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 successfully accounts for the dynamics of global shipping observed in the aftermath of COVID-19, at business cycle frequencies, and following shipping disruptions in the Red Sea. We find that accounting for global shipping is critical for 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 this industry during recent decades has been critical in supporting the growth of the global economy and the increased role of international trade. But despite its steady growth, the shipping industry is also highly cyclical and sensitive to changes in global economic activity, which lead to significant fluctuations of shipping supply, demand, and costs. In this paper, we ask: What accounts for global shipping dynamics and what are their aggregate implications? With shipping disruptions becoming increasingly prevalent, such as recent attacks to vessels in the Red Sea or due to the impact of COVID-19, the need to better understand global shipping dynamics and their implications is greater than ever.

In answering this question, we make five key contributions. First, we document novel evidence on the dynamics of global shipping supply, demand, and costs. Second, and motivated by this evidence, we develop a dynamic 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 shipping capacity affects global shipping and macroeconomic dynamics following shocks. Fourth, we use our model to quantify how well it accounts for global shipping dynamics following large shipping disruptions as well as at business cycle frequencies. Fifth, we use the model to quantitatively assess the implications of global shipping for aggregate macroeconomic dynamics.

Our findings provide insights to better understand the waves of global shipping: how to interpret fluctuations in shipping costs, evaluating their potential aggregate implications. We document that shipping supply is rigid in the short-run, as investments in increased shipping capacity take time and the global containership fleet typically operates close to capacity. Thus, we show that shipping cost fluctuations are highly correlated with fluctuations of excess demand for shipping capacity, which are primarily accounted for by changes in demand rather than supply. We then show that modeling the market for global shipping featuring time-intensive shipping investments and high capacity utilization can largely account for the observed dynamics of global shipping supply and costs. In particular, the value of shipping costs relative to imports is critical in accounting for the size of the shipping cost change required to balance shipping demand and supply. Moreover, we show that global shipping dynamics have a significant impact on aggregate outcomes via supply chain linkages, as the constrained short-run access to tradable goods impacts firms that rely on international trade to access intermediate inputs.

We begin the paper by documenting novel features of the dynamics of the global shipping industry. We focus on containerships given their critical role in the international trade of goods.[2] We first document that international shipping supply has grown steadily in recent decades and that the global fleet is typically used at near-full capacity along both the extensive (ships in operation and their associated capacity) and intensive (degree to which ships are loaded) margins. We find that fluctuations of shipping demand have been much more significant than those of shipping supply, and the difference is tightly associated with changes in international shipping costs. We also observe that periods of high shipping costs increase the earnings of shipping companies, leading them to increase orders for new containerships. But these investments take time to materialize: We document that the production of new containerships is very time-intensive, with a lag of around three years for large ships.

Motivated by these observations, we construct a dynamic general equilibrium model of international trade with input-output linkages and an endogenous demand and supply for global shipping services. Our model features importing firms and a global shipping company. The importing firms buy goods from other countries subject to per-unit international shipping costs in addition to standard ad-valorem iceberg trade costs. The shipping company owns the global stock of ships and rationally chooses investments to adjust shipping capacity and maximize profits. Thus, the global shipping company can adjust shipping capacity by ordering new ships, but as we observe in the data, doing so takes time. The shipping company can also adjust effective capacity by changing the rate at which the installed capacity is used. International shipping costs are the equilibrium price that clears the market for global shipping services, equating shipping demand with supply.

We analytically characterize the key determinants of import demand, shipping costs, capacity utilization, and shipping investment. First, we show that shipping costs affect the demand for imports differently than standard iceberg trade costs given shipping costs are per-unit rather than ad-valorem. Second, we show that the per-unit nature of shipping costs is critical in determining how shipping costs respond to shocks, such as an increase in the demand for tradable goods. We show analytically that equilibrium shipping costs are determined by the trade elasticity and by the ratio of shipping costs to total import costs. Third, we characterize how the global shipping firm adjusts capacity utilization and shipping investment following shocks.

We study how well the model accounts for the dynamics of global shipping and

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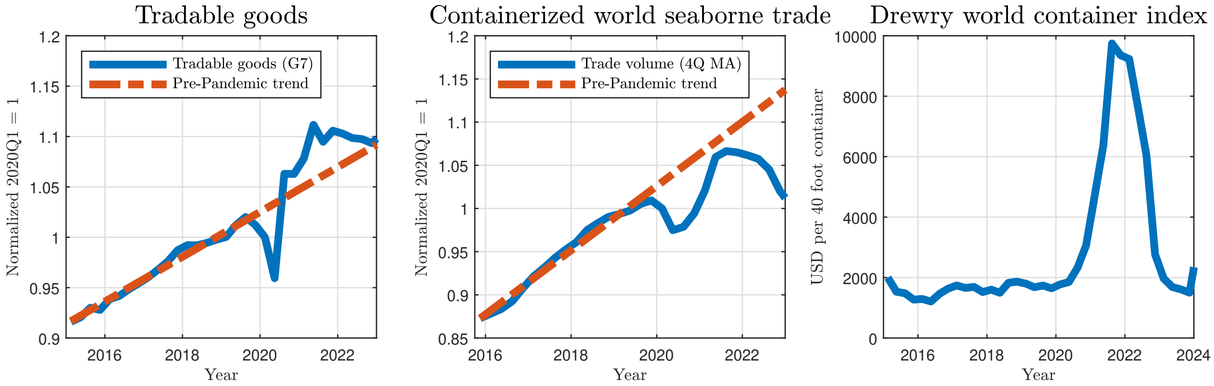
[2] As of 2020, seaborne trade accounted for 80% of total international trade, with containerships transporting 60% of the total value of seaborne trade (Heiland and Ulltveit-Moe 2020).

Figure 1: Global shipping dynamics following COVID-19



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

quantify their aggregate implications during the aftermath of the COVID-19 recession, at business cycle frequencies, and following shipping disruptions in the Red Sea. We begin by focusing on the unprecedented disruptions of global shipping following COVID-19. During this period, the world economy experienced a sizable increase in the demand for tradable goods relative to the pre-pandemic trend. (The left panel of Figure 1 illustrates this with data for G7 countries.) This resulted from the reallocation of demand from contact-intensive services toward tradable goods, mitigating exposure to the disease, and was further amplified by fiscal transfers aimed at mitigating the economic impact of the pandemic. Despite this unprecedented demand for tradables, we observe that the effective supply of shipping capacity contracted during this period, likely as a result of COVID-19 containment measures. This can be observed in the middle panel of Figure 1, which shows that the volume of trade has remained below trend ever since the start of the pandemic. Finally, we observe that global shipping costs experienced an unprecedented increase during this period. For instance, the right panel of Figure 1 shows that the Drewry World Container Index, an index of global shipping costs across major routes, increased from less than $2,000 per 40 foot container to almost $10,000 at the peak.

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

We find that our model successfully accounts for salient features of the dynamics of global shipping observed in the aftermath of COVID-19. The increased demand for tradables along with the reduced and inelastic supply of shipping services lead to a reduction of international trade along with a sizable increase of shipping costs, as the limited capacity is rationed across the increased demand for shipping. We find that the model accounts for 77% of the peak increase of shipping costs observed in the data while also exhibiting a substantial reversal when the shocks subside. Moreover, we find that the model implies dynamics of shipping capacity production that are in line with the data.

We then investigate the extent to which global shipping dynamics affect the aggregate implications of the shocks. To do so, we contrast the implications of our model with those of an otherwise identical counterfactual economy with a perfectly elastic supply of shipping capacity, as implicit in standard models of international trade and international business cycles. We find that the differences in the shipping technology across the two models have important aggregate implications. For instance, real GDP decreases significantly more in the baseline than in the model with perfectly elastic shipping supply — the decline is 2.5 times larger at the trough in the former than in the latter. Similarly, we find significant quantitative differences in the dynamics of tradable output and international trade flows.

We examine the key channels of the model that account for our various findings. We first study the relative role played by each of the shocks by examining their effect in isolation. We then study the role of various features of the global shipping technology as well as of the macroeconomic environment in which it operates. We identify key parameters that control the size of the shipping cost response as well as its persistence. Moreover, we find supply chains as captured by input-output linkages are critical in accounting for the aggregate implications of global shipping dynamics.

Given the shocks and dynamics following COVID-19 are rare and unprecedented, we then investigate the implications of our findings for the dynamics of global shipping and macro dynamics during normal times. We are motivated by the observation that global shipping costs are also very volatile over the business cycle, as illustrated in Figure 2. Note, in particular, that global shipping costs are significantly more volatile than global imports, which are already significantly more volatile than variables like GDP. Thus, we examine whether our model can account for these dynamics and study their aggregate implications. Following previous studies, we capture business cycle fluctuations by introducing shocks to productivity and time-varying trade costs, and we re-estimate it to target moments that capture salient features of the cross-section and dynamics.

Figure 2: Global shipping cost fluctuations over the business cycle

Note: Data from OECDstat and Drewry Supply Chain Advisors. Both series are Hodrick-Prescott filtered (in logs) with smoothing parameter 1600.

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

To conclude the analysis, we investigate the global impact of regional shipping disruptions by studying the 2023/2024 attacks on vessels in the Red Sea. We quantify the effects of these disruptions on global shipping and macro dynamics using our estimated model. We find that the model accounts for salient features of global shipping dynamics during this episode. We find that although 12% of global trade is shipped through the Red Sea, the rerouting of vessels due to the attacks has a significant impact on global shipping costs and trade volumes, as observed in the data. The model implies a significant contraction in global trade and GDP, illustrating how shipping disruptions can propagate through the global economy. We then use the model to evaluate the potential implications of periodic shipping disruptions of this nature on business cycle fluctuations. We show that if disruptions of the size and persistence observed in the Red Sea become a frequent occurrence due to rising geopolitical tensions, they could lead to a significant increase in business cycle volatility.

Our findings point to the importance of improving our understanding of the drivers and implications of global shipping in international trade. Our paper belongs to a growing literature studying models of the market for global shipping services to understand salient features of this market observed in the data (Ganapati et al. 2024; Brancaccio et al. 2020; Greenwood and Hanson 2015; Kalouptsidi 2014). Our work contributes to this literature by documenting novel evidence on the dynamics of global shipping, and using a general equilibrium model of international trade with an endogenous market for global shipping services to interpret the dynamics observed in the data and to study their macroeconomic implications.

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 a recent overview of developments in international shipping over recent decades.[3]

Moreover, our work also contributes to a growing literature that studies the aggregate implications of supply chain disruptions in the aftermath of COVID-19 (Bai et al. 2024; Comin et al. 2024; Alessandria et al. 2023; among many others).[4] Relative to much of this literature, our key contribution is to investigate the role of global shipping during this period using a model featuring a market where both shipping global shipping demand and supply are determined endogenously. Our findings are complemented by recent empirical studies that investigate the aggregate implications of the unprecedented increase of ship-

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

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

ping costs during this period on inflation (Isaacson and Rubinton 2023; Carrière-Swallow et al. 2023).

The rest of the paper is organized as follows. Section 2 documents salient features of the global shipping industry. Section 3 develops a dynamic model of international trade with endogenous shipping supply. Section 4 characterizes how shipping affects import demand and global shipping dynamics. Sections 5 to 7 present our quantitative analysis of shipping and aggregate dynamics in the aftermath of COVID-19, over the business cycle, and following shipping disruptions in the Red Sea and beyond, respectively. Section 8 concludes.

2 Salient features of global shipping

In this section, we document salient features of the market for global shipping services. The goals of this section are twofold. On the one hand, our goal is to identify key features of how this market operates to guide the theoretical analysis of the following sections. On the other hand, the evidence that we document allows us to discipline and evaluate the extent to which the model that we develop in the following section can successfully account for key features of global shipping dynamics.

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 examine the dynamics of global shipping costs, documenting the extent to which they co-move with fluctuations in global economic activity. Third, we investigate the determinants of investments in shipping capacity and document the time lags involved to expand it. Our focus throughout is on the shipment of goods via containerships given its large share of global trade.

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

2.1 Shipping capacity

We begin with global shipping capacity. Panel A of Figure 3 reports the evolution of global shipping capacity over time. We focus on two measures: the total number of containerships (orange dashed line) and the corresponding volume these ships can carry (blue solid line), which is measured in Twenty-Foot Equivalents Units (TEUs). We find that the total size of the global containership fleet has grown steadily over the past 15 years, particularly for the volumetric capacity of the fleet (TEUs). This suggests the growth of global shipping supply is fairly independent of short-run shocks.

Panel B of Figure 3 reports level and dynamics of the global containership fleet's capacity utilization along the extensive and intensive margins. The extensive margin is defined as the fraction of the total fleet that is non-idle in a given year, expressed in terms of the number of ships and in TEUs — this statistic is computed as the annual average of a daily measure of idle containerships.[5] The intensive margin is defined as the ratio of traded TEUs relative to the fleet's total capacity of available TEUs. We find that the global containership fleet operates close to maximum capacity at all times. Since 2014, the fraction of ships in use, measured in TEUs, has averaged over 96%. Additionally these ships are consistently operating with over 90% of their crates filled. This suggests that, in the short run, the containership shipping industry has limited room to increase shipping supply to address fluctuations in demand. Thus, in the short run, fluctuations in demand are instead likely to be accommodated via fluctuations in shipping costs.

2.2 Shipping demand, supply, and costs

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

Standard demand and supply logic suggests that fluctuations in the degree of excess demand for global shipping services are likely to be positively correlated with shipping costs. That is, in periods in which the growth of demand for global shipping services exceeds the growth of global shipping supply, we are likely to observe higher increases in global shipping costs. Panel D of Figure 3 shows that this is indeed the case: Excess

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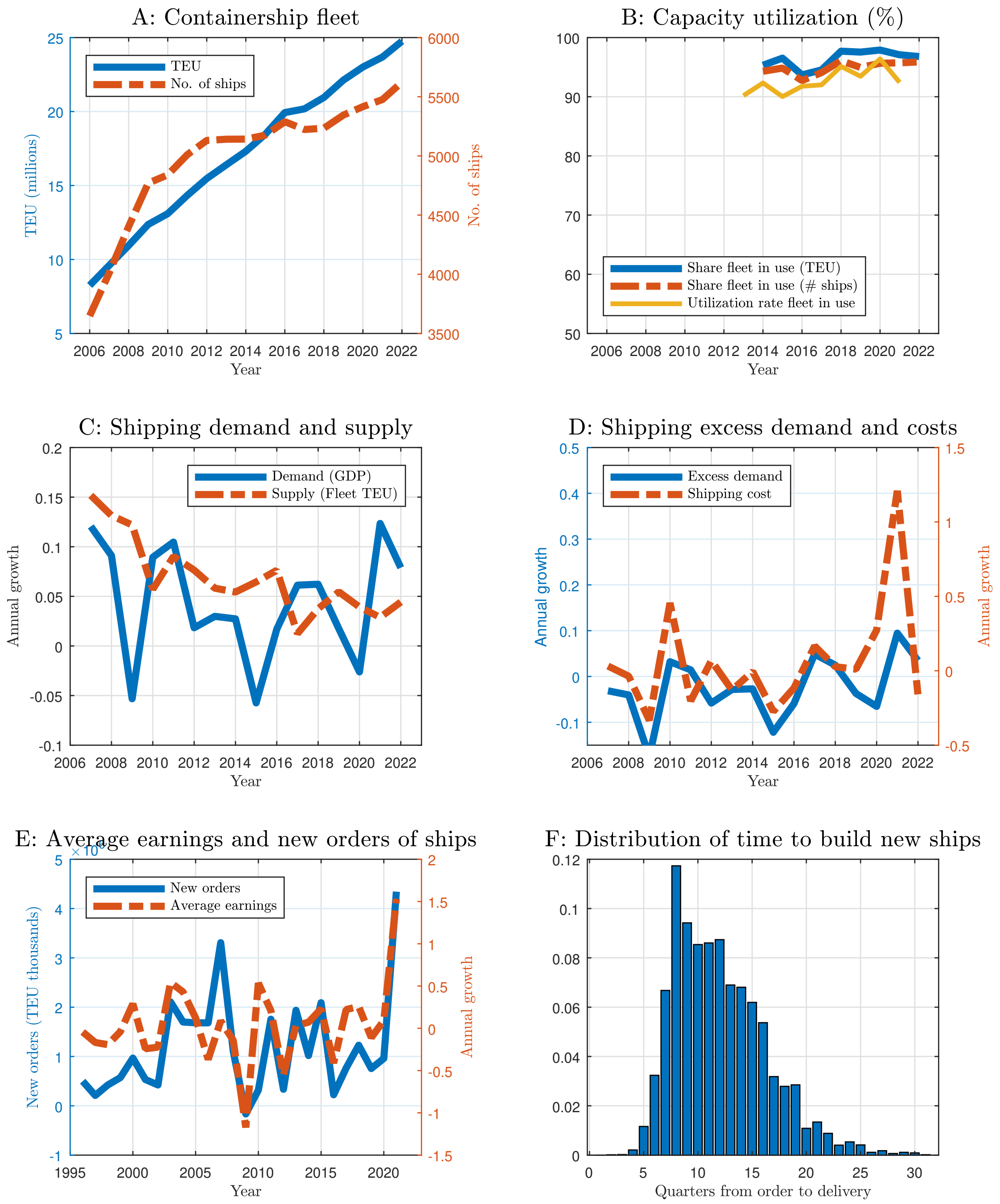
[5] Idle status is applied to containerships not recorded with an average speed $>$ 1 knot for at least 7 days, not identified as subject to another status (e.g. laid-up, under repair, storage or similar), and not subsequently recorded with an average speed $>$ 1 knot for 2 or more consecutive days or not having moved more than 20 km. The time series is based on daily data and aggregated to annual frequency.

Figure 3: Shipping industry dynamics



Note: Data from Clarkson's *Shipping Intelligence Network*, the International Monetary Fund's *World Economic Outlook*, and Alphaliner Shipping Solutions

demand for shipping tracks closely with shipping costs, with the annual growth of these variables featuring a correlation of 0.65 from 2006 to 2022 using annual data. Note that this logic holds both during periods of excess demand as well as during periods of excess supply of shipping services: in the latter case, we observe declines in global shipping costs.

2.3 Shipping investment

Finally, we turn to investigating the dynamics and determinants of investments in shipping capacity. Panel E of Figure 3 reports new orders of containerships over time (measured in TEUs) alongside the annual growth of average containership earnings.[6] We observe that investments in containerships track average containership earnings closely, with a correlation of 0.68. One interpretation is that, as fluctuations of excess demand lead to changes in shipping costs, average containership earnings are also affected. At the same time, shipping companies invest in new ships to take advantage of these higher earnings, placing orders to increase future shipping capacity.

But these investments in future shipping capacity take time. Panel F of Figure 3 shows a histogram with the distribution of ship production times by number of quarters, taken from a snapshot of the total containership fleet in 2023. We observe that it typically takes 2-4 years (8-16 quarters) to finish ship construction. Then, while these orders are made contemporaneously to cost changes, the ships take a few years to be built before they become operational. Once these ships finally enter the market, they are likely to ease the level of excess demand and subsequently lower shipping costs.

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

3 Model

In this section, we set up a model of international trade with an endogenous market for global shipping services to investigate the underlying channels accounting for the dynamics observed in the data and their aggregate implications. Motivated by the evidence documented above, we model global shipping consistent with the following features: (*i*) shipping costs result from the interaction between shipping demand and supply, (*ii*) ships available are typically always operational with limited spare capacity, constraining the potential to adjust shipping supply in the short run, and (*iii*) shipping capacity responds sluggishly to changes in shipping costs since shipping investments take time.

We study a world economy with two countries: home and foreign. Each country is populated by a representative household, as well as by four types of firms: a producer of domestic tradable varieties, a producer of non-tradable varieties, a producer of a bundle

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

of intermediate inputs, and a producer of a bundle of final goods. Tradable varieties from each country are traded internationally, and there is also trade in financial assets. Finally, the world economy is populated by a global shipping firm that provides shipping services to all countries.

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

3.1 Household

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

Households are endowed with a unit of time, which they allocate between work and leisure, and begin each period owning a given amount of physical capital k_t. Households earn labor income from supplying n_t units of labor at wage rate w_t and earn capital rental income r_{Kt} from renting out the physical capital used for production by firms. In addition, households earn dividends from owning the various firms in the economy. In particular, they are sole owners of the various domestic producers, and they own a fraction ψ of the shares of the global shipping firm.[7]

Households accumulate physical capital internally by investing i_t units of final goods subject to a quadratic investment adjustment cost. Given capital depreciates at rate δ, the evolution of the aggregate capital stock consists of:

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

where Φ_k is a constant that controls the cost of choosing investment levels different from the steady-state. Given this formulation, i_t denotes gross investment used to pay for both the increase in physical capital and the investment adjustment costs.

Households have access to international financial markets, where they can trade a one-period risk-free bond vis-a-vis households in the other country subject to bond-holding costs. The bond is denominated in units of home final goods and trades at interest rate

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

r_t. Following Schmitt-Grohé and Uribe (2003), households' bond-holding choices b_{t+1} in period t are subject to a quadratic bond-holding cost given by $\frac{\Phi_b}{2}\left(b_{t+1}-\bar{b}\right)^2$, where Φ_b controls the cost of holding bond levels different from steady-state bond-holdings $\bar{b}$.

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

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

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

The household's problem is then given by:

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

subject to

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

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

k_0 and b_0 given,

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

3.2 Producers of domestic tradable varieties

A representative firm produces domestic tradable varieties with a constant returns-to-scale Cobb-Douglas technology using capital k_{Tt}, labor n_{Tt}, and intermediate inputs m_{Tt}, with time-invariant sector-specific productivity a_T and time-varying aggregate productivity z_t. The production function is then given by:

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

where y_{Tt} denotes the amount of domestic tradable varieties produced, θ controls the capital share, and φ controls the contribution of intermediates to gross output.

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

$$\begin{aligned}
&\max_{k_{Tt},n_{Tt},m_{Tt}} \pi_{Tt} = p_{Tt}y_{Tt} - w_t n_{Tt} - r_{Kt}k_{Tt} - p_{Mt}m_{Tt} \\
&\text{subject to} \\
&y_{Tt} = z_t a_T \left(k_{Tt}^{\theta} n_{Tt}^{1-\theta}\right)^{\varphi} m_{Tt}^{1-\varphi},
\end{aligned}$$

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

3.3 Producers of non-tradable varieties

A representative firm produces non-tradable varieties by operating a linear technology using labor n_{Nt} with time-invariant sector-specific productivity a_N and time-varying aggregate productivity z_t. The production function is then given by:

$$y_{Nt} = z_t a_N n_{Nt},$$

where y_{Nt} denotes the amount of non-tradables produced.

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

$$\begin{aligned}
&\max_{n_{Nt}} \pi_{Nt} = p_{Nt}y_{Nt} - w_t n_{Nt} \\
&\text{subject to} \\
&y_{Nt} = z_t a_N n_{Nt}.
\end{aligned}$$

3.4 Producers of intermediate goods

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

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

where the parameter ζ controls the relative importance of domestic and foreign intermediates, and the elasticity of substitution between these two types of tradable varieties is given by $\nu > 0$.[8]

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

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

subject to

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

3.5 Producers of final goods

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

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

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

where the parameter χ controls the relative importance of the two goods for the aggregate absorption bundle, and η denotes the elasticity of substitution between tradable and non-tradable goods.[9]

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

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

where q_{Tt}^h and q_{Tt}^f denote domestic and foreign purchases of tradable varieties, respectively.

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[8] If the elasticity of substitution ν is equal to one, then the production technology is Cobb-Douglas, with exponents given by ζ and $1-\zeta$.

[9] If the elasticity of substitution η is equal to one, then the production technology is Cobb-Douglas, with exponents given by χ and $1-\chi$.

The elasticity of substitution between these two types of tradable varieties is given by $\rho > 0$.

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

$$\begin{aligned}
&\max_{y_t, q^h_{Tt}, q^f_{Tt}, q_{Tt}, q_{Nt}} \quad \pi_t = p_t y_t - p_{Tt} q^h_{Tt} - (\tau p^*_{Tt} + h_t) q^f_{Tt} - p_{Nt} q_{Nt} \\
&\text{subject to} \\
&y_t = \left[\chi q_{Tt}^{\frac{\eta-1}{\eta}} + (1-\chi) q_{Nt}^{\frac{\eta-1}{\eta}} \right]^{\frac{\eta}{\eta-1}} \\
&q_{Tt} = \left[q^{h\;\frac{\rho-1}{\rho}}_{Tt} + q^{f\;\frac{\rho-1}{\rho}}_{Tt} \right]^{\frac{\rho}{\rho-1}}.
\end{aligned}$$

3.6 Global shipping firm

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

Consider the start of some given time period t. The global shipping firm begins the period with ownership of 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 to producers of intermediate and final goods from each country at cost h_t per unit shipped. That is, producers of tradable goods need to pay shipping cost h_t per unit of tradable variety purchased internationally, on top of the underlying price of these goods and iceberg trade costs.

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

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

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

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

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

While installed shipping capacity g_t cannot be adjusted within a given period, the global shipping firm can invest to adjust shipping capacity in the future. However, producing new ships takes time, as documented in Section 2. Thus, we assume that investments in new ships i_{Gt} in period t increase shipping capacity by $a_G i_{Gt}$ units in period $t + J$, where $J \geq 1$ denotes the shipping production lag and a_G controls the productivity of shipping investments. Shipping capacity depreciates at rate $\delta_G(\upsilon_t)$, as described above. Thus, shipping capacity evolves according to the following law of motion:

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

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

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

$$\max_{\{g_{t+1}, \upsilon_t, i_{Gt}\}} \mathbb{E}_0 \sum_{t=1}^{\infty} m_t \left\{ h_t \upsilon_t \bar{g} g_t - \left[p_t \psi + (1-\psi) p_t^*\right] i_{Gt} - \left[p_t \psi + (1-\psi) p_t^*\right] \frac{\Phi_G}{2} \left(i_{Gt} - \bar{i}_G\right)^2 \right\}$$

subject to

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

$g_{t+1} \geq 0$

g_0 given,

where m_t denotes the stochastic discount factor of the owners of the global shipping firm, g_0 denotes the initial level of shipping capacity, and the second constraint requires shipping capacity to be positive. In particular, we define m_t as the weighted average between the stochastic discount factor of the domestic and foreign households, with weights given by the relative ownership shares.

3.7 Equilibrium

We let the price of final goods in the home country p_t be the numeraire. Then, a *competitive equilibrium of the world economy* consists of prices, home allocations, foreign allocations, and global shipping allocations such that the following conditions hold in every period t:

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

11. Intermediate goods clear: $m_{Tt} = m_t$
12. Final goods clear:

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

- Foreign country:

1. Given prices, allocations solve household problem
2. Given prices, allocations solve problem of producers of tradable varieties
3. Given prices, allocations solve problem of producers of non-tradable varieties
4. Given prices, allocations solve problem of producers of intermediate goods
5. Given prices, allocations solve problem of producers of final goods
6. Profits from producers rebated to households: $\Pi^*_t = \pi^*_t + \pi^*_{Mt} + \pi^*_{Tt} + \pi^*_{Nt}$
7. Labor market clears: $n^*_{Tt} + n^*_{Nt} = n^*_t$
8. Capital market clears: $k^*_{Tt} = k^*_t$
9. Tradable varieties clear: $y_{Tt}{}^* = \tau q^f_{Tt} + q^{f*}_{Tt} + \tau m^f_t + m^{f*}_t$
10. Non-tradable varieties clear: $y^*_{Nt} = q^*_{Nt}$
11. Intermediate goods clear: $m^*_{Tt} = m^*_t$
12. Final goods clear:

$$y^*_t = c^*_t + i^*_t + (1-\psi) i_{Gt} + \frac{\Phi_b}{2}\left(b^*_{t+1} - \bar{b}^*\right)^2 + (1-\psi)\frac{\Phi_G}{2}\left(i_{Gt} - \bar{i}_G\right)^2$$

- Global shipping:

1. Given prices, allocations solve problem of global shipping firm
2. Shipping services clear: $q^f_{Tt} + q^{h*}_{Tt} + m^f_t + m^{h*}_t = \upsilon_t \bar{g} g_t$

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

4 Mechanism: How shipping affects equilibrium outcomes

In this section, we study the key channels through which shipping affects equilibrium outcomes in our model. We first show how shipping affects the demand for imports. Then, we study how shocks affect equilibrium imports and shipping costs, as well as global shipping dynamics. To sharpen the analysis, we consider one specific shock: An increase in the demand for tradable goods. However, the forces and channels that we study are more generally at play. As in the previous section, while we focus our discussions on the home country, the analyses and forces are symmetric for the foreign country.

4.1 Import demand

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

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

where Imports_t denotes the total imported tradable varieties purchased in period t (that is, $q^f_{Tt} + m^f_t$), and $\widetilde{p_{Tt}}$ denotes the implicit ideal price index for tradable goods.[10] The first term denotes imports used to produce final goods, while the second term denotes imports used to produce intermediate goods. As in standard models of international trade with a constant elasticity of substitution demand for imports, we observe that imports are increasing in total demand for both final goods and intermediates, and decreasing in both the price of imports and the value of iceberg trade costs.

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

Note also that, insofar as $\rho \neq \nu$, the elasticity of imports to changes in shipping costs differs between final and intermediate goods. Thus, for instance, higher shipping costs lead to lower imports across the board, but with less significant import declines in those uses that are more inelastic.

4.2 Increase in demand for tradables

To study how shipping costs, imports, and global shipping dynamics respond to shocks, we consider a shock that increases the demand for tradable final goods q_{Tt}. This is a key force in two of the quantitative exercises that we study in the following sections. In Section 5, we characterize the aftermath of COVID-19 in part through a shock that

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

increases the demand for q_{Tt}. Moreover, cyclical fluctuations in the demand for tradable final goods are a standard feature of business cycle fluctuations, as we study in Section 6.

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

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

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

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

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

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

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

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

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

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

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

The left-hand side is the marginal return to increasing shipping utilization today — earning price h_t on the marginal unit of shipping capacity. The right-hand side is the marginal cost — a higher depreciation of ships, which reduces shipping capacity from next period onwards. Given shipping capacity is durable, the reduced shipping capacity affects earnings in every subsequent period. These costs are discounted back to the present by the stochastic discount factor $\beta^k\frac{\lambda_{t+k}(s_{t+k})}{\lambda_t}$.

An increase in h_t today makes the return to utilization higher, as the firm earns more for each unit of capacity. But the shipping firm understands this comes at the expense of having less capacity to earn revenue with in the future. The more transitory the increase in h_t is expected to be, the more the firm is willing to sacrifice future capacity to earn high returns today. The term $\delta_G'(\upsilon_t)$ governs how changes in utilization affect the depreciation rate — with a very convex depreciation function, utilization will respond gradually to smooth out the intertemporal tradeoff. But with nearly-constant marginal depreciation costs, utilization will adjust sharply in line with shipping cost changes.

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

$$\underbrace{\mathbb{E}_t \sum_{k=J}^{\infty} \left[\beta^k \frac{\lambda_{t+k}}{\lambda_t} a_G \left[1 - \delta_G(\upsilon_{t+k})\right]^{k-J} h_{t+k} \upsilon_{t+k} \right]}_{\text{Returns from selling shipping services}} = \underbrace{\left[p_t \psi + (1-\psi) p_t^*\right] \left\{ 1 + \Phi_G \left[i_{Gt} - \frac{\delta_G(\overline{\upsilon})}{a_G} \right] \right\}}_{\text{Investment cost}}$$

The left-hand side is the lifetime expected stream of discounted marginal revenue products from investing in a marginal unit of capacity today. In period $t + J$, J periods after the investment, the increased shipping capacity begins to operate and earns a per-period rate of $h_{t+J} \upsilon_{t+J}$, which is the shipping cost h_{t+J} adjusted by the prevailing utilization rate. In each subsequent period, the revenue earned per unit of the new ship is reduced by depreciation due to ageing and utilization.

The right-hand side is the marginal cost of investing in shipping capacity today, which depends on the price of domestic and foreign final goods used for investment, as well as on the shipping adjustment cost that is increasing in investment relative to the steady-state level.

This condition reveals two key determinants of the shipping investment response to a demand shock. First, it depends on the expected path of discounted marginal products $h_{t+k} \upsilon_{t+k}$ from period $t + J$ onwards. If the elevated demand and shipping costs are expected to be short-lived, dissipating before the J-period time-to-build lag, then there will be little incentive to invest, because the increased capacity will enter service in an environment where the marginal product has returned to normal. The more persistent the shift in demand is expected to be, the more investment will rise today to earn the elevated returns.

Second, the response will be tempered by the adjustment costs Φ_G. With $\Phi_G = 0$, investment each period would simply track the expected discounted marginal product at $t + J$. But a positive Φ_G means that large period-to-period changes in investment are costly, so firms will prefer to smooth out their investment over time. Higher values of Φ_G imply a more gradual investment ramp-up, even for highly persistent demand shocks.

4.3 Aggregate implications

The combination of the inelastic short-run shipping supply with imperfect substitution across the various goods can have significant aggregate implications when the economy faces a positive tradable demand shock.

The aggregate impact is likely to depend on the magnitude and persistence of the demand shock and the substitution elasticities. Larger, more persistent shocks are likely to induce more sizable responses in shipping costs, trade, and output. Lower elasticities of substitution, either between domestic and foreign inputs (ν and ρ) or between tradables and non-tradables (η), amplify the costs by limiting the economy's flexibility to adjust absorption patterns to overcome rigidities in shipping supply.

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

5 Quantitative analysis: Dynamics following COVID-19

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

We use this framework to address two key questions. First: To what extent can the reallocation of demand toward tradable goods and the contraction of shipping supply account for the dynamics of global shipping observed in the aftermath of COVID-19? Second, we ask: What are the implications of global shipping dynamics for aggregate outcomes?

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

5.1 Experiment

To study the dynamics following COVID-19, we consider the following experiment. We assume the economy is in steady-state prior to the pandemic and that it experiences two unexpected shocks to the economic environment in the third quarter of 2020.[11] On the one hand, the economy experiences an increase in the demand for tradable goods. On the other hand, the economy experiences a contraction in the effective shipping capacity. We model these as an increase in the share χ of tradables in the production of final goods, along with a decrease of $\overline{g}$ that reduces effective shipping capacity $\upsilon_t \overline{g} g_t$.

We assume these shocks are persistent but transitory, with χ increasing to χ_H and $\overline{g}$ decreasing to $\overline{g}_L$ for 8 quarters, reverting back linearly to their original values over the course of the following 8 quarters. We let period 0 denote the initial steady state and assume that the full path of shocks is observed in period 1.

5.2 Parameterization

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

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

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

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

tradables and non-tradables, as well as domestic and imported tradable intermediates, be complementary.[12]

To parametrize the share of tradables χ in the production of final goods and the share of intermediate inputs φ in the production of tradable goods, we begin by classifying goods as tradable and non-tradable. We define tradable goods as those classified as goods in the BEA's expenditure-based GDP tables. Non-tradable goods are defined as those classified as services in the BEA tables. Based on these data, we compute the fraction of aggregate absorption accounted by these types of goods, and we set χ to 0.31 and φ to 0.58.

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

Finally, we normalize the productivity of producers of tradable varieties a_T and the productivity of producers of non-tradable goods a_N to unity. We focus on an economy with integrated financial markets, where bond-holding costs Φ_b are set to 0. We set $\overline{g}g_t$ to unity, and given our focus on symmetric countries, we set the share of the shipping firm ψ owned by households in the home country to 0.50.

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

We choose these parameters to ensure that the steady state of our model captures the following features of the U.S. economy in 2019, prior to the onset of COVID-19: (*i*) the imports-to-absorption ratio in tradable goods, (*ii*) the imports-to-absorption ratio in tradable intermediates, and (*iii*) the shipping costs-to-imports ratio. We compute empirical counterparts to moment (*i*) using data from the BEA, classifying goods into tradable and non-tradable as described above. For moment (*ii*), we use data from the BEA to target the share of intermediate inputs that are imported across manufacturing industries. For moment (*iii*), we target the ratio of shipping costs to imports that we estimate using U.S. Census data from Schott (2008).

The estimated parameters as well as the empirical targets and their model counterparts are reported in Table 2. We find that the three estimated parameters can be chosen to exactly match the three targets. Trade costs τ determine the extent to which tradable

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

Table 1: Predetermined parameters

Parameter	Value	Description
β	0.99	Discount factor
$1/\gamma$	0.5	Intertemporal elasticity of substitution
μ	0.34	Consumption share in household utility
δ	0.025	Capital depreciation rate
θ	0.36	Tradable varieties: Share of capital in gross output
φ	0.58	Tradable varieties: Share of intermediates in gross output
ν	1	Intermediates: Elasticity between domestic and imported
η	1	Final goods: Elasticity tradable and non-tradables
ρ	1.50	Final goods: Elasticity between domestic and imported
χ	0.31	Final goods: Share of tradables
J	6	Shipping production lag

final goods are imported. Similarly, the weight ζ on imports of tradable intermediates determines the share of imported intermediate inputs. Finally, the magnitude of shipping costs in imports in the steady-state is determined by shipping investment productivity a_G.

Parameters estimated to match dynamics following COVID-19 We estimate the remaining parameters to match salient features of the dynamics following the onset of COVID-19: the higher weight χ_H of tradables in final goods following the pandemic, the negative shock $\overline{g}_L$ to effective shipping supply following the pandemic, the investment adjustment cost Φ_k, the shipping adjustment cost Φ_G, and the shipping utilization cost ξ. In addition, we also estimate the shipping utilization shifter $\overline{v}$ and the shipping capacity depreciation parameter $\overline{\delta}_G$. While we estimate these to capture salient features of the data prior to the pandemic, we do so jointly with the dynamic targets given their implications are jointly determined with ξ.

We estimate the first five parameters to match the following features of the data after the onset of COVID-19 relative to pre-pandemic levels: (i) the growth of tradable absorption in the U.S., (ii) the decline of global effective shipping supply, (iii) the growth of capital investment in the U.S, (iv) the global change in the shipping investment rate, and (v) the global change of the shipping capacity utilization rate. In addition, we target the following features of the data prior to COVID-19, which are jointly determined by ξ: (*vi*) the average level of shipping capacity utilization in 2019, and (*vii*) the average shipping depreciation rate over the period 1996 to 2022.

We compute empirical counterparts for these moments as follows. We compute moment (*i*) using data on tradable absorption from the BEA. Moment (*ii*) is computed based on ship trip length data (in days) from Flexport as well as from data on world seaborne containership trade from Clarksons. We compute moment (*iii*) using investment data from the BEA. For moment (*iv*), we use data on new ship orders and total fleet capacity from Clarksons *Shipping Intelligence Network*. For moments (*v*) and (*vi*) we use shipping capacity utilization data for Far East — U.S. routes from the July 2022 Monthly Monitor publication of Alphaliner. Finally, we estimate shipping depreciation (*vii*) from Clarksons. To isolate the impact of the increased demand for tradables, we let period 1 be 2020Q3. Then, targets (*i*) and (*iii*) are expressed relative to a pre-2020 linear trend, while targets (*iv*) and (*v*) are relative to the 2019 average. We compute moment (*ii*) by averaging the change of the inverse of ship trip length relative to 2020Q3, with the average log deviation of world seaborne container trade from its pre-2020 trend.

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

Figure 4 plots the estimated shocks along with the dynamics of tradable absorption and effective shipping supply in both the model and the data. We find that the estimated shocks account well for the increase of tradable absorption and for the decline in effective shipping capacity throughout the pandemic. In particular, note that the model matches these dynamics fairly well despite our restriction that χ (and $\overline{g}$) increases (decreases) to a single higher (lower) value that remains constant following the pandemic.

Similarly, Figure A1 in the Appendix plots the model and data dynamics of the shipping investment rate, capital investment, and shipping capacity utilization rate. We observe that the model accounts relatively well for the movements of these three variables throughout the pandemic.

5.3 Aggregate dynamics

We now investigate the impact of the higher demand for tradable goods and lower effective shipping capacity following COVID-19. We begin by examining the dynamics of key

Table 2: Estimated parameters

Steady-State Parameter	Value	Description
τ	6.03	Iceberg trade cost
ζ	0.31	CES weight on domestic intermediates
a_G	0.12	Shipping investment productivity

Steady-State Moment	Data	Model
Tradables: Imports/Absorption, 2019	0.146	0.146
Intermediates: Imports/Absorption, 2019	0.263	0.263
Shipping costs/Imports, 2019	0.043	0.043

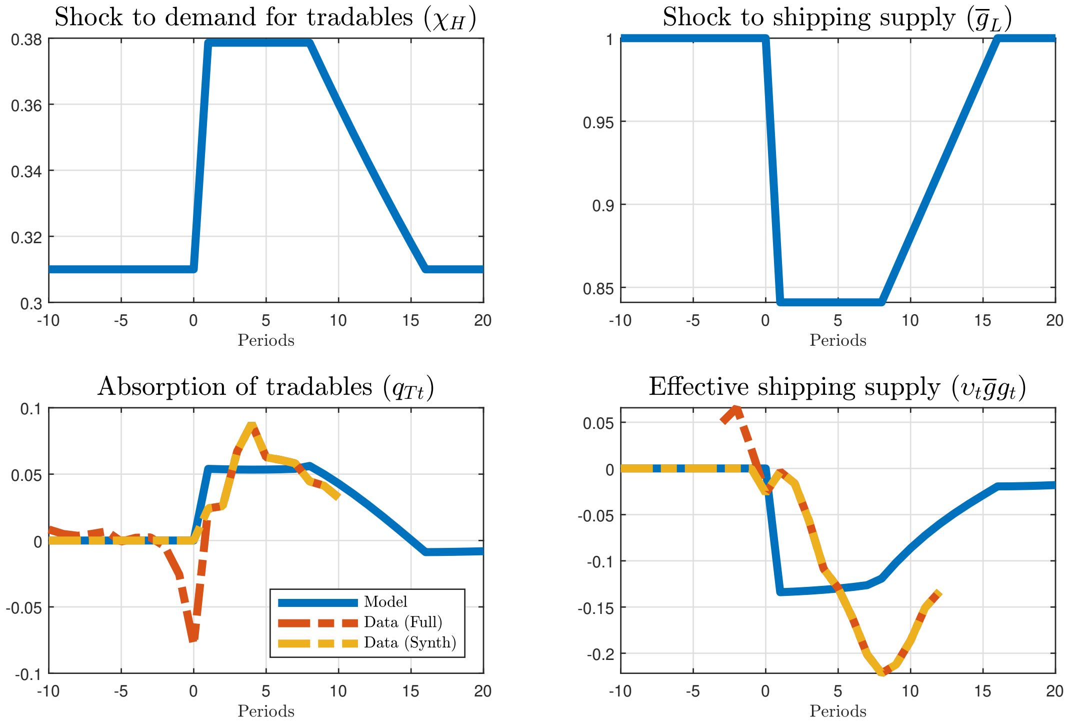
Dynamic Parameter	Value	Description
χ_H	0.20	Global shock to demand for tradables
$\overline{g}_L$	0.84	Global shock to shipping supply
Φ_k	39.37	Investment adjustment cost
Φ_G	106.57	Shipping adjustment cost
ξ	1.28	Shipping utilization cost
$\overline{\upsilon}$	0.90	Shipping utilization shifter
$\overline{\delta}_G$	0.029	Shipping depreciation shifter

Dynamic Moment	Target value	Model
Real tradable absorption, avg. log-change 2020Q3-2022Q2	0.054	0.054
Effective shipping supply, avg. log-change 2021-2022	-0.128	-0.128
Real investment, avg. log-change 2020Q3-2021Q2	-0.042	-0.042
Shipping investment/Shipping fleet, avg. change 2020Q3-2021Q2	0.037	0.037
TEU Liftings/Total Capacity, avg. change 2020Q3-2021Q2	0.042	0.042
TEU Liftings/Total Capacity, avg. 2019	0.93	0.93
Shipping depreciation rate, avg. 1996-2022	0.0292	0.0299

aggregate variables following the shocks to χ and $\overline{g}$ presented in Figure 4. We plot the dynamics of key variables in Figure 5, expressed as log-deviations from their steady-state values. We restrict attention to the dynamics over the five years (20 periods) following the onset of the pandemic.

The increase of χ increases the role of tradables in the production of final goods, with an immediate impact on the relative demand for tradable and non-tradable goods. Final good producers now demand more tradable goods and less non-tradables, leading to an increase in aggregate absorption of tradable goods (q_{Tt}) and to a decline in the aggregate absorption of non-tradables (q_{Nt}). Tradable output, however, decreases as a result of the reduced effective shipping capacity, which lowers the amount of tradables that countries are able to import from each other. As a result, aggregate absorption of final goods declines.

Figure 4: Shock to χ and $\overline{g}$ and implied dynamics



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

The increase in the relative demand for tradable and non-tradable goods, along with the decline of their relative supply, leads to a significant increase in the relative price between these goods (p_{Tt}/p_{Nt}).[13] Absorption of tradable goods increases as tradables previously meant to be traded internationally are consumed domestically, avoiding iceberg trade costs — yet, total production declines in both sectors given the decline of aggregate demand.

In the aggregate, we find that both aggregate consumption and investment decline (see Figure A2 of the Appendix). But we observe that consumption declines more than investment, as the reallocation of demand toward the tradable sector, which is capital-intensive, increases the demand for investments relative to consumption.

5.4 Shipping dynamics

We now investigate the implications of our model for the dynamics of shipping and international trade. We report these dynamics in Figure 6. We ask: To what extent can

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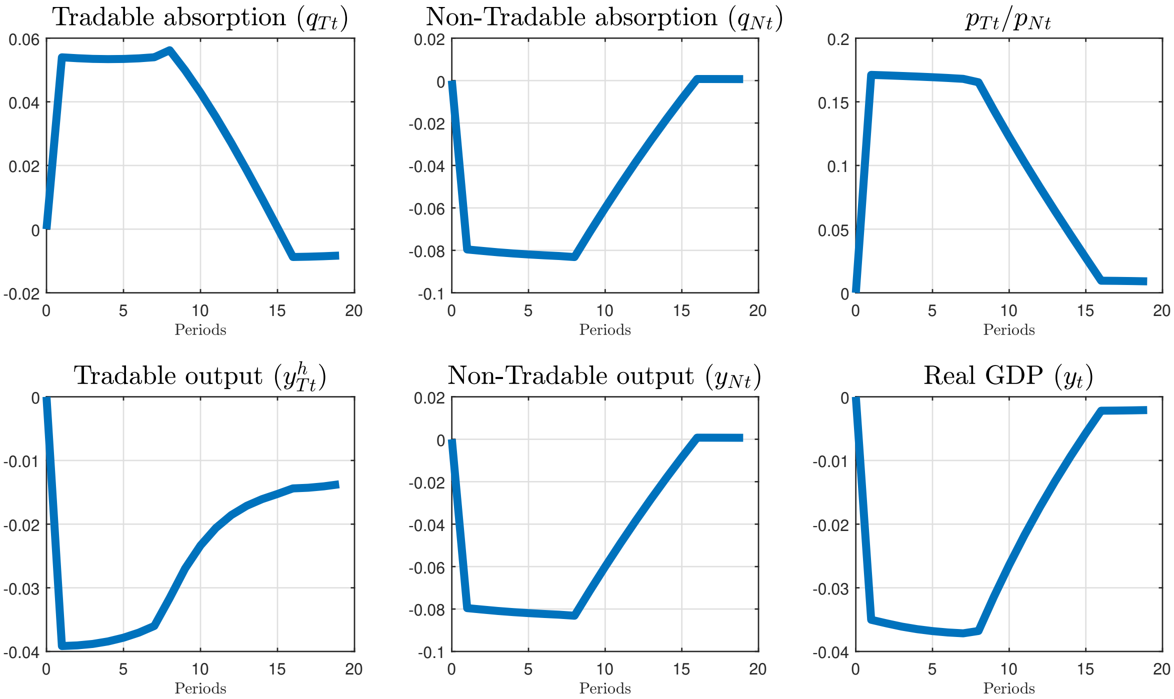
[13] We compute the price of tradable final goods by solving an equivalent version of the model that decomposes the final good producer into two agents. The first produces tradable final goods, and the second produces final goods by aggregating tradable final goods with non-tradables.

Figure 5: Aggregate dynamics following increased demand for tradables



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

the reallocation of demand toward tradable goods along with the contraction of effective shipping capacity account for the dynamics of global shipping observed in the aftermath of COVID-19?

We begin by observing that effective shipping capacity declines as soon as the shocks hit. Thereafter, while effective capacity begins to revert back gradually, it remains below its pre-pandemic level even four years after the onset of the shocks. The dynamics of effective shipping capacity result from the combination of three factors: the exogenous shock to shipping capacity ($\overline{g}$), the endogenous response of shipping capacity utilization (υ_t), and the installed shipping capacity (g_t). The exogenous shock to shipping capacity depresses effective shipping capacity through the first two years, reverting back gradually over the following two years. In response, firms increase the level of shipping capacity utilization chosen, remaining above pre-pandemic levels for 4 years. The cost of this higher shipping utilization is a higher rate of shipping depreciation, which reduces installed shipping capacity over the first 6 periods, before increased shipping investments have raised installed capacity. From period 7 onward, the higher utilization and depreciation rates act as an offsetting force to the impact of increased shipping investments.

The reduced effective shipping capacity implies that real exports (q^*_{Tt}) and imports (q^f_{Tt}) need to contract in order to clear the market for shipping services. Equilibrium between demand and supply of shipping services is restored through a substantial increase of shipping costs (h_t), which reduces demand for trade and shipping services, while increasing supply of shipping services via higher utilization. The relatively small value of shipping costs in total imports (4.3% in the pre-pandemic steady-state, as observed in Table 2) implies shipping costs need to increase considerably to induce a significant reduction of trade. Note, however, that given the global shock and symmetric countries, net exports remain unchanged throughout.

The higher shipping costs raise the returns to investments in shipping capacity, leading to an increase in the shipping investment rate over the first few periods after the shock is realized. The lengthy shipping production lag along with the transitory nature of the shocks imply that shipping investments increase only over the first few periods, reverting thereafter. There are declining incentives to invest after these first periods, since later investments would become operational once the shock begins tapering.

As investments in shipping capacity become operational in period 7 (that is, 6 periods after the investments are made) and the negative effective shipping capacity shock begins tapering in period 9, we observe that real exports and real imports increase in tandem, and shipping costs begin to decline. Note, however, that this is a gradual process, as shipping investments are also subject to adjustment costs that prevent the global shipping firm from concentrating all investments in a single period.

Model vs. data We now contrast the implied shipping and GDP dynamics vis-a-vis evidence from the data. To do so, we focus on variables not targeted throughout our estimation of the model. In particular, Figure 7 plots the dynamics of shipping costs, shipping capacity production, and real GDP for both the model and the data in the aftermath of COVID-19.[14]

Panel A contrasts the dynamics of shipping costs (h_t) in the model with their empirical counterpart. To do so, we plot the dynamics implied by the model along with the Drewry World Container Index reported in Figure 1, which we compute as the log deviation from 2020Q3 onward relative to the 2017Q1-2020Q1 average. We find that the implications of the model mirror the dynamics observed in the data, accounting for around 77% of the peak increase in shipping costs (the peak increase in the data and model are 1.75 and 1.35, respectively), while also exhibiting a gradual decline starting around period 8.

Panel B contrasts the dynamics of shipping capacity production in the model and the data. In the model, we report shipping investment shifted by the shipping production lag to capture the impact of shipping investments on installed capacity. In the data, we report

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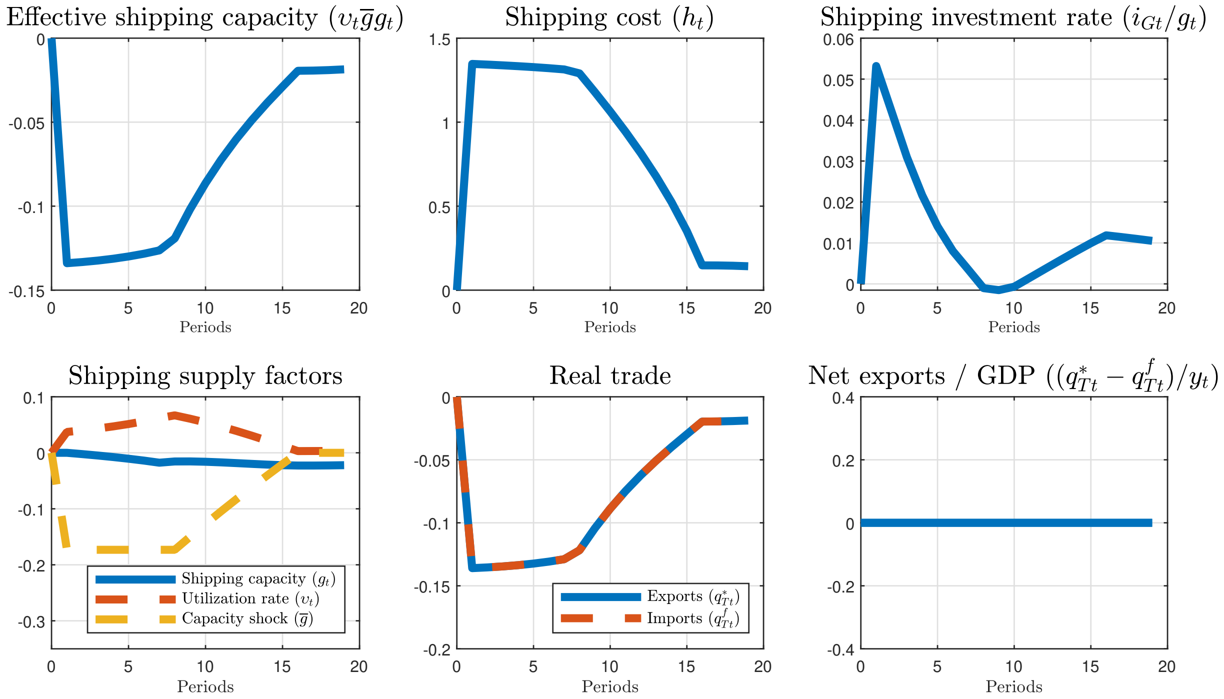
[14] Here and throughout the rest of the paper we compute real GDP as total value added with all prices kept fixed at their steady-state values.

Figure 6: Shipping dynamics following increased demand for tradables



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

the empirical distribution of shipping production lags, which can be interpreted akin to an empirical impulse response function to a one-time transitory increase in shipping investment. We find that the model implies dynamics of shipping capacity production that are in line with the data. This finding provides evidence in support of the assumptions underlying shipping investments and capacity production in the model.

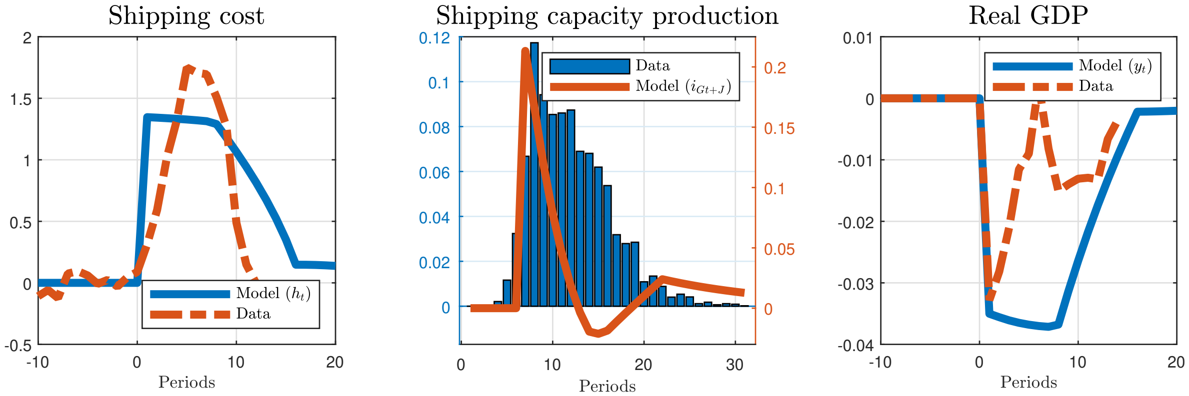
Finally, Panel C compares the dynamics of real GDP in the model and data. Despite not estimating the model to target these dynamics, the two shocks lead to aggregate GDP dynamics in the model that are consistent with their empirical counterpart for the U.S., providing an additional validity check on the implications of our model.

5.5 Aggregate implications of global shipping dynamics

The previous findings show that the model implies realistic shipping and GDP dynamics in response to increased demand for tradable goods and decreased effective shipping capacity. In particular, these findings show that the low elasticity of shipping capacity in the short run significantly limited the adjustment of international trade flows, leading to a sharp increase of shipping costs.

We now investigate the extent to which the rigid short-run supply of shipping capacity

Figure 7: Shipping and GDP dynamics, model vs. data

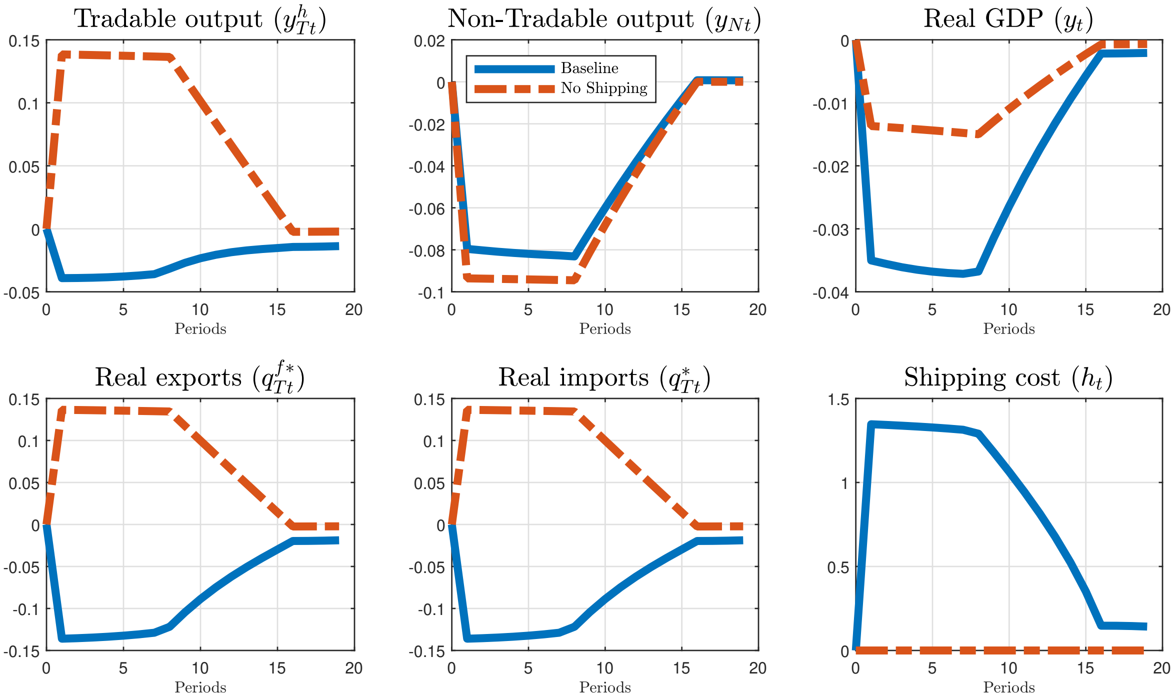


Note: The shipping cost and real GDP impulse-response functions are expressed as log-deviations from their respective steady-state values. The shipping capacity production impulse-response function is expressed as a percent deviation from the steady-state value.

affects the dynamics of key aggregate outcomes of the model. To do so, we contrast the implications of our model with those of a counterfactual economy with a perfectly elastic and costless supply of shipping capacity. This is implicitly the assumption in standard models of international trade and international business cycles (Backus et al. 1995; Heathcote and Perri 2002). That is, we consider an identical model but without the endogenous global shipping firm, where international purchases are only subject to the iceberg trade cost τ. We recalibrate the steady-state parameters in the top panel of Table 2 to ensure both economies look identical in the pre-pandemic steady state. But we keep all the parameters estimated to target dynamics (bottom panel of Table 2) unchanged at their baseline values, avoiding differences in these from driving differences in the implied dynamics. Critically, we examine the dynamics of the two economies in response to the same identical shocks estimated for the baseline.

Figure 8 contrasts the dynamics of key aggregate variables between the two economies in response to these shocks. We refer to the model with endogenous shipping as “baseline” and to the model with perfectly elastic and costless supply of shipping capacity as “no shipping.” We interpret differences in the implied dynamics as accounted for by the different shipping technologies across the two models. In contrast to our baseline, we find that tradable output (y^h_{Tt}) increases in the economy with perfectly elastic shipping supply. In the baseline, while demand for domestic and imported tradables increases, production contracts given the reduced availability of imported intermediates as shipping supply contracts. Production is also reduced since increased shipping costs reduce foreign demand. In contrast, access to intermediates is not constrained in the model with perfectly elastic shipping capacity. In this model, production of tradables increases given that

Figure 8: Aggregate implications of shipping capacity



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

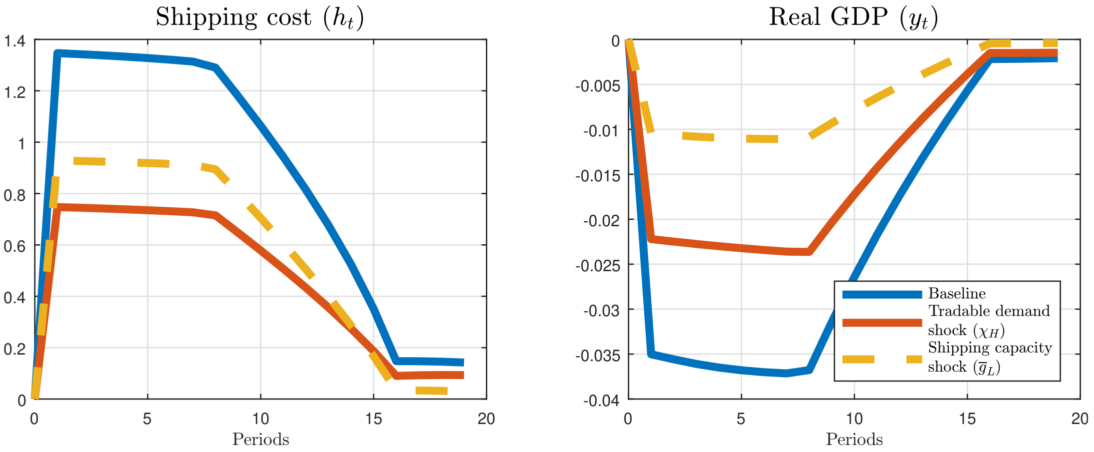
imports and exports of these goods can increase more easily than in the baseline.

These differences in the dynamics of tradable output have important implications in the aggregate. For instance, real GDP (y_t) decreases significantly more in the baseline than in the model with perfectly elastic shipping supply: the decline is 2.5 times larger at the trough in the former than in the latter. Similarly, we find significant quantitative differences in the dynamics of aggregate consumption and investment, among other variables, between the two models (see Figure A2 in the Appendix). Notice that these significant aggregate implications are despite the offsetting dynamics of non-tradable output, which decline relatively less in our baseline as final goods producers are unable to reallocate toward tradables as much as desired. Thus, we conclude that the dynamics of global shipping have significant aggregate effects despite only directly affecting the tradable goods sector, which is just a fraction of aggregate economic activity.

5.6 Shock decomposition: Tradable demand vs. shipping capacity

We now investigate the relative importance of the tradable demand vs. effective shipping capacity shocks in accounting for the key findings documented above. To do so, we restrict attention to the model's implications for shipping costs and real GDP dynamics, and we

Figure 9: Shock decomposition: Tradable demand vs. shipping capacity



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

compute two additional versions of the model. Each of these is identical to the baseline but features only one shock at a time. Specifically, we re-estimate the steady-state, but we keep all other parameters as in the baseline. We interpret differences in the dynamics implied by these models as informative about the relative contribution of the respective shocks to the aggregate dynamics of the baseline model.

Figure 9 reports the implications of the additional versions of the model, along with the baseline, for the dynamics of shipping costs and real GDP. We observe that shipping costs increase relatively more following the effective shipping capacity shock, yet the quantitative impact is similar across shocks. We also observe that the dynamics of shipping costs in the baseline are less than the sum of the impact of each shock separately, suggesting a greater importance of mitigating changes in utilization when excess demand pressures become greater. On the other hand, we find that approximately two-thirds of the decline of real GDP is accounted for by the increase in tradable demand, while the remaining third is accounted for by the contraction in shipping capacity. In contrast to shipping costs, we find these effects are approximately additive in their contribution to the dynamics of real GDP in the baseline.

5.7 Key channels accounting for quantitative results

In the appendix we investigate the relative importance of alternative channels in accounting for our findings. We summarize these findings here and refer readers to the appendix for further details.

First, we examine the role of alternative aspects of how shipping is modeled and parameterized. In particular, we examine the role of the shipping production lag (J), shipping investment adjustment costs (Φ_G), and the productivity of shipping investments (a_G). For each of these dimensions, we consider an alternative parametrization of the respective aspect while keeping all other parameters unchanged at their baseline values. We report the implications for various dimensions of shipping dynamics in Figure A3 of the Appendix. We find that the shipping production lag along with shipping adjustment costs are jointly critical in determining the persistence of shipping cost and trade changes. Moreover, we find that neither the shipping production lag nor the adjustment costs affect the change of shipping costs on impact. Instead, what is key for this effect is the productivity of shipping investments, which pins down the value of shipping costs relative to the value of imports. In particular, in an economy where shipping costs are a higher fraction of the total import costs, a lower increase of shipping costs is required to reduce import demand such that it is in line with effective shipping capacity.

Second, we examine the role of alternative aspects of our setup in accounting for our findings. In particular, we examine the role of input-output linkages (φ) and the degree of complementarity or substitutability between domestic and imported for both consumption-capital goods (ρ) and intermediates (ν). Given the importance of these features for the implications of the model, we sharpen the contrast with the baseline by fully re-estimating each alternative following the same approach as the baseline. For each version, we restrict attention to the effect of shipping on real GDP dynamics, which we report in Figure A4. We find that input-output linkages are critical in accounting for the effect of shipping on real GDP dynamics — in an economy without input-output linkages, real GDP dynamics are much more similar with and without shipping. We observe a similar effect as domestic and imported varieties become more substitutable in the final good or intermediate input bundles. These findings show that a key channel accounting for the effect of shipping on real GDP dynamics is the rationing of intermediate inputs that are critical for production and which are hard to substitute with domestic alternatives.

6 Quantitative analysis: Business cycle dynamics

The previous section shows that our model accounts for a significant fraction of the increase in international shipping costs in the aftermath of COVID-19, as the result of a sizable increase in the demand for tradable goods combined with a negative shock to effective shipping capacity. Given the significant volatility of international shipping costs during normal times, as documented in Figure 2, we now ask: To what extent can our model account for cyclical fluctuations of international shipping costs, and what are their aggregate implications?

To answer these questions, we extend the model along two dimensions. First, we assume that aggregate country-level productivities z_t and z_t^* follow a joint vector autoregressive process of order 1.[15] This is the conventional driving force of international business cycles in much of the literature (Backus et al. 1995; Heathcote and Perri 2002). Second, we assume that the iceberg trade costs faced by each country co-move with changes in domestic aggregate productivities. In particular, we assume iceberg trade costs paid by importers in the home country are given by the following function: $\log \tau_t = \log \tau + \Lambda \log z_t$, where Λ is a scalar and z_t denotes home country productivity.[16] This assumption allows us to generate cyclical fluctuations of tradable goods absorption consistent with the data.[17]

Then, our approach to evaluating the drivers and implications of cyclical shipping cost fluctuations is the following: First, we estimate the parameters controlling the time-varying productivity and trade costs described above. In addition, we re-estimate the parameters of the model to ensure it captures salient features of international business cycles.[18] Second, we simulate the model to compute moments characterizing the typical business cycle dynamics implied by the model. In particular, we examine the implied dynamics of international shipping costs, which are not targeted in the estimation. Finally, we evaluate how global shipping affects international business cycles by considering a version of the model with a perfectly elastic supply of shipping capacity. In particular, we re-estimate the steady-state but keep all other parameters at their baseline values, and we compute the moments implied by simulations of this alternative model. We interpret differences between them as capturing the impact of shipping on business cycle fluctuations.

6.1 Parameterization

We begin by re-estimating the model to capture salient features of international business cycles. We parametrize the productivity process by setting the persistence (ρ_z) and spillover (ρ_{zz}) coefficients as estimated by Backus et al. (1995), but we re-estimate the volatility of the productivity shocks (σ_z) to ensure the model captures the volatility of real GDP observed in the data. In addition, we estimate the elasticity Λ of iceberg trade

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

[16] Iceberg trade costs in the foreign economy are analogously defined.

[17] This approach follows Levchenko et al. (2010), Alessandria et al. (2013), and Leibovici and Waugh (2019), among others, who show that time-varying trade wedges can reconcile standard models with cyclical trade fluctuations.

[18] We also re-estimate the steady-state to target the average ratio of shipping costs to imports equal to 4.6% over the period 1989-2019.

Table 3: Estimated parameters, business cycle analysis

Predetermined Parameter	Value	Description
ρ_z	0.906	Persistence of productivity process
ρ_{zz}	0.088	Cross-country spillover of productivity process

Estimated Parameter	Value	Description
σ_z	0.010	Variance of productivity shocks
Λ	-0.610	Elasticity of trade costs to productivity shocks
Φ_k	1.506	Investment adjustment cost
Φ_G	90.0	Shipping adjustment cost
ξ	0.197	Shipping utilization cost
$\overline{v}$	0.663	Shipping utilization shifter
$\overline{\delta}_G$	0.029	Shipping depreciation shifter

Moment	Target value	Model
Average shipping utilization	0.92	0.92
Shipping depreciation rate	0.03	0.04
Std. dev. real GDP (%)	1.92	1.92
Std. dev. relative to real GDP:		
Real tradable absorption	1.26	1.26
Real investment	3.27	3.27
Shipping investment/Shipping fleet	1.50	1.50
Shipping utilization	1.92	1.92

Note: Model moments are computed as the average across 100 simulations of 120 periods. Unless otherwise noted, statistics are based on Hodrick-Prescott filtered data with smoothing parameter 1600. Statistics on the shipping utilization rate and the shipping investment rate are computed using their level without detrending.

costs to changes in domestic productivity by targeting the volatility of tradable absorption relative to the volatility of real GDP. Unless otherwise specified, all empirical business cycle moments, such as the volatility of real GDP and investment, are from Backus et al. (1995).

We re-estimate the rest of the parameters following an approach analogous to the previous section. In particular, we re-estimate investment adjustment costs, shipping adjustment costs, and the parameters controlling shipping capacity utilization. Each estimated parameter is disciplined by the same data counterpart described in the previous section, but we now target their volatility over the sample relative to the volatility of real GDP. For the shipping utilization moments we use data for 2013-2019, and for the shipping investment rate moment we use data for 1996-2019.[19] All other parameters

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[19] We also re-estimate the steady-state to match an average ratio of shipping costs to imports over the

Table 4: Business cycle fluctuations

	Data	**Baseline**	**No Shipping**
Std. dev. real GDP	1.92	1.92	2.10
Std. dev. relative to real GDP:			
Consumption	0.75	0.76	0.74
Investment	3.27	3.27	3.55
Imports	3.08	0.76	1.63
Tradable absorption	1.26	1.26	1.47
corr(Imports,Real GDP)	0.61	0.51	0.65
corr(Tradable absorption,Real GDP)	0.94	0.88	0.87

are kept unchanged at the values described in the previous section. Table 3 reports the estimated parameters along with the targeted moments and their model counterparts. Model moments are based on 100 simulations of 120 periods. We find the model can be estimated to capture salient features of business cycle and shipping dynamics.

Table 4 reports the implications of the model (second column) for a broader set of moments not targeted in the estimation, along with their empirical counterparts (first column). We find the model with endogenous shipping can account for standard features of business cycle dynamics beyond those targeted directly in the estimation. For instance, the model implies a volatility of consumption and a cyclicality of imports and tradable absorption similar to the data.

6.2 Global shipping cost fluctuations

We now examine the implications of the model for global shipping cost fluctuations. To do so, Table 5 reports the volatility and cyclicality of global shipping costs in our baseline model relative to the data.

We find that our model implies shipping costs that are 8.14 times more volatile than real GDP, accounting for the significant volatility of shipping costs observed in the data. Our model implies that these costs are more correlated with GDP than we see in the data, but this is to be expected given our model features only two countries, whereas in the data no individual country is sufficiently large to be so tightly correlated with global shipping fluctuations.

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period 1989 to 2019 equal to 4.6%.

Table 5: Global shipping cost fluctuations

	Data	**Baseline**
Std. dev. relative to GDP: Shipping costs	7.70	8.14
corr(Shipping costs, Real GDP)	0.38	0.70

6.3 Global shipping and aggregate fluctuations

We now evaluate the impact of global shipping on international business cycle fluctuations. Our goal is to quantify the extent to which observed aggregate fluctuations are accounted for by global shipping. We do so by contrasting the cyclical fluctuations implied by our model vis-a-vis a counter-factual economy with perfectly elastic and costless supply of shipping services. As in the previous section, we keep all parameters unchanged across the two models except for those estimated to match steady-state targets. Table 4 reports our findings — the second column reports the moments implied by our baseline, while the third column reports those implied by the counter-factual economy.

Our main finding is that, in contrast to our findings in the aftermath of COVID-19, global shipping *reduces* the volatility of aggregate fluctuations at business cycle frequencies. In the absence of global shipping rigidities, we find that the volatility of real GDP and tradable absorption would be 9.4% and 16.7% higher, respectively.

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

These effects differ markedly from those implied by the shocks experienced by the global economy in the aftermath of COVID-19, as we show in the previous section. The key difference is that, in the aftermath of COVID-19, the demand for tradables increased during a period of aggregate economic contraction rather than expansion, as is typically observed at business cycle frequencies. In this context, the higher demand for tradables acts as a mitigating force to the contraction of aggregate GDP. But with short-run rigidi-

Table 6: Local vs. global shocks

	Local	Global
Std. dev. shipping costs relative to real GDP		
Baseline	6.30	12.03
No shipping	—	—
Std. dev. real GDP		
Baseline	2.09	1.81
No shipping	2.25	2.11

Note: "Local" refers to the economy without productivity spillovers across countries ($\rho_{zz} = 0$), while "Global" refers to the economy with perfectly correlated productivity shocks across countries.

ties in shipping supply, demand and production of tradables are able to increase relatively less than in a model with elastic shipping supply. Therefore, aggregate GDP declines relatively more in our baseline following COVID-19.

These findings show that the nature of the shocks at play are critical in determining whether global shipping amplifies or mitigates macroeconomic fluctuations.

6.4 Local vs. global shocks

Given the global nature of international shipping, the extent to which shocks are local or global may play an important role in its aggregate implications. To evaluate this, we now investigate the effect of global vs. local shocks on the volatility of shipping and aggregate variables. We do so by contrasting two economies. The first economy is identical to our baseline but is such that there are no productivity spillovers across countries ($\rho_{zz} = 0$) — thus, all shocks are truly country-specific and we refer to it as an economy subject to "local shocks." The second economy is identical to our baseline but is subject to productivity shocks that are perfectly correlated across countries — thus, we refer to it as an economy subject to "global shocks." Table 6 reports the implications of these economies for the fluctuations of shipping costs and real GDP.

We find that the local vs. global nature of the productivity shocks is critical for shipping volatility and its aggregate implications. In particular, in a world where countries have uncorrelated shocks, productivity shocks are country-specific, so shipping capacity is rarely subject to extended periods of significant excess demand. In contrast, if productivity shocks are global, economic booms in the world economy are periods in which both countries have high demand for trade and shipping services, leading to substantial changes in shipping costs. Shipping costs are 91% more volatile in the economy with global shocks. As a result, we find that the aggregate implications of global shipping ridigities become much larger in such case. For instance, while real GDP is 7.7% more volatile without shipping rigidities when subject to local shocks, its volatility increases by 16.6% when subject to global shocks.

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

Building on the findings from the previous sections, we now extend our analysis to study the global impact of regional shipping disruptions due to attacks to vessels in the Red Sea in late 2023. Then, we investigate the implications that periodic shipping disruptions, like recent attacks in the Red Sea, may have on business cycle volatility in a world with growing geopolitical conflict.

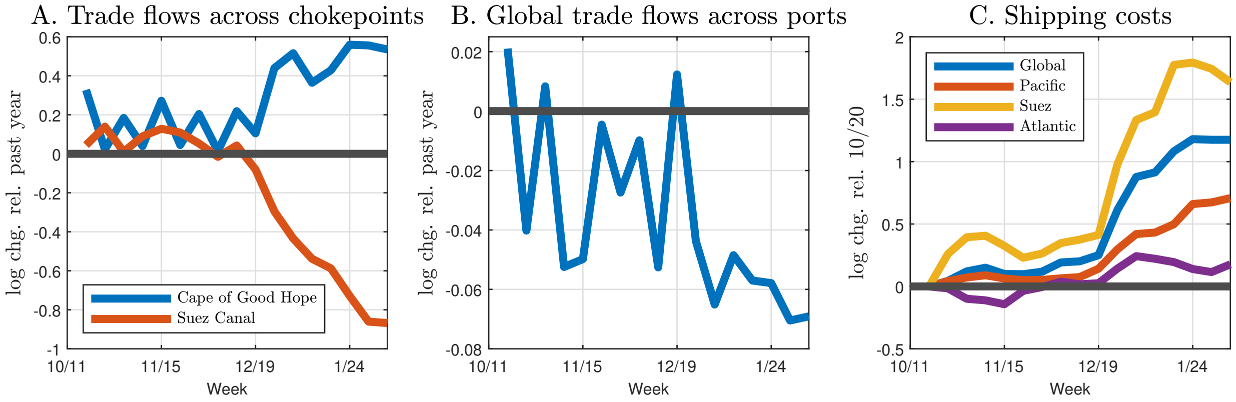
7.1 Shipping disruptions in the Red Sea

In late 2023, attacks on ships navigating the Red Sea led vessels to reroute through the Cape of Good Hope, increasing shipping times by at least 14 days. Panel A of Figure 10 shows that trade flows around the Cape of Good Hope have increased in tandem with the rerouting from the Suez Canal, confirming that this has been the primary alternative route for much of the trade initially intended to ship through the Red Sea.

Despite only 12% of global trade moving through the Suez Canal, this regional shock has impacted global shipping, reducing trade flows and increasing costs. Panel B of Figure 10 plots weekly estimates of global exports based on IMF's Portwatch data across 1,378 major ports. We observe that global exports have declined systematically (relative to the same week the year prior) since mid-December 2023, when major shipping companies began rerouting their voyages away from the Red Sea. Panel C of Figure 10 plots the dynamics of global and regional shipping costs, using data from Freightos. As expected, we observe that shipping prices for routes around the Suez Canal have increased substantially over this period. More surprisingly, we observe that global shipping costs have also increased substantially despite the regional nature of the shock.

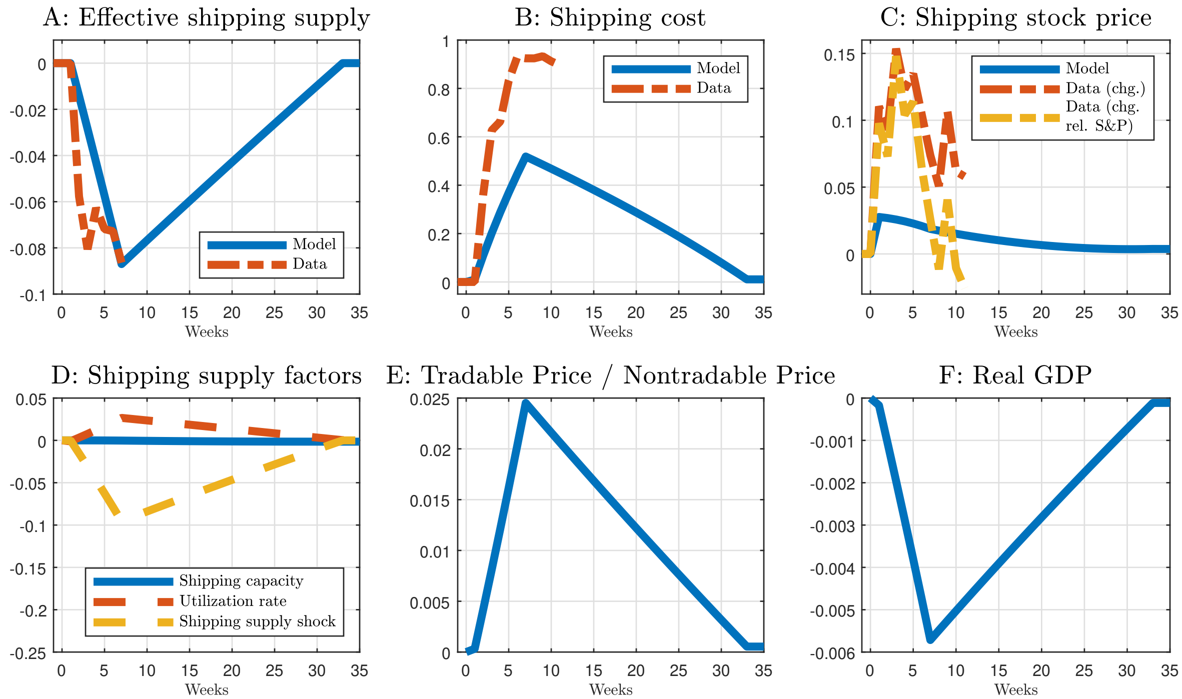
To investigate the channels accounting for the global impact of shipping disruptions and their implications, we study the effect in our model of shipping capacity shocks designed to mimic the reduction of global trade flows observed in the data. Specifically, we study a weekly version of the model, estimated using data prior to the Red Sea disruptions, and assume the economy is in steady state before the disruptions start in mid-December 2023. Information about the rerouting is revealed in the week of December 17-23, 2023,

Figure 10: Impact of attacks on Red Sea vessels on global shipping


A. Trade flows across chokepoints B. Global trade flows across ports C. Shipping costs

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

Figure 11: Shipping and aggregate dynamics following Red Sea disruptions


A: Effective shipping supply B: Shipping cost C: Shipping stock price D: Shipping supply factors E: Tradable Price / Nontradable Price F: Real GDP

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

with negative shipping supply shocks starting the following week, chosen to track the observed global trade flows. Panel A of Figure 11 plots the dynamics of global effective shipping supply in the model and the data. The shocks are assumed to revert gradually to the steady state over the next six months.

The top row of Figure 11 compares the model's implications for global shipping dynamics with their empirical counterparts. Panel B shows that the model generates a substantial increase of global shipping costs. In the model, the rigid short-run supply of shipping capacity, due to high utilization and time-to-build in shipping investment, implies that reductions in effective capacity can only be partially offset in the short run. This leads to higher shipping prices to bring imports in line with the reduced shipping supply. Panel C shows that the model also accounts for the observed increase in the value of shipping firms, as captured by their stock prices.[20] In the model, these effects are accounted by the combination of rigid shipping supply and inelastic demand, which allows for higher prices and profits despite the disruptions.

The model points to key channels through which the shock propagates to the global economy. The reduced shipping capacity constrains the ability of countries to trade, leading to a decline in both exports and imports. The resulting reduction in access to tradable goods causes their relative price to increase, inducing a partial reallocation of consumption and investment towards nontradables. However, the overall effect is contractionary, with declines in aggregate trade, investment, and production. These findings provide a lens through which to interpret the potential implications of shipping disruptions in the Red Sea for the global economy.

While the effects of the Red Sea disruptions may be transitory, our findings highlight the potential importance of shipping in propagating shocks across the global economy.

7.2 Business cycle implications of periodic shipping disruptions

To conclude our analysis, we examine the impact that periodic shipping disruptions can have on business cycle dynamics. To do so, we introduce stochastic shocks to effective shipping capacity into the model as estimated in Section 6 and examine their implications for the volatility of shipping costs and aggregate economic activity. We consider disruptions with standard deviations equal to 1 and 2 times the magnitude of the Red Sea shock, with half-lives of 2 and 7 quarters. Table 7 reports our findings.

To put our findings in context, in Panel A we reproduce the findings reported in Section 6, which show the effect of shipping on business cycle fluctuations (without periodic shipping disruptions). In Panel B, we report the business cycle implications of periodic shipping disruptions. We find that larger and more persistent disruptions lead to a significant increase in the volatility of shipping costs and aggregate economic activity. For instance, with disruptions that are twice as large as the Red Sea shock and a half-life of 7

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

	Std. dev. Real GDP	*Std. dev. relative to GDP* Shipping cost
A. No shipping disruptions		
Data	1.92	7.70
Baseline	1.92	8.14
No shipping	2.10	—
B. Shipping disruptions		
std. dev. = 1X Red Sea, half-life = 2 quarters	1.95	17.23
std. dev. = 2X Red Sea, half-life = 2 quarters	2.05	31.19
std. dev. = 1X Red Sea, half-life = 7 quarters	2.00	22.33
std. dev. = 2X Red Sea, half-life = 7 quarters	2.29	41.65

quarters, the standard deviation of real GDP rises from 1.92% to 2.29% and the volatility of shipping costs relative to GDP rises from 8.14 to 41.65.

However, for disruptions of the magnitude and persistence observed in the Red Sea, the impact on aggregate volatility is relatively modest. With a shock of that size and a half-life of 2 quarters, real GDP volatility only increases from 1.92% to 1.95%. This suggests that while large and persistent shipping disruptions can significantly amplify business cycles, more transitory shocks like those recently observed do not have a major impact on aggregate fluctuations. Thus, our findings point to the importance of the magnitude and persistence of shipping disruptions in determining their ultimate impact on aggregate volatility.

8 Concluding remarks

This paper studies the drivers and aggregate implications of global shipping dynamics. Motivated by salient features of the dynamics of global shipping that we document, we develop a dynamic model of international trade with an endogenous market for global shipping services. We find that the model is consistent with salient features of global shipping dynamics and that the model accounts for shipping cost fluctuations in the aftermath of COVID-19, over the business cycle, and following shipping disruptions in the Red Sea. Moreover, we find that accounting for global shipping dynamics is critical for the dynamics of aggregate economic activity.

Our findings point to the importance of global shipping as the backbone of the global trading system. In particular, we find that accounting for the endogenous dynamics of the global shipping market is critical for understanding the world economy's response to shocks. Moreover, with shipping disruptions becoming increasingly prevalent, our findings point to the importance of evaluating future developments and policies using models that explicitly consider the endogenous dynamics of global shipping.

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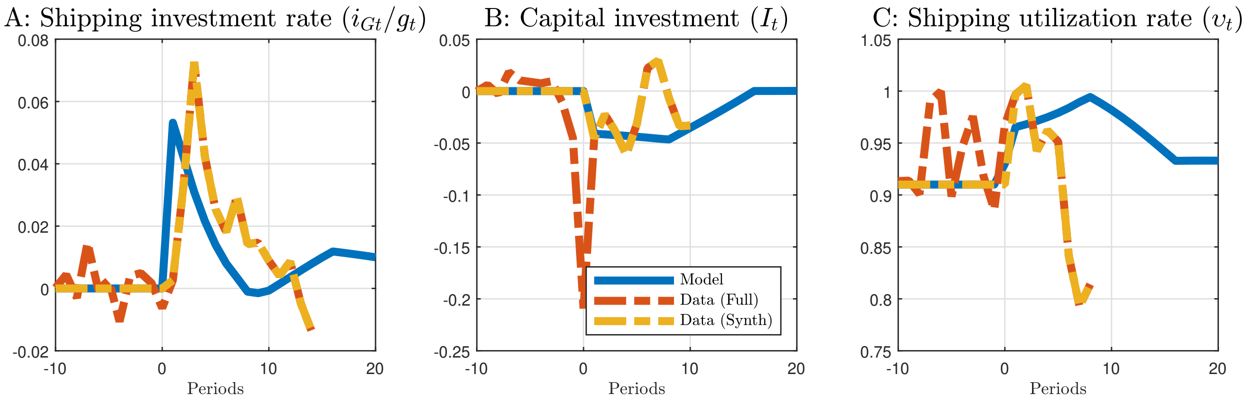
Appendix

A. Dynamics following COVID-19: Model vs. data

In this section, Figure A1 contrasts the implications of our model with their empirical counterpart for the dynamics of key variables targeted in the estimation.

Figure A1: Shipping, capital investment, and utilization dynamics


A: Shipping investment rate (i_{Gt}/g_t)
B: Capital investment (I_t)
C: Shipping utilization rate (υ_t)

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

B. Additional variables

In this section, Figure A2 reports the dynamics of additional variables of the model in the aftermath of COVID-19.

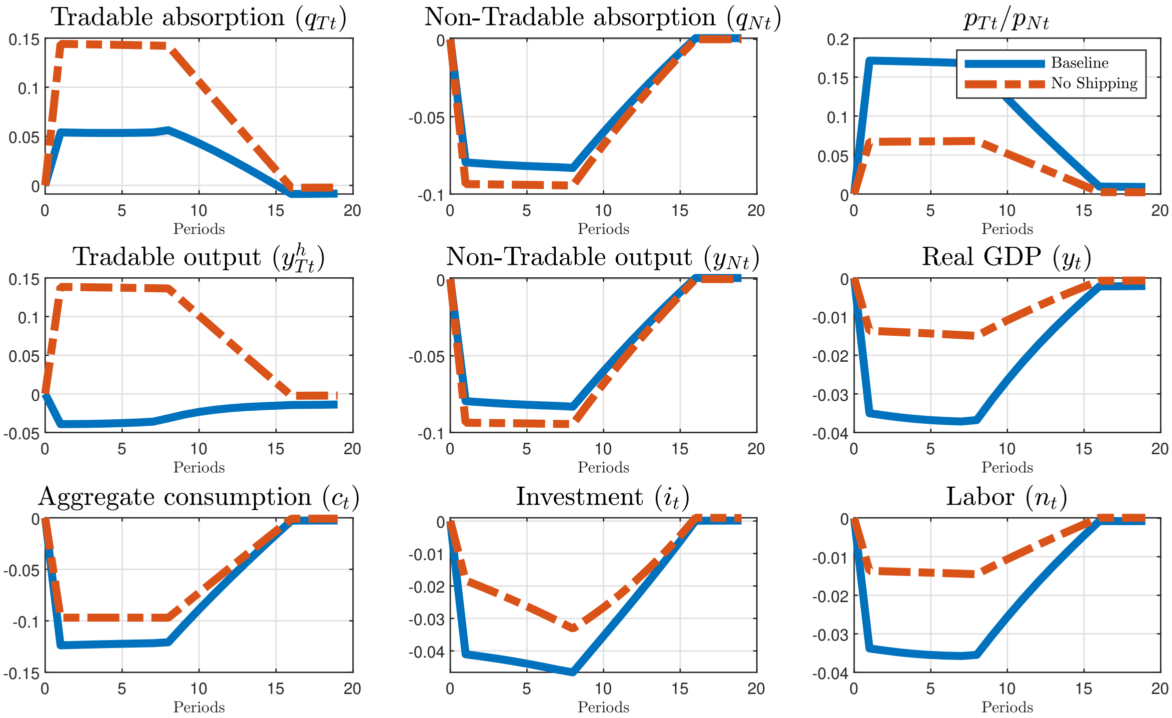
C. Key channels

In this section, we investigate the relative importance of alternative channels in accounting for our findings.

Shipping

First, in Figure A3, we examine the role of the shipping production lag (J), shipping investment adjustment costs (Φ_G), and the productivity of shipping investments (a_G). To do so, we start with the baseline and change one parameter (or set of parameters) while keeping all other parameters at their baseline values. We consider 4 alternative versions of the model: (i) lower shipping investment productivity $a_G = 0.035$, which implies a steady-state ratio of shipping costs to imports equal to 17.2% (vis-a-vis $a_G = 0.12$ in the baseline which implies a value of the ratio equal to 4.3%), (ii) lower shipping adjustment

Figure A2: Additional aggregate implications



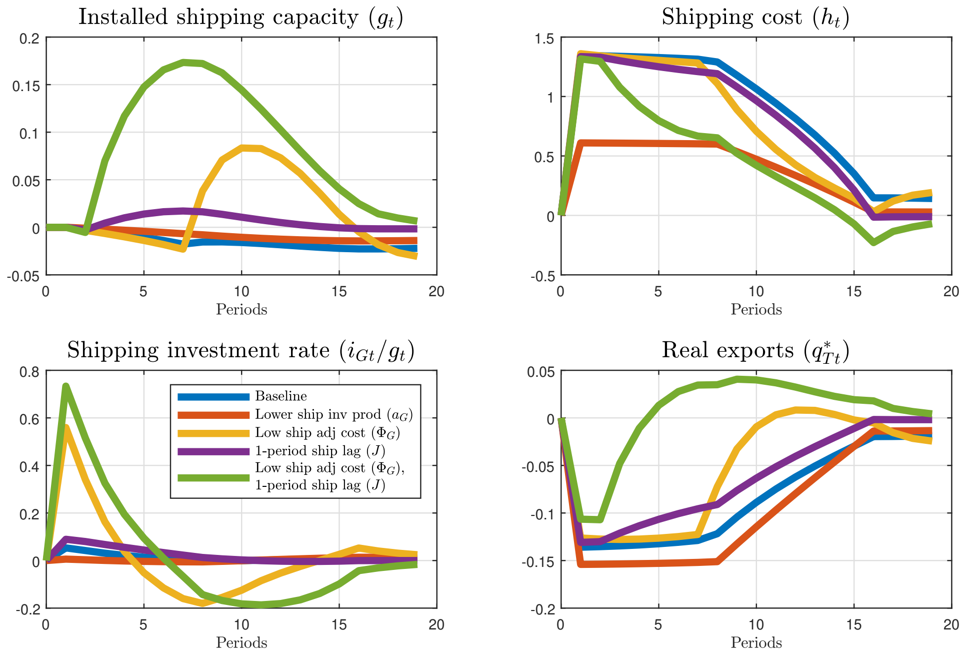
Note: All impulse-response functions (except investment) are expressed as log-deviations from their respective steady-state values. The investment IRFs are expressed as the percentage deviation from the steady-state. Baseline IRF's mirror those shown in Figure 5, while the "No Shipping" IRF's represent those in the counterfactual model with perfectly elastic shipping supply.

cost $\Phi_G = 5$ (vis-a-vis 106.6 in the baseline), (*iii*) a one-period shipping production lag ($J = 1$, vis-a-vis $J = 6$ in the baseline), and (*iv*) the combination of (*ii*) and (*iii*).

Model specifications

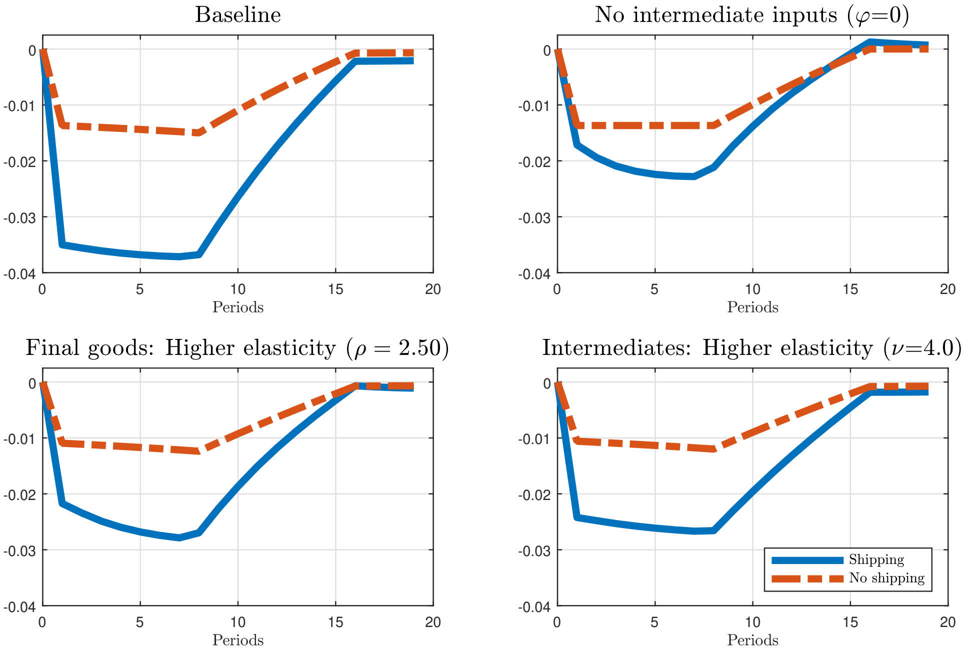
Second, in Figure A4, we examine the role of input-output linkages and the degree of complementarity or substitutability between domestic and imported varieties in final goods (ρ) and intermediates (ν). To do so, we start with the baseline and re-estimate the model under alternative values of the relevant parameters. We consider 3 alternative versions of the model: (*i*) no intermediate inputs ($\varphi = 0$, vis-a-vis $\varphi = 0.58$ in the baseline), (*ii*) higher elasticity between tradable domestic and imported varieties in the production of final goods ($\rho = 2.50$, vis-a-vis $\rho = 1.50$ in the baseline), and (*iii*) higher elasticity between tradable domestic and imported varieties in the production of intermediates ($\nu = 4$, vis-a-vis $\nu = 1$ in the baseline).

Figure A3: Alternative parameter implications for shipping



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

Figure A4: Real GDP under alternative model specifications



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