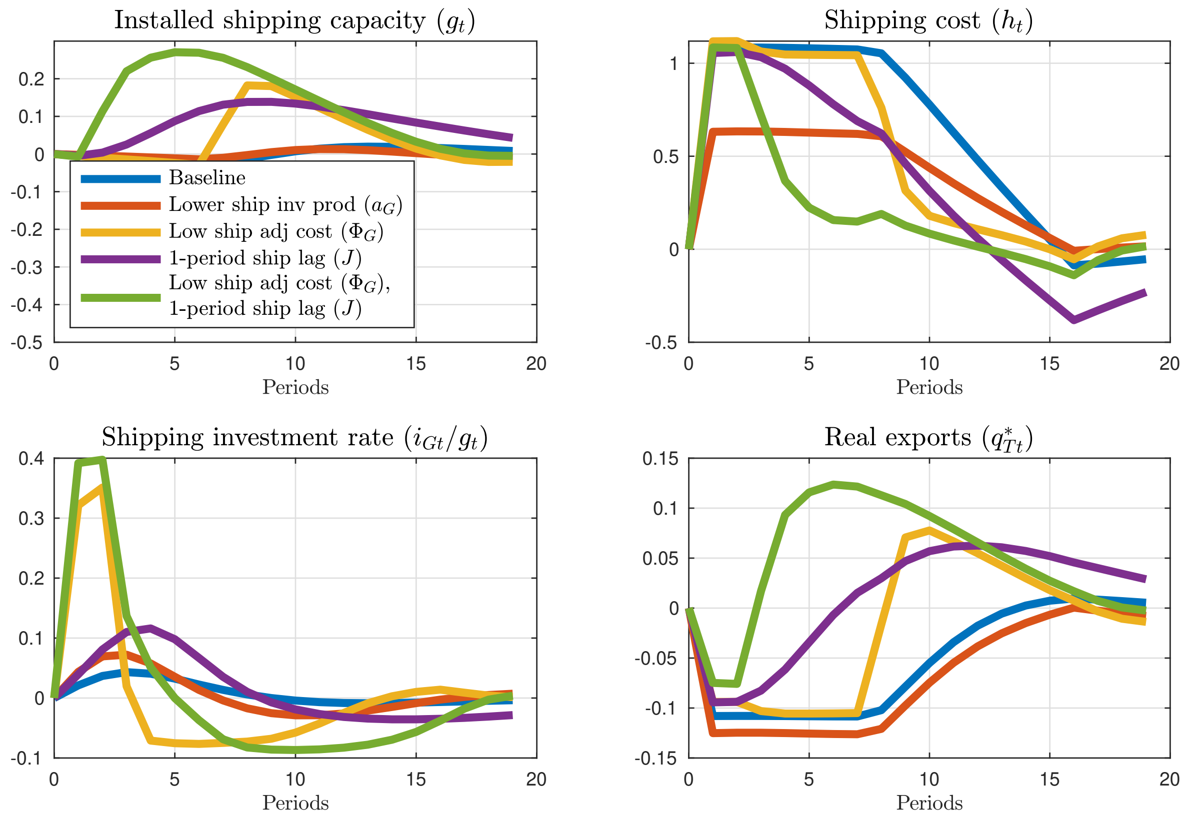
Note: All impulse-response functions (except investment) are expressed as log-deviations from their respective steady-state values. The investment IRFs are expressed as the percentage deviation from the steady-state. Baseline IRF's mirror those shown in Figure 7, while the "No Shipping" IRF's represent those in the counterfactual model with perfectly elastic shipping supply.

8 Business cycle dynamics

8.1 Local vs. global shocks

Given the global nature of international shipping, the extent to which shocks are local or global may play an important role in its aggregate implications. To evaluate this, we investigate the effect of global vs. local shocks on the volatility of shipping and aggregate variables. We do so by contrasting two economies. The first economy is our baseline, that is, an economy with no productivity spillovers across countries ($\rho_{zz} = 0$) — thus, all shocks are truly country-specific and we refer to it as an economy subject to "local shocks." The second economy is identical to our baseline but is subject to productivity shocks that are

Figure 12: Alternative shipping investment technologies



Note: All impulse-response functions are expressed as log-deviations from their respective steady-state values (except for the shipping investment rate, which is a percent deviation).

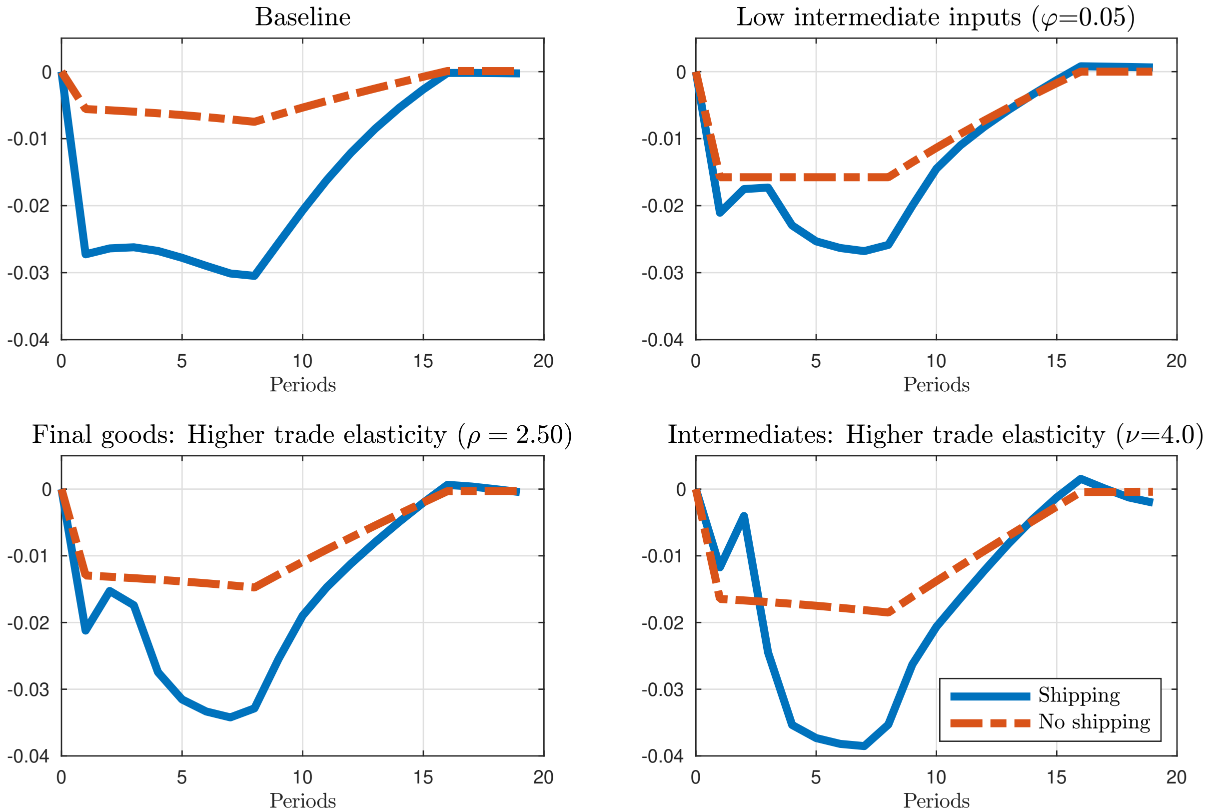
perfectly correlated across countries — thus, we refer to it as an economy subject to "global shocks." Table 4 reports the implications of these economies for the fluctuations of shipping costs and real GDP.

We find that the local vs. global nature of the productivity shocks is critical for shipping volatility and its aggregate implications. In particular, in a world where countries have uncorrelated shocks, productivity shocks are country-specific, so shipping capacity is rarely subject to extended periods of significant excess demand. In contrast, if productivity shocks are global, economic booms in the world economy are periods in which both countries have high demand for trade and shipping services, leading to substantial changes in shipping costs. Shipping costs are 47% more volatile in the economy with global shocks. As a result, we find that the aggregate implications of global shipping ridigities become much larger in such case. For instance, while real GDP is 14.1% more volatile without shipping rigidities when subject to local shocks, its volatility increases by 20.6% in the absence of shipping when subject to global shocks.

8.2 Shipping production lags and shipping cost volatility

Figure 12 shows that the dynamics of shipping costs are driven by several key factors, including the time required to expand shipping capacity and the costs associated with adjusting capacity. In this section, we investigate how these factors affect the volatility of shipping costs in our business cycle analysis. Specifically,

Figure 13: Real GDP under alternative model specifications



Note: All impulse-response functions are expressed as log-deviations from their respective steady-state values. "Baseline" denotes the dynamics implied by the model with endogenous shipping capacity, while "No shipping" denotes the dynamics implied by a model with perfectly elastic shipping supply.

we reduce the shipping production lag from six quarters (baseline) to one quarter and remove shipping adjustment costs. We compute the results in two ways: first, by re-estimating the model parameters to match the target moments under these constraints, and second, by keeping the parameters unchanged from their baseline values.

Table 5 presents the ratio of shipping cost volatility to GDP volatility across the different specifications. In the baseline model, this ratio is 7.08. When we reduce the shipping production lag and remove adjustment costs, the volatility of shipping costs decreases significantly. In both the re-estimated and fixed-parameter versions of the model, the volatility ratio falls to approximately 4.9, representing a reduction of around 30%. These results indicate that time-to-build and adjustment costs play a critical role in amplifying the volatility of shipping costs by limiting the ability of firms to adjust shipping capacity in response to demand shocks.

These results suggest that time-to-build and adjustment costs play a more significant role in amplifying shipping cost volatility than previously documented. In particular, while our findings are broadly consistent with the results in Kalouptsidi (2014), their analysis shows that reducing the shipping production lag to one period results in a shipping cost volatility that is 14% lower. While such analysis focuses on partial

Table 4: Local vs. global shocks

	Local	Global
Std. dev. shipping costs relative to real GDP		
Baseline	7.08	10.42
No shipping	—	—
Std. dev. real GDP		
Baseline	1.92	1.80
No shipping	2.19	2.17

Note: "Local" refers to the baseline economy without productivity spillovers across countries, while "Global" refers to the economy with perfectly correlated productivity shocks across countries.

Table 5: Shipping cost volatility relative to GDP volatility

	Std. dev. shipping costs	% Change from baseline
Baseline model	7.08	-
$J = 1$, No adjustment costs, re-estimated	4.91	-30.7%
$J = 1$, No adjustment costs, fixed parameters	4.88	-31.1%

Note: The standard deviation of shipping costs is expressed relative to the standard deviation of GDP.

equilibrium dynamics, our general equilibrium framework suggests that the interaction between shipping capacity adjustments and aggregate economic conditions can amplify shipping cost volatility further. The key differences are that, in a general equilibrium setting, shipping costs must adjust to clear the market, and changes in the shipping production technology can additionally alter the response of the demand for shipping services relative to what is estimated empirically.

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Brancaccio, G., M. Kalouptsidi, and T. Papageorgiou (2020): "Geography, transportation, and endogenous trade costs," *Econometrica*, 88, 657–691.

Kalouptsidi, M. (2014): "Time to build and fluctuations in bulk shipping," *American Economic Review*, 104, 564–608.