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

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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 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 at business cycle frequencies and in the aftermath of COVID-19. Accounting for global shipping significantly affects the dynamics of aggregate economic activity.

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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, leading to significant fluctuations in 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 those associated with the COVID-19 pandemic and attacks on vessels in the Red Sea, the need to understand global shipping dynamics and their aggregate 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 at business cycle frequencies as well as following large shipping disruptions such as COVID-19. Fifth, we use the model to study the implications for aggregate macroeconomic dynamics.

Our analysis provides a framework to interpret large fluctuations in shipping costs and to understand their aggregate implications. Building on evidence from Kalouptsidi (2014) for bulk shipping markets, we document that containership shipping services are inelastic in the short run: new ships typically take between 1.5 and 4 years to be delivered, and the global fleet operates at high and stable utilization levels, with most ships in service and sailing close to capacity. As a result, shipping cost fluctuations are closely associated with changes in shipping demand relative to available shipping services.

Motivated by these observations, we construct a dynamic general equilibrium model of international trade with input-output linkages and an endogenous market for global shipping services. The model features a global shipping firm that invests in shipping capacity subject to time-to-build frictions and adjusts the utilization of installed capacity at increasing cost. Importing firms demand shipping services when sourcing goods internationally, and international shipping costs are determined endogenously as the equilibrium price that clears the shipping market. Relative to existing models of international shipping such as Kalouptsidi (2014) and Brancaccio et al. (2020), our framework jointly determines shipping costs, capacity utilization, and investment in general equilibrium, allowing us to study how shipping dynamics interact with trade flows and aggregate economic activity and to conduct counterfactual analyses under alternative shipping technologies.

We analytically characterize the key determinants of import demand, shipping costs, capacity utilization, and shipping investment. We show how shocks that increase the demand for tradable goods lead to higher demand for shipping services and put upward pressure on shipping costs. We show that the equilibrium response of shipping costs depends on the elasticity of substitution between domestic and imported goods, the share of shipping costs in total import costs, and the degree of shipping capacity utilization. Finally, we characterize how the global shipping firm responds by adjusting capacity utilization in the short run and shipping investment over time, generating persistent dynamics in shipping costs, trade flows, and aggregate outcomes.

Next, we study the quantitative implications of the model for global shipping and aggregate economic activity. We estimate the model to match salient cross-sectional and business-cycle features of production and trade. Motivated by the observation that global shipping costs are highly volatile over the business cycle, as illustrated in Figure 1, we begin by examining global shipping dynamics during normal times. We assess whether the model can account for these dynamics and study their aggregate implications. Throughout, we conduct our analysis using the second-order solution of the model, allowing agents to make forward-looking decisions under uncertainty.

We find that the model implies global shipping costs that are very volatile over the business cycle, consistent with the data. Moreover, we find that these cyclical dynamics of global shipping have significant implications for aggregate macroeconomic fluctuations. In particular, we find that shipping rigidities shape the response of trade and production to business cycle shocks by limiting the short-run adjustment of shipping-intensive economic activity. During expansions, the constrained response of tradables reduces aggregate volatility relative to a model with a flexible supply of shipping services.

We then turn to the unprecedented disruptions in global shipping following the COVID-19 pandemic. Figure 2 shows that, during this period, the world economy experienced (*i*) an increase in the demand for consumption goods, reflecting a reallocation away from contact-intensive services, (*ii*) a reduction in effective shipping supply that reduced trade volumes, driven by labor shortages, changes in the processing of shipments under COVID-related restrictions, and widespread congestion,[2] and (*iii*) an unprecedented increase in shipping costs. For example, the Drewry World Container Index, which tracks average containership spot rates across major routes, increased from less than \$2,000 per 40-foot container prior to

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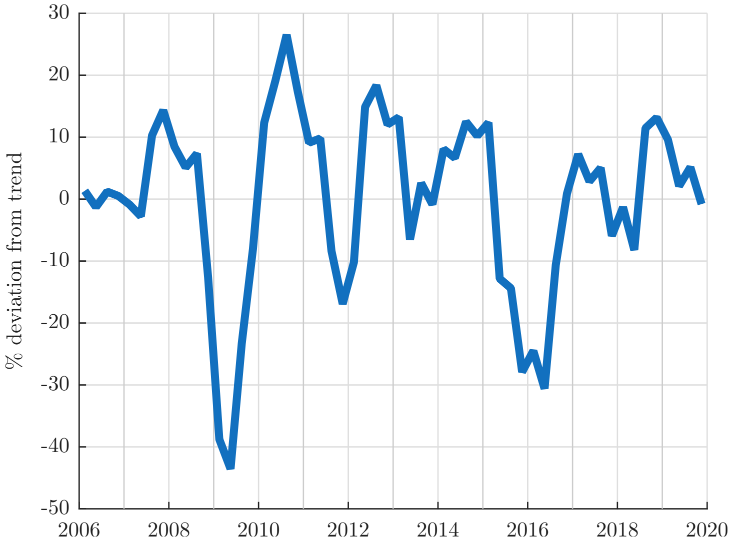
[2] See Section 2 of the Appendix for further details.

Figure 1: Global shipping cost fluctuations over the business cycle



Note: Data from Drewry Supply Chain Advisors. Series expressed in logs and HP-filtered ($\lambda = 1600$).

the pandemic to nearly \$10,000 at its peak.[3]

We use the model to interpret this evidence, evaluating the extent to which it can account for the unprecedented increase in shipping costs and their aggregate implications. To this end, we consider the global economy as subject to a sequence of shocks to aggregate productivity, tradable consumption demand, tradable capital demand, and shipping efficiency, which we estimate to account for the observed paths of real GDP, tradable consumption, tradable capital, and a proxy for shipping efficiency in the aftermath of the COVID-19 pandemic. As in the business-cycle analysis, agents make decisions under uncertainty about future shocks. Given the global nature of the pandemic, we focus on shocks that affect all countries simultaneously.

We use this experiment to assess the extent to which the model accounts for global shipping dynamics in the aftermath of COVID-19 and to quantify the role of shipping in shaping the broader macroeconomic dynamics observed during this period. We find that the model accounts for salient features of global shipping dynamics in the aftermath of COVID-19, generating a contraction in international trade and a sizable rise in shipping costs. The model accounts for a large share of the peak increase in shipping costs observed in the data and reproduces their subsequent reversal as shipping conditions normalize, while also implying dynamics of shipping investment that are consistent with the data.

Using a set of counterfactual economies in which shipping rigidities are progressively

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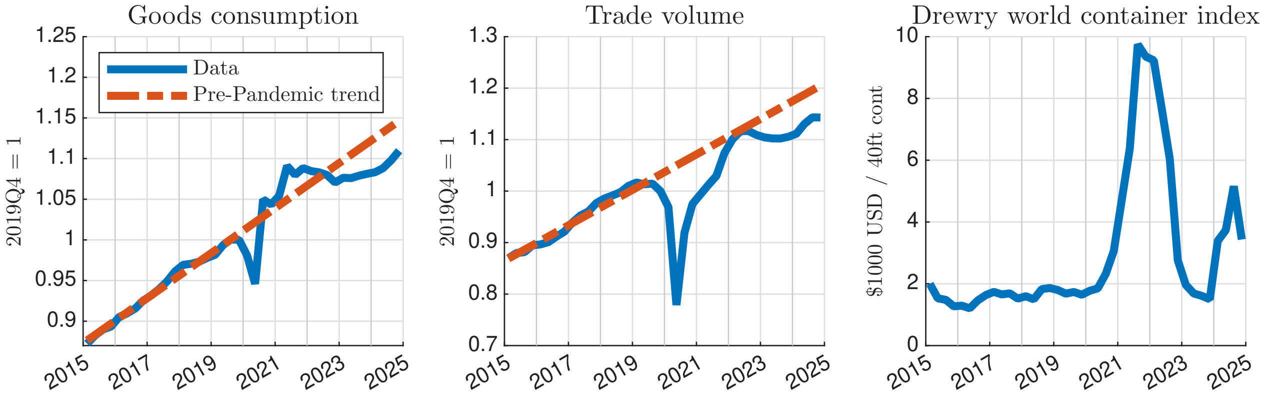
[3] While this series reflects spot rates, effective shipping rates also increased significantly, as documented in Section 3 of the Appendix.

Figure 2: Global shipping dynamics following COVID-19



Note: Data from OECDstat and Drewry Supply Chain Advisors. Series for goods consumption and trade volumes are normalized to 2019Q4. Dashed lines show linear trends estimated over 2015–2019.

relaxed, we show that greater shipping supply flexibility attenuates the magnitude and persistence of declines in real GDP, tradable output, and international trade flows in the aftermath of COVID-19. In contrast to our findings at business cycle frequencies, where shipping rigidities dampen expansions by constraining shipping-intensive activity, we find that these rigidities amplified the post-pandemic contraction. During the business cycle, limited short-run flexibility in shipping supply tempers booms when demand rises. In the aftermath of COVID-19, however, shipping rigidities amplified the downturn. Elevated shipping demand coincided with an aggregate contraction, and restricted shipping capacity deepened the decline by limiting access to imported goods and intermediate inputs.

Our findings highlight the importance of understanding the drivers and aggregate implications of global shipping dynamics. Our paper contributes to a growing literature studying the market for global shipping services (Ganapati et al. 2024; Greenwood and Hanson 2015; Kalouptsidi 2014; Brancaccio et al. 2020). Building on this work, we document novel evidence on the dynamics of container shipping, showing that its investment patterns and short-run adjustment frictions closely mirror those observed in bulk shipping markets. We then develop a dynamic general equilibrium model of international trade with an endogenous market for global shipping services in which shipping costs, capacity utilization, and investment are jointly determined. This framework allows us to study how shipping frictions interact with trade flows and aggregate activity and to conduct counterfactual analyses under alternative shipping technologies, while remaining sufficiently tractable to be embedded in broader macroeconomic and trade frameworks.

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 contributes to a growing literature studying the aggregate implications of supply chain disruptions in the aftermath of COVID-19 (Bai et al. 2024; Bonadio et al. 2021; Comin et al. 2024; Alessandria et al. 2023, among others).[5] Relative to this literature, our key contribution is to study the role of global shipping using a model in which both shipping demand and supply are determined endogenously, highlighting how shipping frictions propagate disruptions through global supply chains. 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. Our findings provide a complementary perspective to recent empirical work examining the impact of rising shipping costs on inflation (Isaacson and Rubinton 2023; Carrière-Swallow et al. 2023) and to structural analyses of how supply chain disruptions propagate to consumer prices (di Giovanni et al. 2022).

The remainder of the paper is organized as follows. Section 2 documents salient features of global shipping dynamics. Section 3 develops a model of international trade with an endogenous shipping market, and Section 4 characterizes its key mechanisms analytically. Sections 5 and 6 study the role of shipping in business-cycle fluctuations and in the aftermath of COVID-19, respectively. Section 7 concludes.

2 Salient features of global shipping

In this section, we document salient features of the market for global shipping services that inform the theoretical framework developed below and provide discipline for the quantitative analysis. 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

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

[5] More generally, our work relates to studies examining the role of shipping in aggregate dynamics, such as Leibovici and Waugh (2019) and Ravn and Mazzenga (2004).

trade value[6] and play a critical role in facilitating the international trade of goods. In Section 4 of the Appendix, we provide evidence that the dynamics observed in the containership sector — including investment patterns, capacity utilization, pricing, and trade — 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.[7]

Throughout, we analyze the containership market at the global level. Our main source of shipping-related data is Clarkson's *Shipping Intelligence Network*, an integrated data provider that collects comprehensive information on the international shipping industry. We use these data to construct global measures of fleet capacity, investment, earnings, and the extensive margin of fleet utilization. To measure fleet utilization along the intensive margin, we rely on draught information from Marine Cadastre's vessel traffic AIS data for vessels calling at U.S. ports. Shipping costs are measured using the Drewry World Container Index, and global shipping demand is proxied by industrial production from the Dallas Fed's *Database of Global Economic Indicators*. Unless otherwise noted, the data span 1996–2024.

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 number of containers that these ships can carry (blue solid line), which is measured in twenty-foot equivalent units (TEUs), a standard measure of container-carrying capacity. We find that the total size of the global containership fleet has grown steadily over the past 30 years, particularly for the capacity of the fleet in 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 over 2014–2024. The extensive margin measures the fraction of total fleet capacity (in TEUs) that is non-idle in a given period.[8] The intensive margin captures how fully active containerships are loaded relative to their carrying capacity. We measure this as the ratio of a vessel's reported draught at

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[6] See Section 4 of the Appendix for evidence on the role of containerships in global seaborne trade.

[7] Although air transport accounts for a larger share of trade value, its share of global trade volume is very small, suggesting limited scope for substitution away from sea shipping; see Section 4 of the Appendix.

[8] Following Clarkson's methodology, 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. Idle ships are reclassified as active if they subsequently report movement exceeding 20 km over two consecutive days. Idle status is determined at the daily level and aggregated to match the frequency of our analysis.

docking to its maximum observed draught. Because a ship's draught increases with the weight it carries, this ratio provides a proxy for how fully the vessel is loaded. We aggregate vessel-level draught ratios using weights proportional to vessel size, proxied by the product of ship length, width, and scantling draught. Given data limitations, we compute this statistic using vessel traffic AIS data for ships calling at U.S. ports. The resulting measure closely aligns with an analogous global load factor series available over a shorter period.[9] We define effective fleet utilization as the share of total fleet capacity that is both active and loaded, computed as the product of the extensive and intensive margins.

We find that capacity utilization in the global containership fleet is remarkably stable over time. Along the extensive margin, there is little scope to expand active capacity in the short run: at least 95% of total fleet capacity is consistently non-idle. Along the intensive margin, ships operate below their maximum reported draught, but variation over time is limited. This suggests that further increases in vessel loading are likely costly and rarely used in the short run.[10] Taken together, these patterns indicate that the containership industry has limited scope to expand effective shipping supply in the short run. Importantly, relatively stable utilization does not preclude substantial variation in trade volumes, which can adjust through other channels such as routing patterns, average voyage lengths, or port-level congestion and efficiency.

2.2 Shipping investment

We now turn to investigating the dynamics and determinants of investments in shipping capacity. Panel C reports new containership orders, expressed in terms of container-carrying capacity (TEUs), alongside the annual growth of shipping costs.[11] We observe that investments in containerships co-move positively with shipping costs, with a correlation of 0.46 over 1996–2024. Thus, in periods in which shipping costs are relatively higher, shipping companies invest in new ships to take advantage of these higher earnings, placing orders to increase future shipping capacity.

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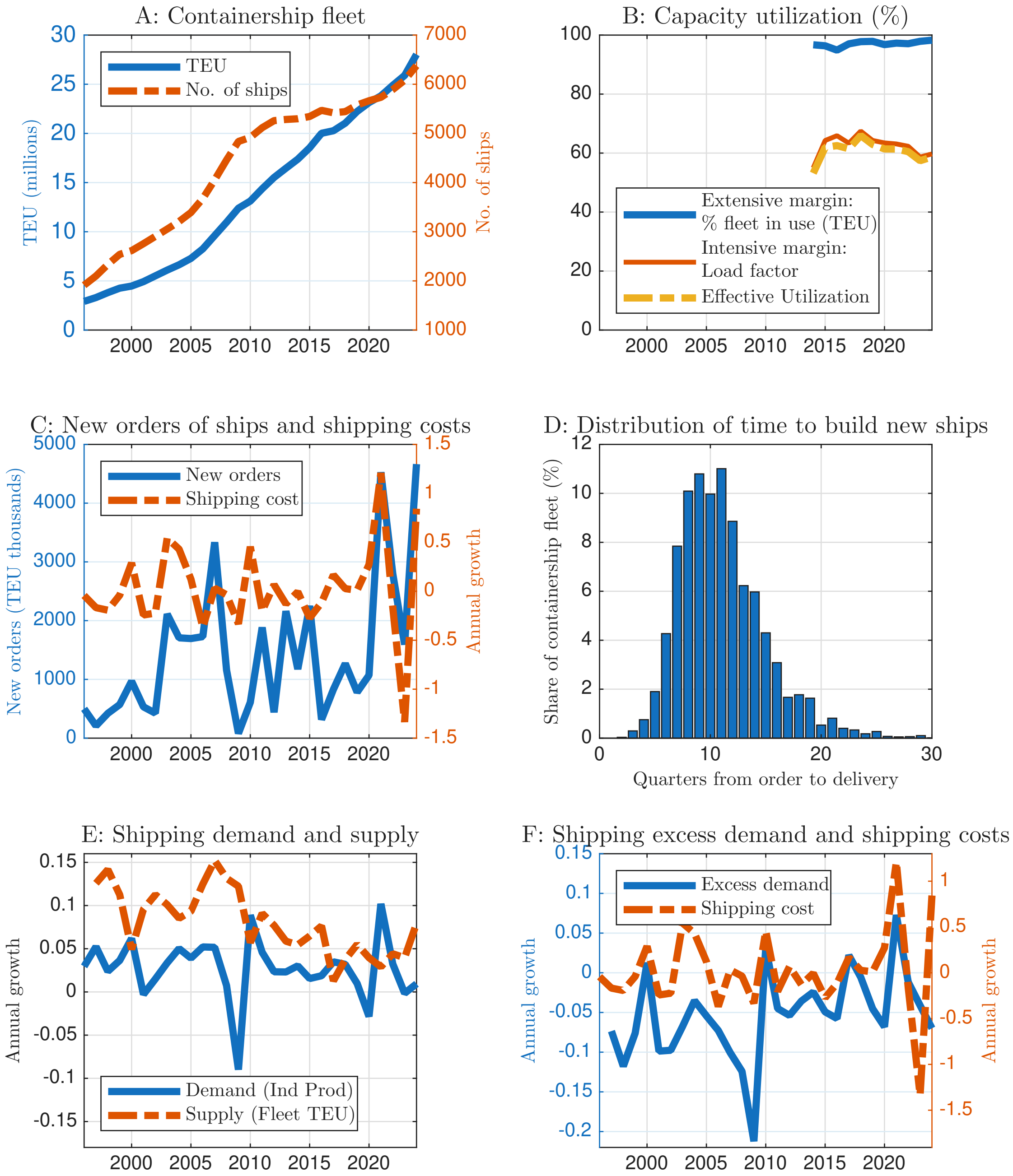
[9] Specifically, we compare our U.S.-based draught measure to an analogous global load factor series constructed from the data used in Ludwig (2025). Over the period in which both measures are available (2016–2018), the two measures exhibit very similar average levels (0.66 for the U.S.-based draught ratio versus 0.67 for the global series).

[10] Our draught-based measure captures weight utilization. Because container loads can be well below their physical payload capacity, containerized cargo may reach space constraints before weight limits. For instance, containership capacity is often reported assuming an average load of about 14 tonnes per TEU, which can reduce effective capacity by 25 percent or more relative to nominal slot counts (Notteboom et al., 2026). As a result, slot-based utilization can be higher than implied by the draught ratio.

[11] We construct our shipping cost series using Clarksons average containership earnings for 1996–2006 and the Drewry World Container Index for 2007–2024, reflecting the availability of each series over different parts of the sample period. Clarksons earnings measure average charter rates across a range of containership sizes, based on a representative basket of vessels and weighted by fleet composition across size classes.

Figure 3: Containership industry dynamics



Note: Global fleet capacity, investment, and the extensive margin of utilization are from Clarksons *Shipping Intelligence Network*. Intensive utilization is constructed using vessel traffic AIS data from Marine Cadastre for ships calling at U.S. ports. Shipping costs are measured using Clarksons average containership earnings (1996-2006) and the Drewry World Container Index (2007-2024). Industrial Production is from the Federal Reserve Bank of Dallas' *Database of Global Economic Indicators*. The distribution of construction times is computed from the cross-section of containerships active in 2023/24. Excess demand is defined as the difference between the annual growth rate of global industrial production and the annual growth rate of global containership capacity in TEUs.

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 the distribution of ship construction times (in quarters) for the cross-section of containerships active in 2023/24. For each vessel, construction time is measured as the number of quarters between its order date and delivery date. We observe that ship construction typically takes between 6 and 16 quarters (roughly 1.5 to 4 years), accounting for 82.4% of all ships in the sample. Therefore, while these orders are placed contemporaneously with shipping cost changes, the ships take a few years to be built before they become operational. Combined with the limited variation in utilization discussed above, this suggests that short-run increases in shipping demand are likely to be accommodated primarily through higher shipping costs rather than through immediate expansions in effective shipping supply.

2.3 Shipping demand, supply, and costs

Finally, we investigate the joint dynamics of global shipping demand, supply, and shipping costs. Panel E of Figure 3 plots the annual growth of global shipping demand, proxied by industrial production, alongside the annual growth of global containership capacity measured in TEUs.[12] We use industrial production rather than trade volumes to proxy shipping demand since the latter are an equilibrium outcome that reflects both the demand for and the supply of shipping services. We define excess demand for shipping services as the difference between growth in global shipping demand and the growth in shipping supply (measured as the annual growth rate of global industrial production and the annual growth rate of global containership capacity in TEUs, respectively). The figure shows that these two series are not synchronized, leading to fluctuations in excess demand over time.

Standard demand and supply forces suggest that excess demand for global shipping services should be positively associated with shipping costs. In periods when demand for shipping grows faster than shipping supply, prices are expected to rise to ration relatively scarce capacity. Panel F of Figure 3 shows that this is indeed the case: excess demand for shipping co-moves positively with shipping costs. Over the pre-COVID period (1996–2019), the annual growth rates of the two series exhibit a correlation of 0.56.[13] The relation holds in both periods of excess demand and excess supply, with shipping costs rising in the former and falling in the latter.

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[12] Shipping supply is measured in terms of physical fleet capacity (TEUs) and does not account for utilization, as the effective utilization series is available only for a shorter sample period. As a result, fluctuations in effective shipping capacity may differ from those implied by physical capacity.

[13] The COVID period was characterized by disruptions to effective shipping supply, including congestion, delays, and changes in routing, that are not directly captured by measures of physical fleet capacity or utilization. As a result, our measure of excess demand may imperfectly reflect true supply conditions during this period.

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. Shipping is required to move goods across countries, so the volume of international trade in a given period is limited by available shipping capacity. Motivated by the evidence documented above, we model global shipping consistent with the following features: (*i*) shipping costs are determined by 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 doing so is increasingly costly, limiting the expansion of effective shipping supply.

We study a world economy with two countries: home and foreign. Each country is populated by a representative household and a set of perfectly competitive firms. At the sectoral level, firms produce domestic tradable and non-tradable varieties, so that only a fraction of economic activity is directly exposed to international shipping. These varieties are then combined into intermediate inputs, consumption goods, and capital goods by competitive producers. 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 both 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 $\beta < 1$. The household's period utility function is of the constant relative risk aversion (CRRA) class over a Cobb-Douglas bundle between consumption c_t and leisure $1 - n_t$: $\frac{\left[c_t^{\mu}(1-n_t)^{1-\mu}\right]^{1-\gamma}}{1-\gamma}$. 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.[14]

Households accumulate physical capital internally by investing i_t units of capital goods. Given capital depreciates at rate δ, the evolution of the aggregate capital stock is given by

$$k_{t+1} = (1-\delta)k_t + i_t.$$

Investment is subject to quadratic adjustment costs that penalize deviations from steady-state replacement investment: $\frac{\Phi_k}{2}\left(i_t - \delta\overline{k}\right)^2$, which are incurred in units of capital goods. Parameter Φ_k governs the magnitude of these costs and $\overline{k}$ denotes the steady-state capital stock.

Households have access to international financial markets, where they can trade a one-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 consumption 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 $\frac{\Phi_b}{2}b_{t+1}^2$, incurred in units of consumption goods, where Φ_b controls the cost of holding bonds.

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

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

where p_t^c and p_t^k denote the prices of consumption and capital goods, respectively, Π_t denotes the combined profits from 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

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

$$k_{t+1} = (1-\delta)k_t + i_t \quad \forall t,$$

k_0 and b_0 given.

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

3.2 Producers of domestic varieties

Each country produces two types of domestic varieties indexed by $j \in \{T, N\}$, where T denotes tradable varieties and N denotes non-tradable varieties. Tradable varieties are sold both domestically and internationally, while non-tradable varieties are sold only domestically.

In each sector j, a representative firm produces output y_{jt} using capital k_{jt}, labor n_{jt}, and intermediate inputs m_{jt} by operating the following Cobb-Douglas production technology:

$$y_{jt} \;=\; z_t \, a_j \left(k_{jt}^{\theta_j} n_{jt}^{1-\theta_j}\right)^{\varphi_j} \, m_{jt}^{1-\varphi_j},$$

where a_j is sector-specific productivity, z_t denotes aggregate productivity common to both sectors, θ_j determines the capital share in value added, and φ_j determines the value-added share in gross output.

Firms in sector j are perfectly competitive and take as given the output price p_{jt}, the wage w_t, the rental rate of capital r_{Kt}, and the price of intermediate inputs p_t^m. The firm chooses input demands $\{k_{jt}, n_{jt}, m_{jt}\}$ to maximize period profits:

$$\max_{k_{jt},\, n_{jt},\, m_{jt}} \quad \pi_{jt} \;=\; p_{jt}\, y_{jt} \;-\; w_t\, n_{jt} \;-\; r_{Kt}\, k_{jt} \;-\; p_t^m\, m_{jt},$$

subject to the production technology.

3.3 Producers of intermediate, consumption, and capital goods

Each country is populated by perfectly competitive firms that combine domestic tradable varieties, imported tradable varieties, and non-tradable varieties to produce three distinct bundles: an intermediate input bundle used in production, a consumption goods bundle consumed by households, and a capital goods bundle used for investment. We index these bundles by $\ell \in \{m, c, k\}$, where m denotes the intermediate inputs, c denotes final consumption goods, and k denotes capital goods.

Technology. In each sector ℓ, a representative firm aggregates tradable goods q_{Tt}^{ℓ} and non-tradable goods q_{Nt}^{ℓ} using a Cobb–Douglas technology:

$$y_t^{\ell} = \left(q_{Tt}^{\ell}\right)^{\chi^{\ell}} \left(q_{Nt}^{\ell}\right)^{1-\chi^{\ell}},$$

where $\chi^{\ell} \in (0,1)$ is a parameter that controls the weight on tradables in the production of sectoral good ℓ, and the implied elasticity of substitution between q_{Tt}^{ℓ} and q_{Nt}^{ℓ} equals one.

The tradable bundle q_{Tt}^{ℓ} is produced using domestic tradable varieties $q_{Tt}^{\ell h}$ and imported tradable varieties $q_{Tt}^{\ell f}$ with a CES technology:

$$q_{Tt}^{\ell} = \left[\zeta^{\ell} \left(q_{Tt}^{\ell h}\right)^{\frac{\rho-1}{\rho}} + \left(1-\zeta^{\ell}\right)\, \xi_t \, \left(q_{Tt}^{\ell f}\right)^{\frac{\rho-1}{\rho}}\right]^{\frac{\rho}{\rho-1}},$$

where ζ^{ℓ} controls the relative weight on domestic tradable varieties in sector ℓ, ξ_t is a time-varying weight on imported tradable varieties, and $\rho > 0$ is the elasticity of substitution between domestic and imported tradable varieties. Here and throughout, superscripts h and f denote the country of origin (home and foreign), and an asterisk indicates variables chosen by the foreign country.

Firm's problem. Producers of each bundle $\ell \in \{m, c, k\}$ combine domestic and imported tradable varieties with non-tradables and sell the resulting bundle domestically. The firm takes prices as given and chooses inputs to maximize profits π_t^ℓ. Imports face proportional iceberg trade costs τ and per-unit shipping costs h_t. The firm's problem is given by:

$$\max_{y_t^\ell, q_{Tt}^\ell, q_{Tt}^{\ell h}, q_{Tt}^{\ell f}, q_{Nt}^\ell} \quad \pi_t^\ell = p_t^\ell y_t^\ell - p_{Tt}\, q_{Tt}^{\ell h} - \big(\tau p_{Tt}^* + h_t\big) q_{Tt}^{\ell f} - p_{Nt}\, q_{Nt}^\ell$$

subject to

$$y_t^\ell = \big(q_{Tt}^\ell\big)^{\chi^\ell} \big(q_{Nt}^\ell\big)^{1-\chi^\ell}, \qquad q_{Tt}^\ell = \Big[\zeta^\ell \big(q_{Tt}^{\ell h}\big)^{\frac{\rho-1}{\rho}} + \big(1-\zeta^\ell\big)\, \xi_t \, \big(q_{Tt}^{\ell f}\big)^{\frac{\rho-1}{\rho}}\Big]^{\frac{\rho}{\rho-1}}.$$

Time–varying weight on imports. To capture cyclical fluctuations in the demand for trade, we allow the relative weight on imported tradable varieties, ξ_t, to vary with aggregate economic activity. We normalize the steady–state value to one so that it does not affect steady–state allocations or prices. In particular, we let $\log \xi_t = \phi_\tau \big(\log z_t - \log \bar{z}\big)$, with an analogous expression governing the foreign country's weight.

3.4 Global shipping firm

Finally, we describe the global shipping firm, which supplies shipping services to producers of intermediate, consumption, and capital goods when purchasing tradable varieties across countries.

Consider the start of some given time period t. The global shipping firm begins the period with 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 competitively at rate h_t per unit shipped.[15] 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 costs.

The effective supply of shipping services depends on both exogenous and endogenous

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[15] Although the containership sector is concentrated, its investment and pricing dynamics closely resemble those of the more competitive bulk shipping sector (Brancaccio et al., 2020; Kalouptsidi, 2014), suggesting market structure differences are not critical in accounting for these dynamics. See Section 4 of the Appendix for details. Sections 8 and 11.2 of the Appendix report results from a version of the model with market power in the shipping industry, which show our findings are robust to this alternative market structure.

factors. Shipping capacity g_t is converted into effective shipping services according to

$$\upsilon_t \, \overline{g} \, g_t,$$

where $\overline{g} > 0$ captures exogenous shipping efficiency and $\upsilon_t \in [0, 1]$ denotes the endogenous utilization rate chosen by the shipping firm. In Section 6, we allow $\overline{g}$ to vary in order to model disruptions to effective shipping capacity following the outbreak of COVID-19.

Increasing utilization raises effective shipping supply in the short run, but doing so is costly. Let $C(\upsilon_t)$ denote the utilization cost per unit of capacity g_t:

$$C(\upsilon_t) = \phi \left(\frac{\upsilon_t}{1 - \upsilon_t} \right)^2, \qquad \phi > 0,$$

which is strictly increasing and convex in υ_t. This specification ensures that raising utilization becomes increasingly expensive as the firm approaches full use of installed capacity.

Then, we have that the global shipping firm is a necessary intermediary between producers of tradable varieties and their international buyers. Thus, effective 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:[16]

$$\sum_{\ell \in \{m,c,k\}} \left(q_{Tt}^{\ell f} + q_{Tt}^{\ell h^*} \right) \leq \upsilon_t \overline{g} g_t,$$

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

Finally, while 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, increasing shipping capacity takes time, as documented in Section 2. Thus, we assume that shipping investments 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 δ_G. Thus, shipping capacity evolves according to the following law of motion:

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

Shipping investments consist of capital goods from each of the countries, with the relative weights given by each country's respective ownership shares of the global shipping firm.

The problem of the global shipping firm consists of choosing shipping investments and

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[16] While iceberg trade costs represent real resource losses, we assume they do not require shipping services. We do so to treat iceberg costs as capturing broad trade frictions rather than literal physical losses during transport. Accordingly, only delivered units require shipping capacity.

capacity utilization to maximize the lifetime discounted sum of period profits Θ_t:

$$\max_{\{g_{t+J},\, \upsilon_t \in [0,1),\, i_{Gt}\}} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \Lambda_t \left\{ h_t\, \upsilon_t\, \overline{g}\, g_t - p_{Gt}\, i_{Gt} - p_{Gt}\, C(\upsilon_t)\, g_t \right\}$$

$$\text{subject to} \quad g_{t+J} = (1-\delta_G)\, g_{t+J-1} + a_G i_{Gt}, \qquad g_{t+J} \geq 0, \qquad \{g_t\}_{t=0}^{J-1} \text{ given,}$$

where Λ_t is the shareholders' discount factor,[17] and $p_{Gt} \equiv \psi\, p_t^k + (1-\psi)\, p_t^{k*}$ denotes the price of shipping investment and utilization costs.

3.5 Stochastic processes

Aggregate productivity in each country follows a first-order autoregressive process. Let z_t and z_t^* denote the aggregate productivity levels in the home and foreign country. Then, productivity in each country evolves according to:

$$\log z_t = (1-\rho_z) \log \bar{z} + \rho_z \log z_{t-1} + \varepsilon_t,$$

$$\log z_t^* = (1-\rho_z) \log \bar{z}^* + \rho_z \log z_{t-1}^* + \varepsilon_t^*,$$

where $\bar{z}$ and $\bar{z}^*$ denote their respective steady–state values, and $\rho_z \in (0,1)$ controls the degree of persistence. The innovations ε_t and ε_t^* are i.i.d. over time and across countries with zero mean and common variance σ_z^2.

3.6 Equilibrium

We let the price of consumption goods in the home country p_t^c be the numeraire. We provide a formal definition of the equilibrium in Section 6.1 of the 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 and capital markets clear; (*iv*) markets for tradable and non-tradable varieties clear; and (*v*) the markets for consumption goods, capital goods, and intermediate inputs clear. In addition, (*vi*) given prices, allocations solve the global shipping firm's problem; (*vii*) the market for shipping services clears,

$$\sum_{\ell \in \{m,c,k\}} \left(q_{Tt}^{\ell f} + q_{Tt}^{\ell h*} \right) \; = \; \upsilon_t\, \overline{g}\, g_t;$$

and (*viii*) the international financial market clears.

4 Mechanism: How shipping affects equilibrium outcomes

In this section, we study the mechanisms through which shipping shapes equilibrium trade and macroeconomic outcomes in our model. We begin by characterizing how shipping costs

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[17] We define $\Lambda_t \equiv \psi\, \lambda_t + (1-\psi)\, \lambda_t^*$, where ψ denotes the ownership share of the home household and λ_t and λ_t^* are the Lagrange multipliers on the budget constraints of the home and foreign households, respectively.

affect import demand. We then examine how an increase in the demand for tradable goods propagates to equilibrium imports, shipping costs, capacity utilization, and investment in global shipping capacity. This analysis illustrates the interaction between demand channels and the short- and long-run margins of shipping supply.

4.1 Import demand

The demand for imports in our model is determined by the use of imported tradable varieties in the production of consumption goods, capital goods, and intermediate inputs. Aggregate imports of tradable varieties by the home country in period t are given by

$$\text{Imports}_t = \sum_{\ell \in \{c,k,m\}} \left[(1-\zeta^{\ell})\xi_t\right]^{\rho} \left(\frac{\tau p_{Tt}^{*} + h_t}{p_{Tt}^{\ell}}\right)^{-\rho} q_{Tt}^{\ell}, \tag{1}$$

where p_{Tt}^{*} denotes the foreign price of tradable varieties, τ denotes iceberg trade costs, and h_t denotes per-unit shipping costs. For each sector $\ell \in \{c, k, m\}$, q_{Tt}^{ℓ} is the demand for tradable goods used in that sector and p_{Tt}^{ℓ} is the associated ideal price index.[18]

4.2 Increase in demand for tradables

To illustrate how shipping costs, imports, and global shipping dynamics respond to shocks, we consider a disturbance that increases the demand for tradable goods. This increase may result from a shift in households' relative demand toward tradable consumption, or more generally from any shock that raises effective tradable absorption, such as a positive aggregate productivity shock. Higher tradable absorption increases import demand for final consumption goods and, as tradable production expands, raises the demand for intermediate inputs and capital goods, further increasing imports of tradable varieties. In the model, these channels are captured by equation (1), which aggregates import demand across consumption, capital, and intermediate goods.

Effect on shipping costs To study the impact of an increase in import demand on shipping costs, we examine how the supply of shipping services adjusts to accommodate higher demand. In the short run, increases in import demand cannot be fully accommodated through expansions in shipping supply. Installed shipping capacity adjusts slowly due to time-to-build, and while utilization responds endogenously, operating the fleet more intensively becomes increasingly costly as capacity constraints tighten. As a result, higher import demand puts upward pressure on shipping costs h_t, which rise to restore equilibrium in the market for shipping services by reducing import demand until it equals effective shipping supply.

To analytically characterize the determinants of shipping cost adjustments, we consider a

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[18] In the model, the ideal price index for tradable goods in sector ℓ corresponds to the unit cost of producing the associated tradable bundle.

simplified version of the model with symmetric countries, symmetric sectoral aggregators, and a symmetric global increase in tradable demand. Under these assumptions, sectoral tradable demand can be summarized by a single composite index q_{Tt} that aggregates the demands q^{ℓ}_{Tt} across $\ell \in \{c, k, m\}$. Abstracting from general equilibrium changes in other prices, the elasticity of shipping costs with respect to tradable demand is given by:[19]

$$\frac{\partial \ln h_t}{\partial \ln q_{Tt}} = \left[\rho \frac{h_t}{\tau p^*_{Tt} + h_t} + \frac{1 - \upsilon_t}{1 + 2\upsilon_t} \right]^{-1}. \tag{2}$$

Equation (2) shows that the response of shipping costs to higher tradable demand depends on three factors. The first factor is the elasticity of substitution ρ, which captures how responsive import demand is to changes in shipping costs. A lower elasticity implies that substitution away from imported varieties is more limited, so shipping costs must increase by a larger amount to reduce import demand and restore equilibrium in the shipping market.

The second factor is the share of shipping costs in total import costs, given by the ratio $h_t/(\tau p^*_{Tt} + h_t)$. If shipping costs account for a small fraction of total import costs, larger percentage changes in h_t are required to induce a given reduction in import demand. Conversely, if shipping costs are a larger share of total import costs, changes in shipping costs have a stronger effect on import demand, so a smaller increase in shipping costs is sufficient to restore equilibrium in the shipping market.

The third factor is shipping capacity utilization, given by the term $(1-\upsilon_t)/(1+2\upsilon_t)$. This term captures the extent to which effective shipping supply can expand along the intensive margin in response to higher demand. When utilization is low ($\upsilon_t \approx 0$), spare capacity is abundant and the fleet can be operated more intensively at relatively low marginal cost, implying that supply responds elastically. In this case, adjustments in utilization absorb a substantial portion of the demand shock, limiting the increase in shipping costs required to restore equilibrium. As utilization rises, spare capacity becomes scarce and operating the fleet more intensively becomes increasingly costly, reducing the responsiveness of supply. Accordingly, as υ_t approaches one, utilization absorbs a smaller portion of the shock, and shipping costs must adjust more strongly to clear the market.

Effect on capacity utilization Faced with higher shipping demand and shipping costs, the global shipping firm chooses how intensively to operate the existing fleet by adjusting the capacity utilization rate υ_t. Increasing utilization raises the effective supply of shipping services within the period by allowing a larger share of installed capacity to be deployed. The optimal utilization choice equates the marginal revenue from deploying an additional unit of

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[19] The expression is obtained by differentiating the shipping market clearing condition, using the import demand equation and the first-order condition for utilization, and abstracting from general equilibrium movements in other prices.

effective shipping capacity to the marginal utilization cost:

$$h_t\,\overline{g} = p_{Gt}\,C'(\upsilon_t),$$

where h_t is the equilibrium shipping cost per unit shipped, $\overline{g}$ denotes shipping efficiency, p_{Gt} is the price of shipping investment goods, and $C'(\upsilon_t)$ is the marginal cost of utilization.

The left-hand side captures the marginal return to increasing utilization: higher shipping costs raise the revenue earned from deploying an additional unit of effective shipping capacity. The right-hand side captures the marginal cost of operating the fleet more intensively. Because utilization costs are convex, the marginal cost of increasing υ_t rises as the fleet is operated closer to capacity.

As a result, an increase in shipping demand that raises shipping costs induces the shipping firm to increase utilization, expanding effective shipping supply in the short run. However, as utilization rises, marginal costs increase rapidly, limiting the extent to which higher demand can be accommodated through this margin. As described above, when utilization is already high, further increases in shipping demand translate primarily into higher shipping costs rather than large increases in effective shipping supply.

Effect on shipping investment While capacity utilization allows the shipping firm to adjust the effective supply of shipping services within the period, this margin is subject to convex costs. As utilization rises, operating the fleet more intensively becomes progressively more costly, limiting the extent to which higher demand can be accommodated through further increases in utilization. Consequently, sustained expansions in shipping supply require investment in new capacity, which expands the fleet itself rather than increasing the intensity with which it is used. Unlike utilization, however, capacity cannot adjust intratemporally. Because shipping investments are subject to a production lag, investment decisions are inherently forward looking, with newly installed capacity becoming operational after J periods.

The optimality condition for shipping investment equates the marginal cost of investing in new capacity today to the expected discounted value of the future net revenues generated once that capacity becomes operational:

$$\mathbb{E}_t \sum_{k=0}^{\infty} \left\{ \beta^{J+k} \frac{\Lambda_{t+J+k}}{\Lambda_t} (1-\delta_G)^k \left[h_{t+J+k}\upsilon_{t+J+k}\overline{g} - p_{Gt+J+k} C(\upsilon_{t+J+k}) \right] \right\} = \frac{p_{Gt}}{a_G}$$

The right-hand side captures the marginal cost of investing in shipping capacity today. The left-hand side represents the expected present discounted value of the future net revenues generated by the additional unit of capacity once it becomes operational at date $t+J$. In each future period $t+J+k$, the installed capacity generates shipping revenues $h_{t+J+k}\upsilon_{t+J+k}\overline{g}$ net of utilization costs $p_{Gt+J+k}C(\upsilon_{t+J+k})$, with future profits discounted by the stochastic discount factor $\beta^{J+k}\Lambda_{t+J+k}/\Lambda_t$ and reduced over time by physical depreciation at rate δ_G.

This condition shows that shipping investment depends on the expected path of future shipping revenues. Because new ships become productive only after a J-period production lag, temporary increases in shipping demand provide limited incentives for capacity expansion, as new ships would become operational after revenues have returned to normal levels. In contrast, persistent increases in shipping demand raise the expected returns to new capacity and induce investment.

4.3 Aggregate implications

Limited short-run flexibility in shipping supply, combined with imperfect substitution between domestic and foreign tradable varieties, can have significant aggregate implications following shocks. When capacity adjusts slowly due to time-to-build and utilization is already elevated, increases in tradable demand are absorbed primarily through higher shipping costs rather than through immediate expansions in trade volumes. As a result, shipping rigidities may transmit demand shocks beyond trade flows to production, investment, and aggregate output. These effects are especially pronounced when shocks are large and persistent, since sustained increases in demand raise shipping costs for longer and strengthen incentives for capacity expansion, while low substitution elasticities restrict the economy's ability to reallocate absorption away from shipping-intensive goods. The following sections quantify the importance of these mechanisms for global shipping dynamics and aggregate macroeconomic outcomes.

5 Quantification: Estimation and Business Cycle Implications

In this section, we study the model's implications for global shipping dynamics and aggregate fluctuations at business-cycle frequencies. We address two questions. First, to what extent can the model account for salient features of shipping dynamics over the business cycle? Second, how does the inelastic supply of shipping capacity shape aggregate fluctuations?

To answer these questions, we first discipline the model to match key features of the data. We then use impulse response functions to illustrate how aggregate shocks propagate through the shipping sector to impact trade flows and aggregate economic activity. Next, we assess the model's implications for business-cycle fluctuations by comparing key second moments to their empirical counterparts. Finally, we quantify the role of shipping on aggregate fluctuations by contrasting the baseline economy with endogenous shipping to a counterfactual economy in which shipping supply is perfectly elastic.

5.1 Quantification approach

To parameterize the model, we divide the parameters into three groups: predetermined parameters, parameters estimated to match cross-sectional moments, and parameters estimated to match business-cycle dynamics.

We study a world economy populated by two symmetric countries that interact through international trade and a global market for shipping services. This approach allows us to study shipping dynamics at the global level while abstracting from cross-country heterogeneity. The two countries share identical structural parameters but may differ in equilibrium outcomes as a result of asymmetric realizations of shocks. Consistent with the global nature of shipping markets, we construct empirical targets as GDP-weighted aggregates of country-level variables. This ensures the model captures key cross-sectional and cyclical features of the global economy.

We solve the model using a second-order approximation around the steady state, allowing us to capture the effects of uncertainty on shipping dynamics and aggregate outcomes. A period in the model corresponds to one quarter. We estimate the parameters of the model using a simulated method of moments procedure. Unless otherwise specified, empirical targets are constructed using OECDstat data for aggregate variables and Clarkson's *Shipping Intelligence Network* data for global shipping variables, based on observations from 1996–2019 prior to the COVID-19 pandemic.[20] Details of the parameterization and targeted moments are provided below, with additional information on data sources and moment construction reported in Section 1 of the Appendix. Section 6.2 of the Appendix defines the model counterparts to the empirical variables, including real GDP, imports, tradable and non-tradable absorption, import prices, and relative prices.

Predetermined parameters We begin by assigning the set of predetermined parameters. Table 1 reports their values. Unless otherwise specified, parameter choices follow Backus et al. (1995). We set the discount factor to $\beta = 0.99$, implying an annual real interest rate of four percent. The intertemporal elasticity of substitution is set to $1/\gamma = 0.5$, and the consumption share in household utility to $\mu = 0.34$. The quarterly capital depreciation rate is set to $\delta = 0.025$, implying an annual depreciation rate of approximately ten percent, consistent with estimates for U.S. manufacturing capital (Albonico et al., 2014). The capital share in both sectors is set to $\theta = 0.36$, close to estimates documented in Valentinyi and Herrendorf (2008). Finally, we set the elasticity of substitution between domestic and imported tradable varieties to $\rho = 4$, consistent with values commonly used in the quantitative trade literature (Simonovska and Waugh 2014).

On the production side, input and expenditure shares are calibrated using national ac-

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[20] The baseline set of countries used to compute the OECDstat-based moments consists of Austria, Canada, Costa Rica, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Iceland, Italy, Korea, Latvia, the Netherlands, Norway, Poland, Portugal, the Slovak Republic, Slovenia, Sweden, the United Kingdom, and the United States.

Table 1: Predetermined parameters

Parameter	Value	Description
β	0.99	Discount factor
$1/\gamma$	0.50	Intertemporal elasticity of substitution
μ	0.34	Consumption share in household utility
δ	0.025	Capital depreciation rate
θ	0.36	Capital share
$1-\varphi_T$	0.63	Intermediate share in gross output: T
$1-\varphi_N$	0.40	Intermediate share in gross output: NT
χ^c	0.29	Share of tradables: Consumption goods
χ^k	0.48	Share of tradables: Capital goods
χ^m	1.00	Share of tradables: Intermediate goods
ρ	4	Elasticity of substitution: Domestic vs. imported
δ_G	0.01	Shipping depreciation
J	6	Shipping production lag

counts data. For each moment, we compute country-level averages over 1996–2019, and then construct global shares by aggregating country-level averages using GDP weights. Using OECDstat data, we obtain intermediate input shares of $1-\varphi_T = 0.63$ in the tradable sector and $1-\varphi_N = 0.40$ in the non-tradable sector. Using OECDstat and Penn World Tables data, the tradable shares in consumption and capital absorption are $\chi^c = 0.29$ and $\chi^k = 0.48$, respectively. We let intermediate inputs be fully tradable ($\chi^m = 1$), consistent with the high tradable intensity of intermediate goods in the data.[21]

Turning to the shipping sector, we set the quarterly depreciation rate of shipping capacity to $\delta_G = 0.01$, consistent with observed fleet turnover rates.[22] We set the shipping production lag to $J = 6$, a lower bound for the time-to-build of containerships documented in Section 2.

Finally, we normalize a subset of the parameters. The weight on domestic varieties in tradable consumption, ζ^c, is set to 0.5 and does not affect steady-state allocations. The scale parameter for shipping efficiency is normalized to $\overline{g} = 1$. Aggregate productivity in the steady-state is a scale normalization and does not affect equilibrium outcomes; we assume it is identical across countries. Given our focus on a symmetric world economy, households in each country own an equal share of the global shipping firm, $\psi = 0.5$. We assume integrated

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[21] In the BEA 2017 use table, tradable goods account for about 82 percent of intermediates used in tradable production overall and about 83 percent in manufacturing. Similarly, Guci and Mead (2014) report a goods share of about 85 percent for U.S. manufacturing.

[22] We estimate shipping capacity depreciation using Clarksons data on the global containership fleet. Let K_{fleet} denote fleet capacity and let I_{fleet} denote new ship orders, both measured in TEUs. The law of motion for shipping capacity along a balanced growth path implies $(g_{fleet} + \delta_G)K_{fleet} = I_{fleet}$, where g_{fleet} denotes the fleet growth rate. Solving for $\delta_G = I_{fleet}/K_{fleet} - g_{fleet}$ and using average values over the sample yields an annual depreciation rate of about 4 percent.

financial markets and set bond-holding costs Φ_b to a small value, 0.01, to ensure stationarity.

Parameters estimated to match cross-sectional targets The parameters estimated to match salient cross-sectional features of the data are the weights on domestic tradable varieties used in the production of capital and intermediate goods, ζ^k and ζ^m, the iceberg trade cost τ, the productivity of shipping investment a_G, the productivity of non-tradable producers a_N, and the utilization cost parameter ϕ.

We choose these parameters so that the steady state of the model matches key cross-sectional patterns of global trade and shipping. In particular, we target: (*i*) the share of capital goods in aggregate imports, (*ii*) the share of intermediates in aggregate imports, (*iii*) the ratio of aggregate imports to aggregate absorption, (*iv*) the ratio of expenditures on shipping costs to total imports, (*v*) the average utilization rate of shipping capacity, and (*vi*) the relative price of tradable to non-tradable consumption goods.

We compute these moments using several data sources. Aggregate imports and absorption ratios are constructed using data from OECDstat. Import shares for capital and intermediate goods are computed using data from Comtrade. The ratio of shipping costs to imports is measured using CIF–FOB import ratios from UNCTAD's Trade-and-Transport Dataset over the period 2016–2019 due to data availability.[23,24] Average shipping capacity utilization is constructed using the effective utilization series described in Section 2. Finally, the relative price of tradable to non-tradable consumption goods is normalized to unity in the steady state.[25]

Table 2 reports the estimated parameters along with their targeted moments and model counterparts. The iceberg trade cost τ is estimated at its lower bound of one, preventing an exact match of all targets, though the model matches the data closely. The relationship between parameters and moments can be summarized as follows, reflecting the moments most informative about each parameter.[26] The parameters ζ^k and ζ^m determine the composition of imports across capital and intermediate goods by shifting the relative importance of domestic and imported varieties in production. The iceberg trade cost τ governs the overall level of trade openness and pins down the aggregate imports-to-absorption ratio. Shipping investment productivity a_G and the utilization cost parameter ϕ jointly determine the steady-state level of shipping costs and capacity utilization. Finally, the productivity of the non-tradable sector,

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[23] CIF–FOB ratios include both freight and insurance costs. Section 3 of the Appendix shows that the insurance component is small and has a negligible effect on these ratios.

[24] See `https://unctadstat.unctad.org/datacentre/reportInfo/US.TransportCosts` for further details.

[25] Because production technologies differ across sectors, we normalize the steady-state relative price to prevent productivity rescaling across sectors from affecting real allocations.

[26] For a more formal exercise calculating the elasticity of each cross-sectional moment to estimated structural parameters, see Section 7.1 of the Appendix.

Table 2: Parameters estimated to match cross sectional targets

Parameter	Value	Description
ζ^k	0.462	Weight on domestic tradable varieties: Capital
ζ^m	0.574	Weight on domestic tradable varieties: Intermediates
τ	1.000	Iceberg trade cost
a_G	2.036	Productivity: Shipping investment
a_N	0.582	Productivity: Non-tradable varieties
ϕ	0.00082	Utilization cost

Moment	Data	Model
Share of agg. imports: Capital	0.179	0.185
Share of agg. imports: Intermediates	0.582	0.588
Imports / Absorption	0.177	0.169
Shipping cost expenditures / Imports	0.081	0.078
Shipping utilization rate	0.629	0.629
Relative consumption price (T/NT)	1.000	1.000

a_N, pins down the relative price of tradable to non-tradable consumption goods.

Parameters estimated to match time-series targets The parameters estimated to match key business-cycle moments of the data are the variance of aggregate productivity shocks, σ_z^2, the investment adjustment cost parameter Φ_k, and the parameter governing the time-varying weight on imported tradable varieties, ϕ_τ.

We choose these parameters so that the model matches key second moments of aggregate business cycle fluctuations. In particular, we target: (*i*) the standard deviation of real GDP, (*ii*) the standard deviation of investment relative to that of real GDP, and (*iii*) the standard deviation of real imports relative to that of tradable output. In addition, we set the persistence of the aggregate productivity process, $\rho_z = 0.86$, to equal the persistence of an AR(1) process estimated from real GDP data.

These moments are computed using quarterly data from OECDstat over 1996–2019, with tradable output measured using data on industrial production. Unless otherwise specified, series are expressed in logs and detrended using a Hodrick–Prescott filter with smoothing parameter 1600. As described above, we construct empirical targets as GDP-weighted aggregates of country-level statistics. Model-implied moments are computed from simulated data generated by the stochastic processes, based on 100 simulations of 96 periods, corresponding to the length of the data sample (1996–2019).

Table 3 reports the estimated parameters along with their targeted moments and model counterparts. We find the parameters can be estimated to match the time-series moments. The relationship between parameters and moments can be summarized as follows, reflecting the moments most informative about each parameter. The variance of productivity shocks,

Table 3: Parameters estimated to match time series targets

Parameter	Value	Description
σ_z	0.00325	Productivity process: Shock standard deviation
Φ_k	0.234	Adjustment cost: Investment
ϕ_τ	3.547	Time-varying import weight

Moment	Data	Model
Std. dev. Real GDP	1.20	1.20
Std. dev. Investment / Std. dev. Real GDP	4.22	4.22
Std. dev. Imports / Std. dev. Tradable Output	1.35	1.35

σ_z^2, governs the overall volatility of aggregate activity, while the investment adjustment cost parameter, Φ_k, controls the relative volatility of investment. The parameter ϕ_τ determines the sensitivity of import demand to aggregate conditions and allows the model to capture the observed cyclicality of imports.[27]

5.2 Impulse responses and shipping dynamics

We begin by characterizing how shipping affects the model's propagation mechanisms through impulse response functions to a positive one-percent aggregate productivity shock in the home country. Figure 4 reports the response of shipping and aggregate variables as percent deviations from steady state, with shipping utilization and the shipping investment rate expressed in percentage-point deviations from their steady-state rates.[28]

Following the productivity shock, output and absorption increase, raising demand for tradable goods and imports and, in turn, for shipping services. Because the global shipping firm has limited ability to expand supply in the short run, the initial increase in shipping demand translates into higher shipping costs and greater utilization of existing capacity.

In addition, the global shipping firm increases the shipping investment rate, but installed capacity expands sluggishly given the production lags. Effective shipping capacity therefore adjusts first along the intensive margin through higher utilization, and only later through an increase in the stock of shipping capacity. As new capacity becomes operational, shipping costs gradually decline, reflecting the delayed expansion of effective supply.

These shipping dynamics feed back into aggregate outcomes. Higher shipping costs partially restrain the expansion of tradable output and imports. Import prices rise on impact and fall as capacity expands. Import volumes increase on impact, decline as the effects of

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[27] For a more formal exercise calculating the elasticity of each targeted moment to the estimated parameters, see Section 7.1 of the Appendix.

[28] Section 9 of the Appendix reports additional impulse response functions that further illustrate the model's transmission mechanisms, including foreign responses to a home productivity shock and a comparison between the baseline and a counterfactual economy without shipping.

the productivity shock gradually revert, and then rise again once the earlier increase in shipping investment translates into higher installed capacity. The relative price of tradables to non-tradables declines following the productivity shock, as the increase in domestic demand places greater upward pressure on non-tradable prices. Rising shipping costs moderate this decline by raising the cost of imported tradable varieties.

Overall, the impulse responses highlight the central role of shipping supply rigidities in shaping the economy's response to productivity shocks. In the short run, limited shipping capacity translates higher demand into higher shipping costs rather than larger trade volumes. Over time, investment gradually expands capacity, leading to persistent movements in shipping costs, trade flows, and aggregate outcomes. These mechanisms form the basis for the quantitative results that follow.

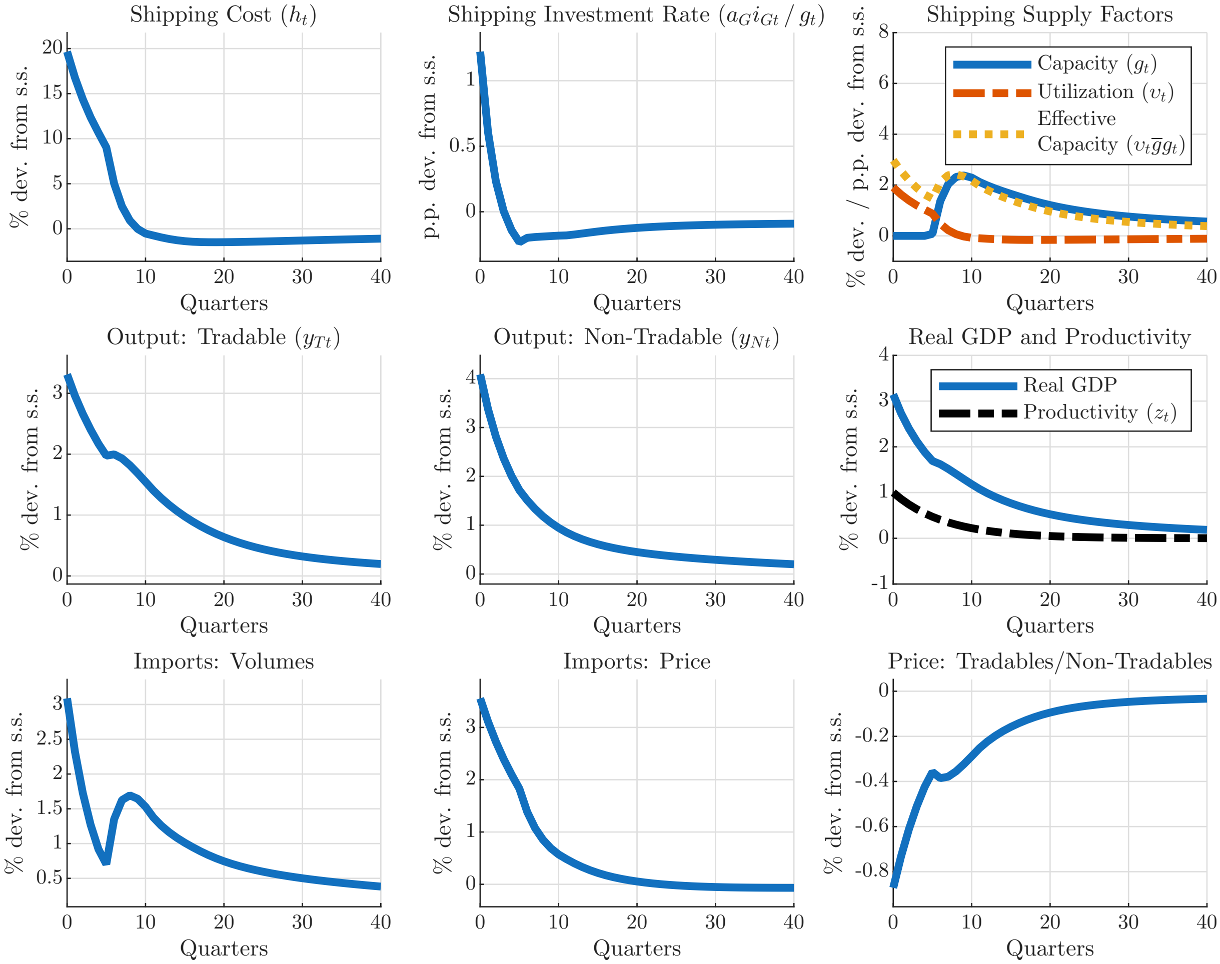
5.3 Business-cycle fluctuations and the role of shipping

We now study the business cycle implications of the model. Table 4 reports second moments from the data, the baseline model with endogenous shipping, and a counterfactual economy described below. These moments allow us to assess the business-cycle properties of the model and the role of shipping supply rigidities in shaping aggregate fluctuations.

Business-cycle dynamics in the baseline economy. We begin by assessing the business-cycle implications of the baseline model with endogenous shipping. Panel A of Table 4 reports the volatility of aggregate quantities, while Panel B reports the volatility of relative prices. By construction, the baseline model matches the volatility of real GDP and investment observed in the data. Beyond these targeted moments, the model delivers a reasonable characterization of aggregate fluctuations with, for instance, consumption less volatile than output and net exports to GDP almost as volatile as in the data. The model also generates meaningful variation in relative prices, such as the terms of trade.

Panel C reports the volatility of shipping-related variables. In both the data and the model, shipping costs are substantially more volatile than real GDP, with the model accounting for about 81% of the shipping cost volatility observed in the data. As discussed in Section 4, two channels are critical in determining the dynamics of shipping costs. First, because shipping capacity adjusts slowly and utilization is high on average and subject to convex costs, equilibrium in the shipping market in the short-run is primarily restored through changes in shipping costs rather than by expansions in shipping supply. Second, since shipping expenditures represent a relatively small share of total import costs and there is imperfect substitution between imported and domestic tradable varieties, substantial changes in shipping costs are required to meaningfully alter import demand. The model also generates volatility in other shipping-related variables, including shipping capacity and shipping investment.

Figure 4: Impulse responses to an aggregate productivity shock



Note: The figure reports impulse responses to a one-percent aggregate productivity shock. Variables are expressed as percent deviations from their respective steady-state values (100 times log deviations), except for shipping utilization and the shipping investment rate, which are expressed in percentage-point deviations. Effective shipping capacity is defined as the product of installed shipping capacity and capacity utilization. See Section 6.2 of the Appendix for definitions of variables not defined explicitly.

The role of shipping supply rigidities. We investigate the role of shipping supply rigidities in accounting for the business cycle implications of the model by comparing the baseline model to a counterfactual economy that differs only in its shipping technology. In the counterfactual economy, shipping supply is perfectly elastic and costless such that international purchases are only subject to iceberg trade costs. All parameters governing preferences, production technologies, and shock processes are identical across the two economies. In Table 4, we report the business cycle implications of this economy under the "No Shipping" column.[29] This counterfactual economy is not intended to represent a realistic alternative description of shipping markets. Rather, it corresponds to the implicit assumption made in standard mod-

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[29] In the Appendix we report additional business-cycle results, including alternative specifications (Table 7), business-cycle correlations (Table 8), and a comparison between local and global shocks (Table 9).

Table 4: Business cycle fluctuations

	Data	Shipping	No Shipping
Panel A: Economic Activity			
Std. dev.			
Real GDP	1.20	1.20	1.41
Net Exports / GDP	0.57	0.67	0.64
Std. dev. relative to real GDP			
Consumption (c_t)	0.60	0.46	0.48
Investment (i_t)	4.22	4.22	4.75
Labor (n_t)	0.80	0.49	0.61
Panel B: Prices			
Std. dev. relative to real GDP			
Price: Tradables/Nontradables	1.29	0.28	0.49
Terms of trade	1.41	1.17	0.98
Real exchange rate	2.93	0.97	0.81
Panel C: Shipping			
Std. dev. relative to real GDP			
Shipping costs (h_t)	12.15	9.84	–
Shipping capacity (g_t)	1.41	1.03	–
Std. dev.			
Shipping investment rate ($a_G i_{Gt}/g_t$)	1.00	0.67	–

Note: The table reports business-cycle moments from the data, the baseline model with endogenous shipping ("Shipping"), and a counterfactual economy with perfectly elastic and costless shipping supply ("No Shipping"). In the counterfactual economy, international trade is subject only to iceberg trade costs, and shipping costs do not respond endogenously to aggregate conditions. Data moments are constructed using the same data sources described in Section 5.1; see also Section 1 of the Appendix. Model moments are computed from simulated quarterly data and averaged across simulations. Unless otherwise indicated, moments are computed from HP-filtered logged series (smoothing parameter 1600) and reported as standard deviations in percent. Moments reported relative to real GDP are ratios of standard deviations to the standard deviation of real GDP. Net exports to GDP and the shipping investment rate are reported as standard deviations of levels; the shipping investment rate is computed as the quarterly growth rate of fleet capacity, in percentage-point units. Entries marked "–" denote variables that are not defined in the counterfactual economy. See Section 6.2 of the Appendix for definitions of variables not defined explicitly.

els of international trade and international business cycles, where international trade costs are exogenous and shipping supply is implicitly assumed to be perfectly elastic.

Comparing these economies reveals that shipping supply rigidities have important aggregate implications. Relative to the counterfactual, the baseline exhibits lower volatility of real GDP and several aggregate quantities, including consumption and investment. The intuition follows from the impulse responses discussed in the previous subsection. During economic expansions, higher productivity raises demand for tradable goods and international trade, increasing demand for shipping services. With an inelastic short-run supply of shipping capacity, shipping costs increase and partially ration this demand, dampening the expansion of tradable production and trade. In the counterfactual economy with perfectly elastic shipping supply, this constraint is absent, allowing larger expansions of international trade flows and tradable output. Quantitatively, real GDP volatility in the counterfactual is approximately 18 percent higher than in the baseline economy.

These findings suggest that the elasticity of shipping supply is an important determinant of aggregate volatility. With an inelastic supply of shipping capacity, higher demand for shipping during expansions raises shipping costs and limits the expansion of tradable activity, dampening the cyclical response of output.[30]

6 Shipping and Aggregate Dynamics Following COVID-19

In this section, we use the estimated model to study the dynamics of global shipping during the COVID-19 pandemic. We evaluate the extent to which the model can account for the dynamics of shipping costs and quantify their implications for aggregate economic activity.

We begin by estimating the sequences of shocks that account for the observed dynamics since 2020. In addition to aggregate productivity shocks, we consider changes in the demand for tradable goods and disruptions to the effective throughput of shipping capacity. We discipline the paths of these shocks using a set of empirical targets that capture the joint dynamics of aggregate economic activity and effective shipping capacity.

Given the estimated shocks, we evaluate the model's implications for aggregate economic activity, relative prices, and shipping dynamics. We then quantify the role of shipping supply rigidities by comparing the baseline economy to an otherwise identical counterfactual economy with a more flexible shipping technology, isolating the contribution of shipping frictions to the dynamics of shipping costs and aggregate economic activity.

6.1 Shock identification

We begin by describing how we use the model as estimated in Section 5 to recover the sequence of shocks that accounts for the observed dynamics of key empirical series since 2020Q3.[31] The model is solved using a second-order approximation around the steady state, which delivers decision rules mapping sequences of shocks into equilibrium paths for shipping and aggregate

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[30] Brancaccio et al. (2020) also show that endogenous shipping costs can dampen the response of trade to shocks but through a complementary mechanism. In their framework, trade imbalances and search frictions determine the spatial allocation of a fixed amount of shipping capacity across markets, thereby generating endogenous freight costs.

[31] We focus on the period following 2020Q3 to abstract from the sharp aggregate global contraction in 2020Q2 associated with the initial pandemic lockdowns.

variables, and allows uncertainty to affect allocations and prices.

We consider four global shocks: an aggregate productivity shock, shocks to the weights on tradable consumption and capital, and a shipping-efficiency shock. The productivity shock is the same process used in the business-cycle analysis, while the remaining three involve allowing parameters that are held constant in that analysis ($\overline{g}$, χ^c, and χ^k) to vary over time. All shocks follow AR(1) processes and are assumed to be common across countries, reflecting the global nature of the COVID-19 pandemic. We smooth the target series to focus on the systematic movement in each series over this period.[32]

We choose the sequences of all four shocks jointly so that the model-implied paths of the targeted variables match their empirical counterparts over the COVID period. Each shock affects all targeted variables in equilibrium, so identification comes from the joint restrictions imposed by the model. In the discussion that follows, we describe each shock alongside the empirical series most informative about it.

Aggregate productivity shock. As described in Section 3, aggregate productivity evolves according to

$$\log z_t = (1-\rho_z)\log \bar{z} + \rho_z \log z_{t-1} + \varepsilon_t^z,$$

where the persistence parameter ρ_z and the innovation variance are parametrized as described in Section 5. During the COVID-19 period, we recover the sequence of productivity innovations $\{\varepsilon_t^z\}$ such that the model-implied path of real GDP matches its empirical counterpart, measured as deviations of log real GDP from a linear trend estimated over 2015–2019.

Shocks to tradable consumption and tradable capital demand. We model changes in the demand for tradable goods as a shock to the weights on tradable consumption (χ_t^c) and tradable capital (χ_t^k), allowing them to vary over time around the steady-state values $\bar{\chi}^c$ and $\bar{\chi}^k$ estimated in Section 5:

$$\log \chi_t^\ell = (1-\rho_{\chi^\ell})\log \bar{\chi}^\ell + \rho_{\chi^\ell}\log \chi_{t-1}^\ell + \varepsilon_t^{\chi^\ell}, \qquad \varepsilon_t^{\chi^\ell} \sim \mathcal{N}(0, \sigma_{\chi^\ell}^2).$$

The persistence parameter ρ_{χ^ℓ} and the innovation variance $\sigma_{\chi^\ell}^2$ are estimated using pre-COVID data on tradable consumption and capital, yielding $\rho_{\chi^c} = 0.736$, $\rho_{\chi^k} = 0.815$, $\sigma_{\chi^c} = 0.009$ and $\sigma_{\chi^k} = 0.036$.[33]

During the COVID-19 period, we recover the sequence of innovations $\{\varepsilon_t^\chi\}$ so that the

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[32] Specifically, we fit a sixth-order polynomial to each data series over 2020Q3–2024Q4, imposing a value of zero at 2020Q3 consistent with the normalization of each series as deviations from its pre-pandemic trend. Our results are robust to using the unsmoothed series as targets.

[33] We estimate the AR(1) process country by country using quarterly pre-COVID data constructed analogously to Section 5. Tradable consumption and capital are measured as log deviations from an HP trend (smoothing parameter 1600). Global parameter values are obtained by aggregating the country-level estimates using GDP weights.

model-implied path of tradable consumption and tradable capital match their empirical counterparts, measured as log deviations from a linear trend estimated over 2015–2019.

Shipping efficiency shock. We model disruptions to effective shipping capacity as a shipping efficiency shock, $\overline{g}_t$. Recall that $\overline{g}_t$ scales the effective supply of shipping services, $\upsilon_t \overline{g}_t g_t$, by governing how installed capacity maps into delivered shipping services. We allow it to vary over time around its steady-state value $\overline{g}$:

$$\log \overline{g}_t = (1-\rho_g)\log \overline{g} + \rho_g \log \overline{g}_{t-1} + \varepsilon_t^g, \qquad \varepsilon_t^g \sim \mathcal{N}(0, \sigma_g^2).$$

To discipline this shock during the COVID-19 pandemic, we rely on data on shipping times. Longer transit times imply that, for a given level of installed capacity and utilization, the shipping network can move fewer goods within a period. Shipping times therefore provide information about disruptions to the effective supply of shipping services. In particular, increases in shipping times capture disruptions such as port congestion, labor shortages, rerouting, and coordination frictions that reduce the effective throughput of the shipping network even when installed capacity and utilization remain elevated.

Our measure of shipping times is based on the Flexport Ocean Timeliness Indicator (OTI), which reports the median time from when cargo is ready for shipment at the exporter's facility to its departure from the destination port and thus provides a direct measure of how long it takes the shipping network to move goods across major trade routes. We adjust these route-level series by netting out changes in container dwell times at ports, while retaining vessel waiting and anchorage time, since those delays directly affect vessel cycle time and effective shipping capacity. We then aggregate the adjusted route-level series into a single index of shipping times.[34]

Our preferred shipping-time series do not extend sufficiently far back in time to estimate the stochastic process directly from pre-COVID shipping-time data. We therefore estimate the persistence parameter ρ_g and the innovation variance σ_g^2 using pre-COVID data on real imports, which provide a longer time series and capture the link between shipping conditions and trade volumes. The resulting estimates are $\rho_g = 0.820$ and $\sigma_g = 0.022$.[35]

We map shipping times into an empirical proxy for shipping efficiency by normalizing

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[34] The OTI is constructed from major east-west routes linking Asia to the U.S. West Coast, the U.S. East Coast, and Northern Europe. We implement the dwell-time adjustment separately for each route using port-level evidence on pre-pandemic and peak COVID container dwell times for the main gateways underlying these routes, including Shanghai/Ningbo at origin and Los Angeles/Long Beach, New York/New Jersey, Norfolk, and Rotterdam at destination. We construct an aggregate index of shipping times by averaging the route-level series. The underlying dwell-time evidence is drawn from publicly available port statistics, port authority reports, and industry sources.

[35] We estimate the AR(1) process country by country using quarterly pre-COVID data constructed analogously to Section 5. Imports are measured as log deviations from an HP trend (smoothing parameter 1600), and global parameter values are obtained by aggregating the country-level estimates using GDP weights.

observed shipping times relative to their average level over 2020Q1–2020Q3, before the sharp rise in shipping times and shipping costs later in the pandemic:

$$\overline{g}_t \equiv \frac{\overline{TT}}{TT_t},$$

where TT_t denotes shipping times in period t and $\overline{TT}$ denotes the average shipping times over 2020Q1–2020Q3. Under this mapping, increases in transit times reduce the effective amount of shipping services supplied per unit of deployed capacity within a given period.

During the COVID-19 period, we recover the sequence of innovations $\{\varepsilon_t^g\}$ so that the model-implied path of shipping efficiency tracks its empirical counterpart. Given these shocks, the model jointly determines the implied dynamics of shipping costs and trade volumes.

Importantly, the shipping efficiency shock is distinct from the other margins of adjustment in the shipping sector. Installed shipping capacity g_t evolves slowly due to time-to-build and depreciation, while utilization υ_t governs how intensively that capacity is used. In contrast, $\overline{g}_t$ captures disruptions that affect the mapping between deployed capacity and delivered shipping services, including congestion, delays, and rerouting. Consequently, even when installed capacity and utilization remain elevated, a decline in $\overline{g}_t$ reduces the effective supply of shipping services within a period.

6.2 Results

We now study the implications of the estimated shocks for the dynamics of shipping and aggregate economic activity. We begin by reporting the paths of the shocks and the variables used as estimation targets, and then examine the model's implications for untargeted variables and broader economic outcomes.[36]

Shocks and targeted variables. We begin by reporting the estimated shocks and the model-implied dynamics of the variables used as estimation targets. Figure 5 shows that the model matches the observed paths of aggregate real GDP, tradable consumption, tradable capital, and shipping efficiency over this period. These variables primarily discipline, respectively, the aggregate productivity shock, the tradable-demand shocks, and the shipping efficiency shock. In Section 10.2 of the Appendix we report the independent contribution of each shock by plotting the dynamics of these variables with only one shock at a time.

The estimated shocks display the following salient features. The demand shock for tradable consumption and tradable capital rose in 2021, consistent with the reallocation toward goods following the pandemic. The shipping efficiency shock declines markedly over the same period, reflecting elevated transit times and congestion in global shipping. Aggregate productivity temporarily contracts in 2020 and gradually recovers thereafter. Together, these

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[36] Section 8 of the Appendix studies the sensitivity of our findings to alternative specifications of the model.

shocks account for the empirical dynamics of tradable consumption, tradable capital, shipping efficiency, and real GDP shown in the last column of the figure.

Untargeted macroeconomic variables. Next, we assess the extent to which our model can account for key macroeconomic variables not directly targeted in the estimation of the shocks. Figure 6 contrasts the model-implied dynamics of consumption, investment, labor, relative prices, tradable absorption, and nontradable absorption with their empirical counterparts. In the data, we measure these variables as the deviation between the log of each variable and their respective linear trend over 2015–2019.

We find that the model can largely account for the dynamics of these variables. The model reproduces the sharp decline in investment in 2020 and its gradual recovery thereafter. It also captures the pronounced drop in consumption and its subsequent rebound, consistent with the timing observed in the data. The contraction in labor input is similarly reflected in the model, with a gradual normalization over time. The model generates an increase in relative prices following the deterioration in shipping conditions, though the magnitude of the spike is smaller than in the data, accounting for roughly a third of the peak increase. This gap likely reflects channels emphasized in related work that are beyond the scope of our framework, such as nonlinearities in the production of imported intermediates and nominal rigidities across sectors (see, e.g., Comin et al. 2024; di Giovanni et al. 2022). Finally, the timing and magnitude of both tradable and nontradable absorption in the model are in line with what we observe in the data. Taken together, these findings show that the estimated shocks generate empirically consistent implications beyond the targeted variables.

Shipping dynamics. We now examine the implications of the model for global shipping dynamics in the aftermath of the COVID-19 pandemic. Figure 7 reports the model-implied dynamics of key shipping and trade variables, along with their empirical counterparts.[37]

Shipping costs increase sharply in 2021, reaching a peak in 2022 before gradually declining. The model reproduces both the timing and persistence of the spike, accounting for 50% of the peak increase observed in the data. Thus, we find that the model accounts for a substantial share of the increase in shipping costs observed in the data, without targeting these dynamics in the estimation of the shocks. In the model, this surge reflects the interaction between a sharp deterioration of shipping efficiency and limited short-run flexibility in shipping supply. With shipping capacity adjusting gradually and utilization already elevated and increasingly costly to expand, equilibrium in the shipping market is restored primarily via

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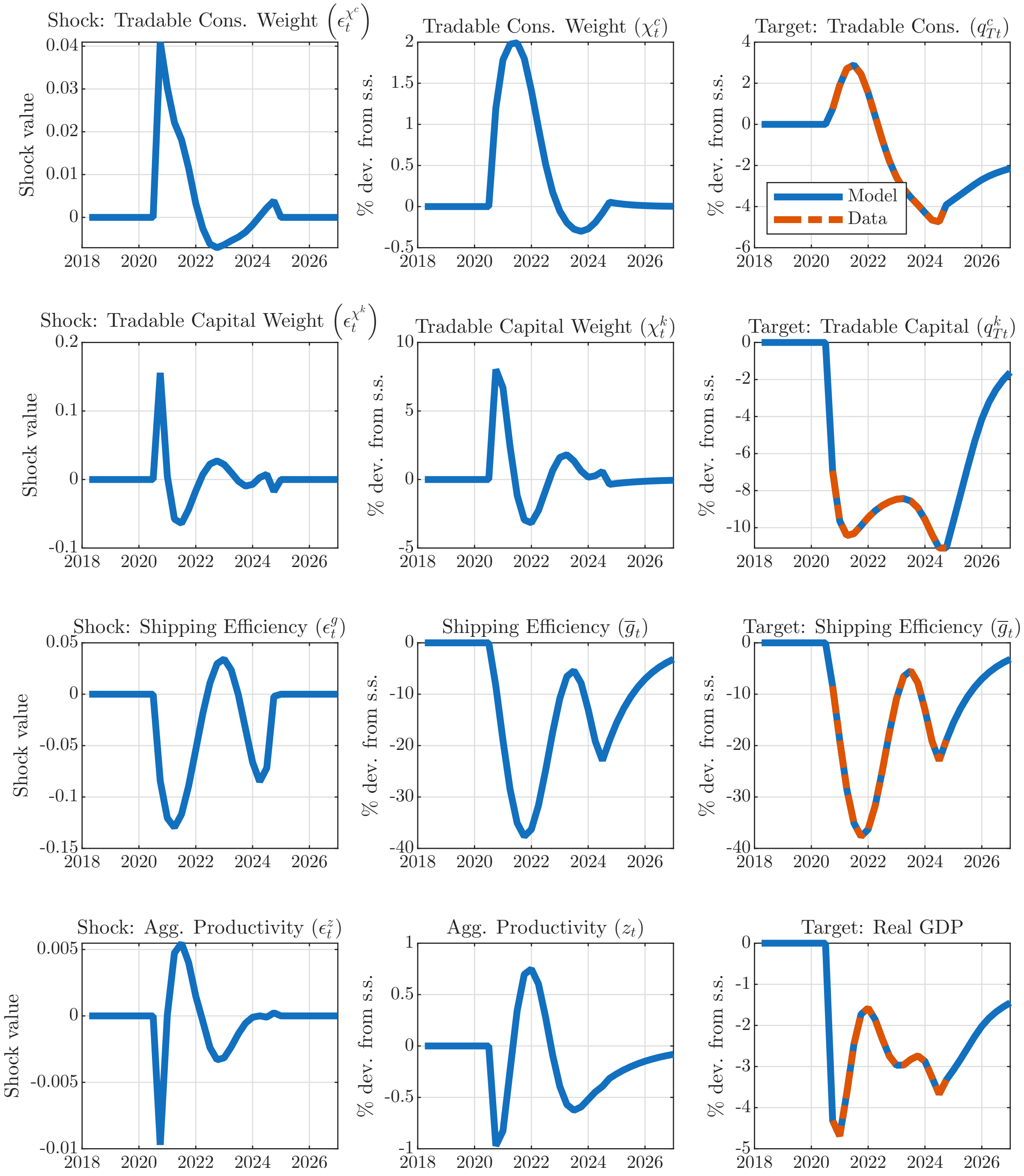
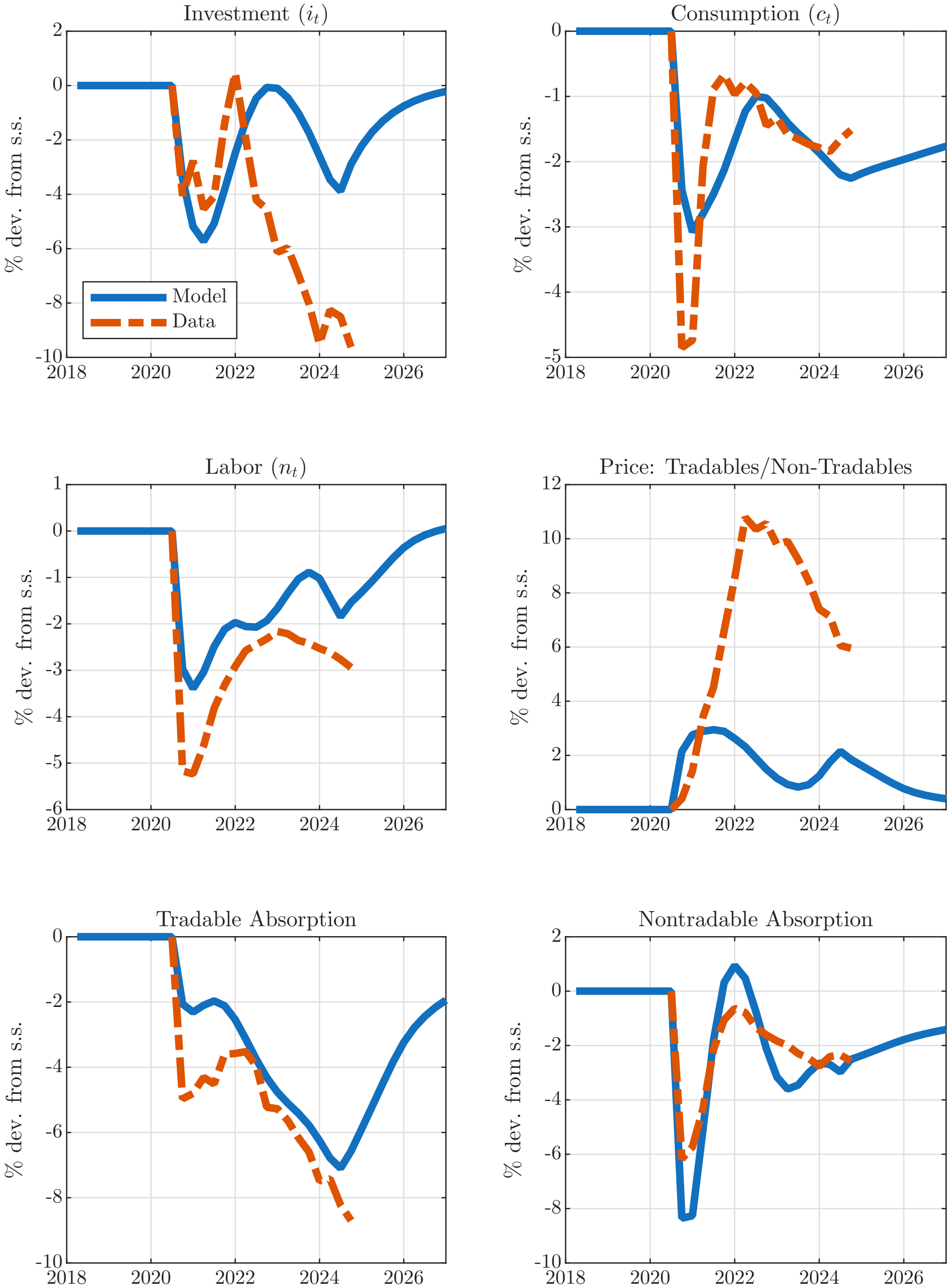
[37] In the data, we measure shipping costs and trade as the deviation between their log and their respective linear trend over 2015–2019. Trade is measured using global containership trade volume data from Clarksons. We measure the shipping investment rate as new containership orders relative to fleet size, both measured in TEUs, reported as its level deviation from the 2015–2019 average.

Figure 5: Shocks and targeted variables



Note: The figure reports the paths of the four global shocks and the model-implied dynamics of the corresponding target variables. For each shock, the first column reports the shock innovations, the second column reports the implied level of the corresponding state variable, and the third column reports the targeted empirical series alongside the model-implied path. In the data, target variables are expressed as log deviations from a linear trend estimated over 2015–2019, except for the shipping efficiency target, which is constructed from shipping times relative to their average over 2020Q1–2020Q3. Model variables are reported as log deviations from their steady state. Shocks are reported in levels. See Section 6.2 of the Appendix for definitions of variables not defined explicitly.

Figure 6: Macroeconomic dynamics: Model vs. data

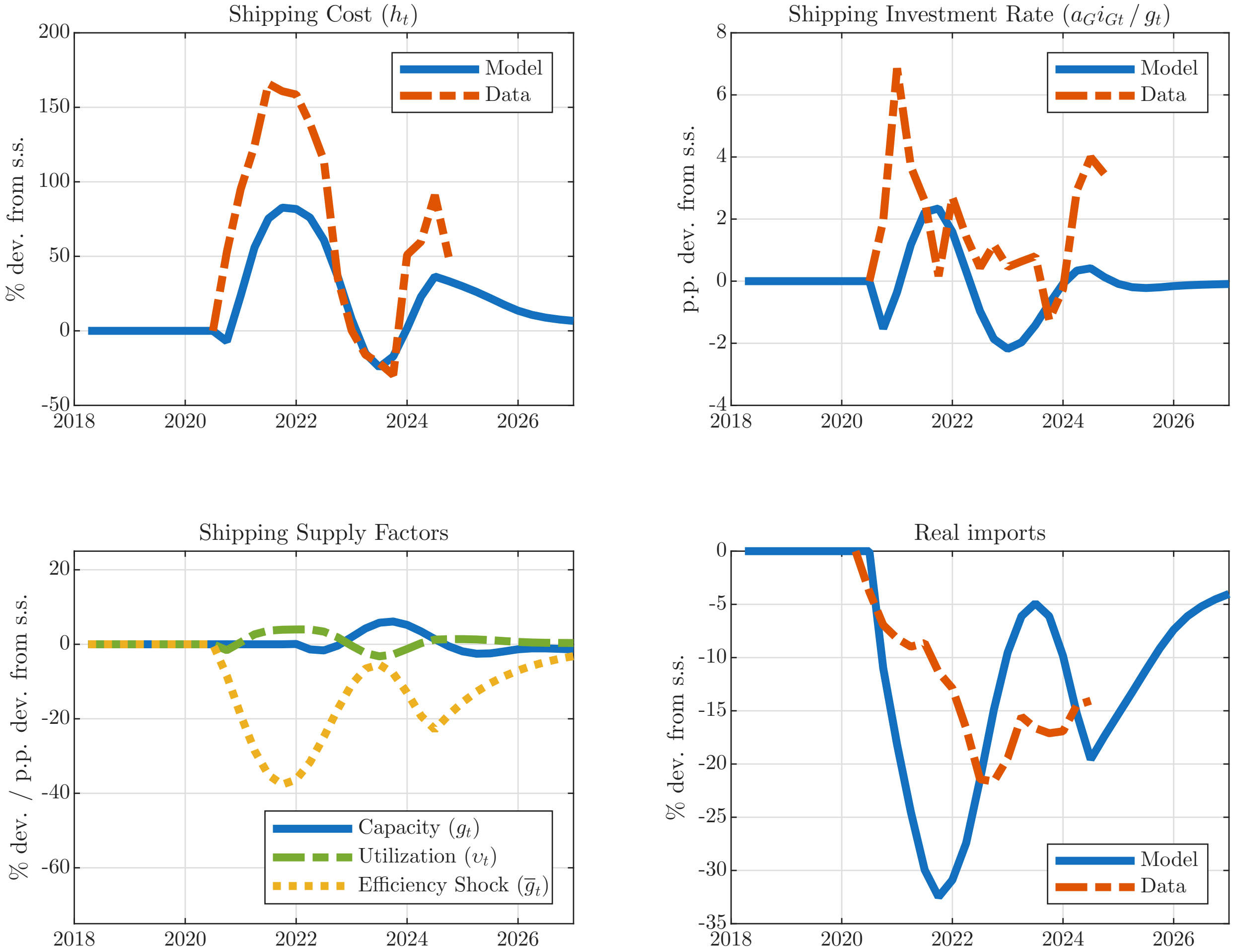


Note: The figure reports the model-implied dynamics of selected macroeconomic variables that are not directly targeted in the estimation of the shocks, along with their empirical counterparts. In the data, variables are expressed as log deviations from a linear trend estimated over 2015–2019. Model variables are expressed as log deviations from their steady state. See Section 6.2 of the Appendix for definitions of variables not defined explicitly.

higher shipping costs. As shipping efficiency recovers and new capacity becomes operational, shipping costs decline toward pre-pandemic levels.

The remaining panels illustrate the adjustment of shipping supply and trade. The de-

Figure 7: Shipping dynamics during COVID-19

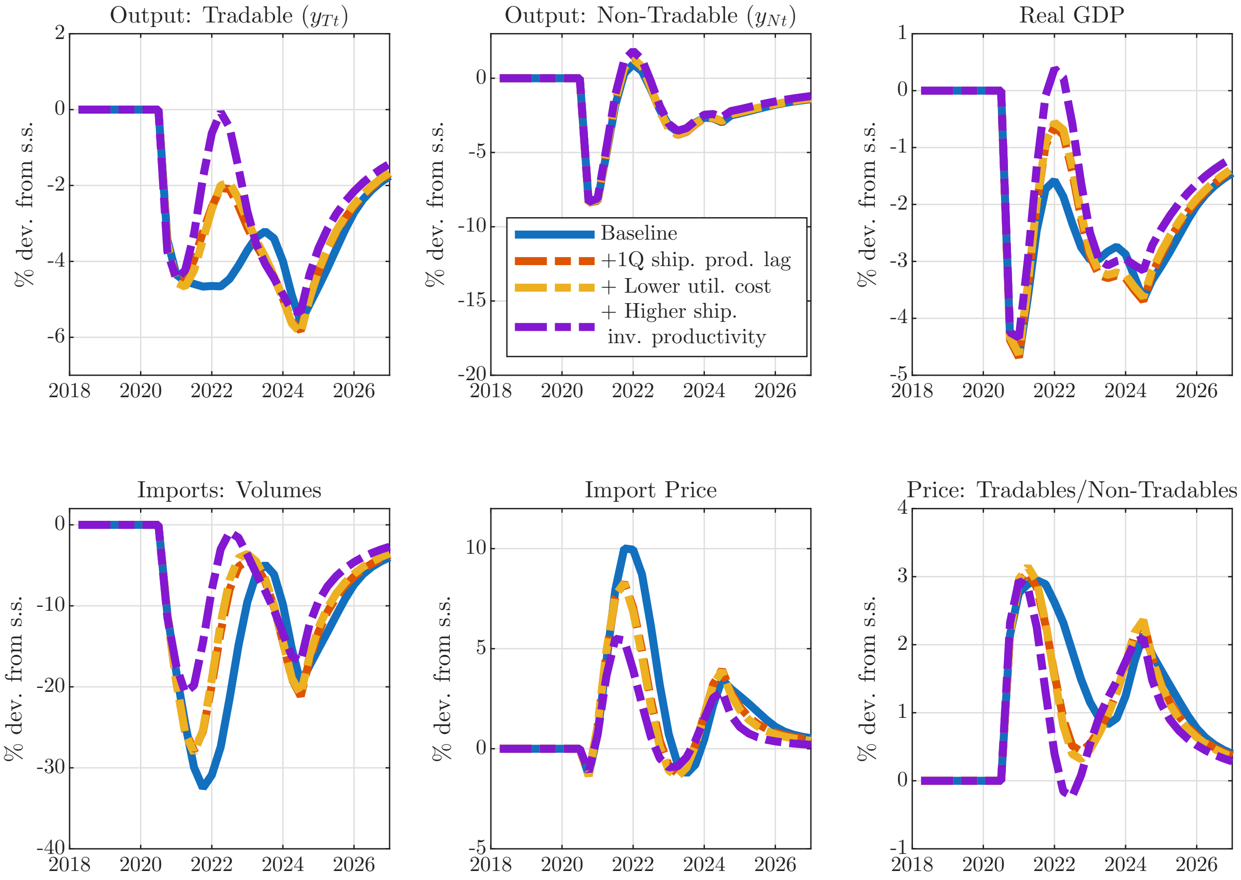


Note: In the data, variables are expressed as log deviations from a linear trend estimated over 2015–2019, except for the shipping investment rate, which is reported in level deviations from its pre-pandemic average. Model variables are expressed as log deviations from their steady state, except for shipping utilization and the shipping investment rate, which are reported in percentage-point deviations from their steady-state values. See Section 6.2 of the Appendix for definitions of variables not defined explicitly.

terioration in shipping efficiency leads to a sharp contraction of effective shipping supply despite increased utilization. In response to higher shipping costs, shipping investment rises significantly, but installed capacity adjusts gradually due to production lags. Utilization increases on impact and subsequently declines as efficiency recovers and new capacity becomes operational. These supply dynamics contribute to the sharp contraction in real trade, which gradually rebounds as shipping conditions normalize. The model captures the broad patterns observed in the data.

Aggregate implications. We now assess the role of shipping supply rigidities in shaping aggregate dynamics in the aftermath of the COVID-19 pandemic. To do so, we compare the baseline economy to a sequence of counterfactual economies that differ only in the flexibility of

Figure 8: Aggregate dynamics under alternative shipping technologies



Note: The figure reports aggregate dynamics implied by the baseline model and by a sequence of counterfactual shipping technologies. The counterfactuals are cumulative: the dashed red line corresponds to a one-period shipping production lag ($J = 1$); the dashed yellow line additionally halves the utilization cost parameter ϕ; and the dashed purple line further doubles the shipping investment productivity parameter a_G. All other parameters and shocks are held fixed. Variables are expressed as log deviations from their steady state. See Section 6.2 of the Appendix for definitions of variables not defined explicitly.

shipping supply. In each case, the estimated shocks and all non-shipping parameters are kept unchanged, allowing us to isolate the contribution of the shipping technology to aggregate fluctuations. Figure 8 reports the dynamics of key aggregate variables for the baseline as well as for each of the counterfactual economies that we consider.

In the baseline economy, the reduced shipping efficiency and the temporary decline in aggregate productivity generates a sharp contraction in tradable output and imports, despite the reallocation of demand toward tradables. With lower productivity and demand, non-tradable output also declines, resulting in a broad-based contraction across sectors and a fall in real GDP. The substantial increase of shipping costs leads to higher import prices and to an increase in the relative price of tradables to non-tradables. As shipping efficiency recovers and capacity adjusts, trade and output revert gradually.

We now contrast the aggregate dynamics of the baseline model to those under three alternative counterfactual shipping technologies. In the first counterfactual, the shipping production lag is shortened to one period, allowing installed capacity to respond more rapidly to changes in shipping demand. The second counterfactual combines the shorter production lag with lower shipping utilization costs, implemented by halving the utilization cost parameter ϕ, thereby increasing short-run flexibility along the intensive margin. The third counterfactual further raises the productivity of shipping investment, implemented by doubling the investment productivity parameter a_G, accelerating the expansion of effective shipping capacity along the extensive margin. These modifications are cumulative, with each successive counterfactual incorporating the previous adjustments to the shipping technology.

We find that, relative to the baseline, greater flexibility in shipping supply reduces the persistence of the contraction in tradable output, imports, and real GDP. Shortening the shipping production lag attenuates the initial decline and leads to a faster recovery. Further lowering utilization costs and increasing the productivity of shipping investment amplify this effect, yielding progressively smaller declines in trade and output across counterfactuals. These results show that if shipping capacity can adjust more rapidly, a smaller share of the aggregate adjustment occurs through higher import prices and contractions of trade and economic activity. Supply chain linkages play an important role in accounting for these findings, as we show in Section 8 of the Appendix, since greater shipping supply flexibility preserves firms' access to imported intermediate inputs and thereby attenuates the decline in production and real GDP.

These findings illustrate how shipping supply rigidities shape the propagation of shocks to aggregate economic activity. In particular, the persistence of the aggregate contraction following COVID-19 is closely tied to the disruptions and rigidities in shipping supply. Relaxing these rigidities attenuates the magnitude and duration of trade and output declines, underscoring the role of shipping technology as an important propagation channel for aggregate shocks.

Shock decomposition. We conclude by assessing the relative contribution of each shock to the dynamics of shipping costs and aggregate output. To do so, we solve the model by feeding each shock in isolation, holding the remaining shocks at their steady-state values, and compare the resulting equilibrium paths to those generated when all shocks operate jointly.[38] Figure 9 reports the implied paths of shipping costs and real GDP under each shock.

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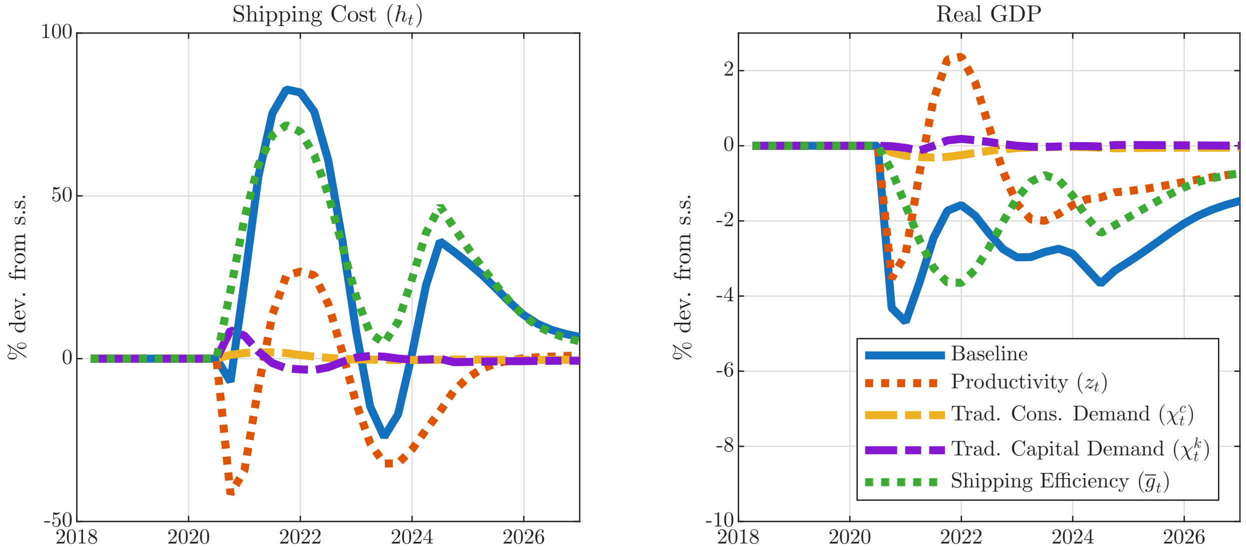
[38] Because the model is solved using a second-order approximation, the responses to individual shocks are not additive and their sum does not exactly reproduce the baseline dynamics. The decomposition is therefore intended to illustrate the relative importance and transmission channels of each shock rather than to provide an exact accounting identity.

Figure 9: Shock decomposition



Note: The figure reports model-implied dynamics of shipping costs and real GDP when each shock is fed into the model in isolation, holding all other shocks at their steady-state values. Variables are expressed as log deviations from their steady state. Because the model is solved at second order, the responses to individual shocks are not additive and do not sum to the baseline dynamics. See Section 6.2 of the Appendix for definitions of variables not defined explicitly.

The left panel of Figure 9 isolates the contribution of each shock to shipping cost dynamics. Shipping-efficiency shocks account for the bulk of both the surge and the persistence in shipping costs, generating a sharp and sustained increase that closely mirrors the baseline spike. Aggregate productivity shocks also impact shipping costs, particularly at the onset of the episode through their effect on shipping demand, but they do not lead to the large and persistent increase observed in the data. Tradable-demand shocks play a comparatively minor role. Overall, disruptions to effective shipping throughput emerge as the primary force underlying the exceptional dynamics of shipping costs during this period.

The right panel of Figure 9 reports the contribution of each shock to real GDP dynamics. Shipping-efficiency shocks generate a pronounced and persistent decline in output, accounting for most of the contraction observed in the baseline. Aggregate productivity shocks contribute to the initial decline in output at the onset of the pandemic, but support the subsequent recovery, particularly during 2021–2022, partially offsetting the effects of shipping disruptions. Tradable-demand shocks have a modest impact on aggregate activity.

Taken together, the decomposition clarifies the role of each shock on the dynamics following the onset of COVID-19. Shipping-efficiency disruptions are the primary driver of the surge in shipping costs and account for a substantial share of the output contraction, whereas aggregate productivity exerts an offsetting expansionary force, particularly during the recovery.

7 Concluding remarks

This paper studies the drivers and aggregate implications of global shipping dynamics. Motivated by salient features of container shipping that we document, we develop a dynamic model of international trade with an endogenous global shipping sector in which shipping costs, capacity utilization, and investment are jointly determined in equilibrium. We show that at business-cycle frequencies, fluctuations in shipping demand interact with gradual adjustments in shipping capacity to generate highly volatile shipping costs, dampening expansions by constraining shipping-intensive activity. We then use the estimated model to interpret the post-COVID period and show that transitory disruptions to shipping efficiency generate large and persistent increases in shipping costs with substantial effects on trade and aggregate output.

Taken together, our findings highlight the importance of explicitly modeling global shipping as an endogenous and dynamic component of the trading system. Accounting for the adjustment of shipping capacity, utilization, and efficiency is essential for understanding how shocks transmit through the global economy and for assessing the aggregate implications of shipping disruptions.

References

Albonico, A., S. Kalyvitis, and E. Pappa (2014): "Capital maintenance and depreciation over the business cycle," *Journal of Economic Dynamics and Control*, 39, 273–286.

Alessandria, G., S. Y. Khan, A. Khederlarian, C. Mix, and K. J. Ruhl (2023): "The Aggregate Effects of Global and Local Supply Chain Disruptions: 2020–2022," *Journal of international Economics*, 146.

Asturias, J. (2020): "Endogenous transportation costs," *European economic review*, 123, 103366.

Backus, D., P. Kehoe, and F. Kydland (1995): "International Business Cycles: Theory vs. Evidence," *Frontiers of Business Cycle Research.*

Bai, X., J. Fernández-Villaverde, Y. Li, and F. Zanetti (2024): "The causal effects of global supply chain disruptions on macroeconomic outcomes: evidence and theory," *Working paper.*

Behrens, K., C. Gaigné, G. I. Ottaviano, and J.-F. Thisse (2006): "How density economies in international transportation link the internal geography of trading partners," *Journal of Urban Economics*, 60, 248–263.

Behrens, K. and P. M. Picard (2011): "Transportation, freight rates, and economic geography," *Journal of International Economics*, 85, 280–291.

Bonadio, B., Z. Huo, A. A. Levchenko, and N. Pandalai-Nayar (2021): "Global Supply Chains in the Pandemic," *Journal of International Economics*, 133, 103534.

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

Carrière-Swallow, Y., P. Deb, D. Furceri, D. Jiménez, and J. D. Ostry (2023): "Shipping costs and inflation," *Journal of International Money and Finance*, 130, 102771.

Casas, F. R. (1983): "International trade with produced transport services," *Oxford Economic Papers*, 35, 89–109.

Cassing, J. H. (1978): "Transport costs in international trade theory: A comparison with the analysis of nontraded goods," *The Quarterly Journal of Economics*, 92, 535–550.

COMIN, D., R. C. JOHNSON, AND C. JONES (2024): "Import Constraints," *AEA Papers and Proceedings*, 114, 118–123.

COŞAR, A. K. AND B. DEMIR (2018): "Shipping inside the box: Containerization and trade," *Journal of International Economics*, 114, 331–345.

DI GIOVANNI, J., Ş. KALEMLI-ÖZCAN, A. SILVA, AND M. A. YILDIRIM (2022): "Global Supply Chain Pressures, International Trade, and Inflation," Working Paper 30240, National Bureau of Economic Research.

FALVEY, R. E. (1976): "Transport costs in the pure theory of international trade," *The Economic Journal*, 86, 536–550.

FINK, C., A. MATTOO, AND I. C. NEAGU (2002): "Trade in international maritime services: how much does policy matter?" *The World Bank Economic Review*, 16, 81–108.

GANAPATI, S., W. F. WONG, AND O. ZIV (2024): "Entrepôt: Hubs, Scale, and Trade Costs," *American Economic Journal: Macroeconomics*, 16, 239–278.

GREENWOOD, R. AND S. G. HANSON (2015): "Waves in ship prices and investment," *The Quarterly Journal of Economics*, 130, 55–109.

GUCI, L. AND C. I. MEAD (2014): "Domestic Trade in Services in Regional Input-Output Models," Working Paper WP2014-2, U.S. Bureau of Economic Analysis.

HAFNER, K. A., J. KLEINERT, AND J. SPIES (2022): "Endogenous transport costs and international trade," *The World Economy*.

HUMMELS, D. (2007): "Transportation costs and international trade in the second era of globalization," *Journal of Economic perspectives*, 21, 131–154.

HUMMELS, D., V. LUGOVSKYY, AND A. SKIBA (2009): "The trade reducing effects of market power in international shipping," *Journal of Development Economics*, 89, 84–97.

HUMMELS, D. AND A. SKIBA (2004): "Shipping the good apples out? An empirical confirmation of the Alchian-Allen conjecture," *Journal of political Economy*, 112, 1384–1402.

ISAACSON, M. AND H. RUBINTON (2023): "Shipping prices and import price inflation," *Federal Reserve Bank of St. Louis Review.*

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

LEIBOVICI, F. AND M. E. WAUGH (2019): "International trade and intertemporal substitution," *Journal of International Economics*, 117, 158–174.

LIMAO, N. AND A. J. VENABLES (2001): "Infrastructure, geographical disadvantage, transport costs, and trade," *The world bank economic review*, 15, 451–479.

LUDWIG, P. (2025): "Can Unilateral Policy Decarbonize Maritime Trade?" Tech. rep., CESifo Working Paper.

NOTTEBOOM, T., A. PALLIS, AND J.-P. RODRIGUE (2026): *Port Economics, Management and Policy*, New York: Routledge, 2nd ed., available at `https://porteconomicsmanagement.org`.

RAVN, M. O. AND E. MAZZENGA (2004): "International business cycles: the quantitative role of transportation costs," *Journal of International money and Finance*, 23, 645–671.

SCHMITT-GROHÉ, S. AND M. URIBE (2003): "Closing small open economy models," *Journal of international Economics*, 61, 163–185.

SIMONOVSKA, I. AND M. E. WAUGH (2014): "The elasticity of trade: Estimates and evidence," *Journal of international Economics*, 92, 34–50.

VALENTINYI, Á. AND B. HERRENDORF (2008): "Measuring factor income shares at the sectoral level," *Review of Economic Dynamics*, 11, 820–835.

WONG, W. F. (2022): "The round trip effect: Endogenous transport costs and international trade," *American Economic Journal: Applied Economics*, 14, 127–66.