Navigating the Waves of Global Shipping: Drivers and Aggregate Implications

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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 prices. Motivated by this evidence, we set up a multi-country dynamic model of international trade with a global shipping market where shipping companies and importers endogenously determine shipping supply and prices. We find the model can successfully account for the dynamics of global shipping observed in the aftermath of COVID-19 and that accounting for these has important implications for the dynamics of aggregate economic activity.

1   Introduction

The global shipping industry plays a crucial role in international trade and commerce, facilitating the movement of goods across the world. The industry has witnessed significant growth over the past few decades, driven by various factors, including technological advancements, globalization, and the rise of emerging economies. However, the industry is also highly cyclical and sensitive to changes in global economic activity, leading to significant fluctuations in shipping demand and prices.

In this paper, we examine the drivers of global shipping dynamics and their aggregate implications for the global economy. We focus on understanding the factors that shape the dynamics of the shipping industry: global shipping supply, demand, and prices. And we investigate how these dynamics feed into broader macroeconomic outcomes, such as fluctuations in international trade and aggregate economic activity. Our findings provide insights into how policymakers and market participants may navigate the waves of global shipping — how to interpret fluctuations of shipping prices, and how to adjust policies and production decisions accordingly.

We begin by documenting three key features of the dynamics of the global shipping industry. Given the critical role of containerships in the international trade of goods, we restrict attention to this segment of the global shipping industry.[2] First, we document that international shipping supply has been growing steadily over recent decades, and is typically used at near full capacity. Second, we document that fluctuations in the demand for shipping services relative to the steady growth of shipping supply are tightly associated with changes in international shipping prices. Third, we observe that periods of high shipping prices and earnings are associated with higher orders for new containerships. But the production of new containerships takes time, around three years for large ships.

Motivated by these observations, we construct a multi-country dynamic general equilibrium model of international trade with endogenous demand and supply for global shipping services. Our model features importing firms and a global shipping company: The firms import goods that are subject to international shipping costs as well as standard iceberg trade costs. The shipping company owns the global stock of ships and rationally chooses investments to adjust shipping capacity to 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. International shipping costs consist of the equilibrium price that clears the market for global shipping services, equating shipping demand with

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

A: Tradable Goods   B: Drewry World Container Index
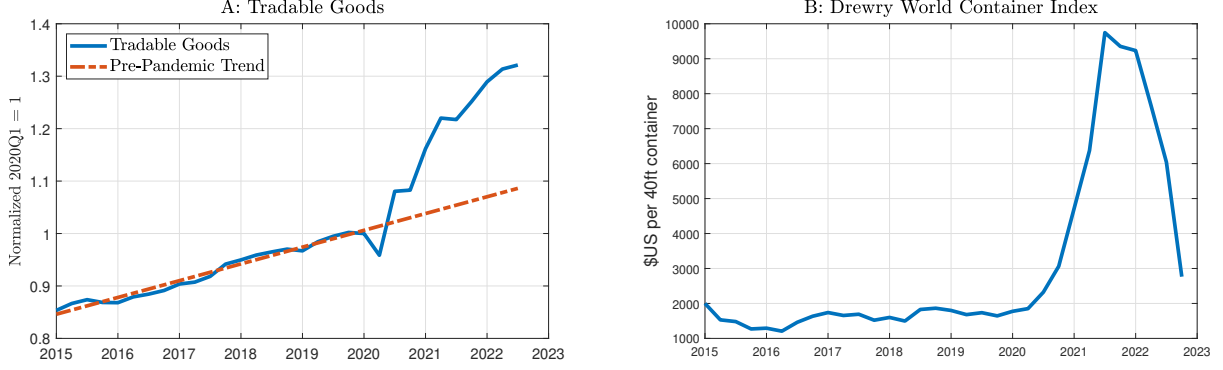
Source: Bureau of Economic Analysis and Drewry Supply Chain Advisors.

Figure 1: COVID-19, absorption of tradable goods, and shipping costs

supply.

To quantify the extent to which our model can account for the dynamics of global shipping that we document and their aggregate implications, our approach is motivated by the unprecedented disruptions in international shipping observed in the aftermath of the COVID-19 recession. First, the world economy experienced a massive increase in the demand for tradable goods during this period (Panel A of Figure 1 illustrates this with data for the U.S.). This resulted from the reallocation of demand from contact-intensive services toward tradable goods that can be used from home while mitigating exposure to the disease.[3] Second, global shipping costs also experienced an unprecedented increase during this period. For instance, Panel B of Figure 1 shows that the Drewry World Container Index, an index of global shipping costs, increased from less than $2,000 per 40 foot container to almost $10,000 at the peak.

Motivated by these post-pandemic dynamics, we study the impact of a rapid increase in the demand for and absorption of tradable goods. Given the global nature of the pandemic, we focus on a world economy populated with symmetric countries subject to identical aggregate shocks. 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 framework 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 does accounting for the dynamics of global shipping affect the aggregate implications of the shock?

We find that our model can successfully account for salient features of the dynamics

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[3]This reallocation of demand was amplified by fiscal transfers implemented throughout this period to mitigate the economic impact of the pandemic.

of global shipping observed in the aftermath of COVID-19. The shock to the demand for tradable goods leads to an increase in the demand for imports and exports. However, shipping capacity is inelastic in the short run, given that investments to increase shipping capacity take several periods to become operational. Thus, the amount of trade remains initially unchanged, while shipping prices increase on impact, helping to ration the limited capacity across the increased demand for international shipments.

We then contrast these findings with the dynamics of shipping prices and shipping capacity observed in the data. We find that the implications of the model mirror their empirical counterparts, accounting for approximately two thirds of the peak increase of shipping prices and exhibiting price declines when the shock subsides. Moreover, we find that the model implies dynamics of shipping capacity in response to changes in shipping investments that are in line with the data. Thus, we conclude that our model can successfully account for salient features of the dynamics of global shipping.

These findings show that the inelastic nature of shipping supply along with the large increase in the demand for tradable goods can account for a substantial fraction of increasing shipping costs in the aftermath of COVID-19. Moreover, these findings provide support for other uses of our model to address shipping-related questions, as well as to conduct counterfactual experiments.

We then investigate the extent to which the rigid short-run supply of shipping capacity affected the dynamics of key macroeconomic aggregates. To do so, we contrast the implications of our model with those of a counterfactual economy with a perfectly elastic supply of shipping capacity, as implicit in standard models of international trade and international business cycles (Backus et al. 1995; Heathcote and Perri 2002). 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 25% larger at the trough in the former than in the latter. Similarly, we find significant quantitative differences in the dynamics of aggregate absorption, consumption, and investment between the two models.

Our findings point to the importance of improving our understanding of the drivers and implications of developments in the international shipping industry. Thus, this paper belongs to a growing literature that has been recently addressing related questions within this realm. On the one hand, our work contributes to a growing literature that investigates global shipping dynamics, such as Brancaccio et al. (2020), Greenwood and Hanson (2015) and Kalouptsidi (2014). On the other hand, our work contributes to recent studies that study the implications of shipping for aggregate dynamics, such as Alessandria et al. 2022,

Leibovici and Waugh 2019, and Ravn and Mazzenga 2004.

Our work also contributes to a 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. 2021; 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.[4]

The rest of the paper is organized as follows. Section 2 documents salient features of the international shipping industry. Section 3 constructs a multi-country dynamic model of international trade with endogenous shipping supply. Section 4 describes our quantification approach. Section 5 presents the quantitative results. Section 6 concludes.

2 Salient features of the global shipping industry

In this section, we document salient features of the market for global shipping services. We focus on three key dimensions. First, we examine the dynamics and level of global shipping capacity and its utilization. Second, we examine the dynamics of global shipping costs and their link to 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. Thus, we abstract from the shipment of goods through other modes of transportation, as well as from the shipment of commodities or goods that require shipment through other types of ships.

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

Our main source of shipping-related data is Clarkson's *Shipping Intelligence Network*, an integrated shipping services provider that collects a broad range of data on the international shipping industry. This is our source of data on shipping supply, utilization, new orders of ships, average earnings, and build time. For shipping prices, we focus on the

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

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. We proxy shipping demand with global GDP as collected by the International Monetary Fund's *World Economic Outlook*.
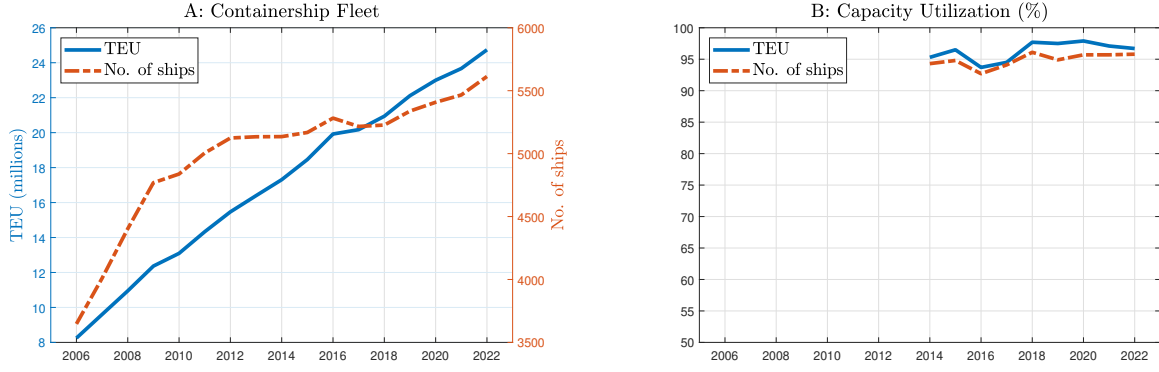
2.1 Shipping capacity

We begin with global shipping capacity. Panel A of Figure 2 reports the evolution of global shipping capacity over time. We focus on two measures: the total number of containerships (orange line) and the total volume available (blue 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. This is particularly the case for the volumetric capacity of the fleet (TEUs). This series is linear over this long time span, suggesting that the growth of global shipping supply is fairly independent of short-run shocks.

Panel B of Figure 2 reports the level and dynamics of the global containership fleet's capacity utilization. This 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 as well as in TEUs — this statistic is computed as the annual average of a daily measure of containerships idle.[5] We find that the global containership fleet operates close to maximum capacity at all times. Since 2014, the capacity utilization of the global supply, measured in TEUs, has averaged over 96%. This suggests that, in the short run, the containership shipping industry has limited room to increase shipping supply to address fluctuations in demand. Thus, fluctuations in demand are instead likely to be accommodated via fluctuations in shipping prices in the short run.

2.2 Shipping demand, supply, and prices

We now investigate the joint dynamics of global shipping demand, supply, and prices. Panel A of Figure 3 plots the annual growth of global GDP (our proxy for global shipping demand) alongside the 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 Figure 2, we observe that global shipping supply is relatively steady and independent of global demand fluctuations. This implies that there are likely to be

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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. Time series based on daily data and aggregated to annual frequency.

Source: Clarkson's *Shipping Intelligence Network*.

Figure 2: Shipping capacity
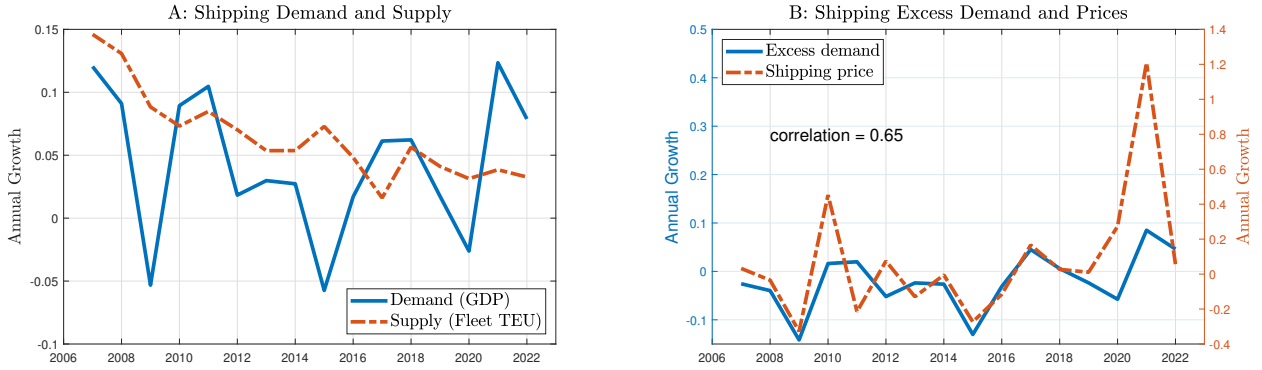
Source: Clarkson's *Shipping Intelligence Network* and the International Monetary Fund's *World Economic Outlook*.

Figure 3: Shipping demand, supply, and prices

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 considerations suggest that fluctuations in the degree of excess demand for global shipping services are likely to be positively correlated with shipping prices. That is, in periods in which the demand for global shipping services exceeds global shipping supply, we are likely to observe higher increases in global shipping prices. Panel B of Figure 3 shows that this is indeed the case: Excess demand for shipping tracks closely with shipping prices, with the annual growth of these variables featuring a correlation equal to 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 of global shipping prices.

A: Average Earnings and New Orders of Ships — B: Distribution of Time to Build New Ships

Figure 4: Shipping investment

2.3 Shipping investment

Finally, we turn to investigating the dynamics and determinants of investments in shipping capacity. Panel A of Figure 4 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 equal to 0.68. One interpretation is that, as fluctuations of excess demand lead to changes in shipping prices, these also affect average containership earnings. 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 B of Figure 4 shows a histogram with the distribution of ship production times (partitioned into less than 8,000 TEU and more than 8000 TEU) by year, taken from a snapshot of a comprehensive containership orderbook in 2022. We observe that ships typically take at least 2 years to finish construction. Then, while these orders are made contemporaneously to price 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 prices.

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[6]We track 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). Average containership earnings series are based on average charter rates weighted by the number of ships in the fleet in different size ranges.

3 Model

In this section, we set up a model of international trade with endogenous shipping capacity to investigate the underlying channels accounting for the dynamics observed in the data and their aggregate implications.

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 tradable goods, a producer of non-tradable goods, and a producer 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.

While the structure of the two countries is identical, we allow some parameters to be country-specific. Thus, 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 ("*").

3.1 Household

Each country is populated by a representative household that is infinitely-lived and discounts the future at rate $\beta < 1$. The household's period utility function is as in Heathcote and Perri (2002): $\frac{\left[c_t^\mu (1-n_t)^{1-\mu}\right]^{1-\gamma}}{1-\gamma}$, 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 capital rental income r_{Kt} from renting out the physical capital to be used for production by firms. In addition, households earn dividends from the ownership of 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 capital adjustment cost. Given capital depreciates at rate δ, the

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

evolution of the aggregate capital stock consists of:

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

where Φ_k is a constant that controls the cost of choosing investment levels different than the steady-state. Given this formulation, i_t denotes gross investment, used to pay for both the increase in physical capital and the capital 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 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 $\frac{\Phi_b}{2} \left(b_{t+1} - \bar{b} \right)^2$, where Φ_b is a constant that controls the cost of holding bonds different than steady-state bond holdings $\bar{b}$.

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

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

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:

$$\max \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \frac{[c_t^\mu (1 - n_t)^{1-\mu}]^{1-\gamma}}{1 - \gamma}$$

subject to

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

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

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} and labor n_{Tt} with time-invariant sector-specific productivity a_T and time-varying aggregate productivity z_t. The production

function is then given by:

$$y_{Tt}^h = z_t a_T k_{Tt}^\theta n_{Tt}^{1-\theta},$$

where y_{Tt}^h denotes the amount of domestic tradable varieties produced, and θ denotes the capital share.

Domestic tradable varieties are sold domestically and internationally to producers of tradable 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} and n_{Tt} to maximize profits π_{Tt}^h. The firm's problem is given by:

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

subject to

$$y_{Tt}^h = z_t a_T k_{Tt}^\theta n_{Tt}^{1-\theta}.$$

3.3 Producers of tradable goods

A representative firm produces tradable goods y_{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:

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

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

The problem of the firm consists of choosing the amounts q_{Tt}^h and q_{Tt}^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 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_{Tt}:

$$\max \pi_{Tt} = p_{Tt}y_{Tt} - p_{Tt}q_{Tt}^h - (\tau p_{Tt}^* + h_t)q_{Tt}^f$$

subject to

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

3.4 Producers of non-tradable goods

A representative firm produces non-tradables 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:

$$\max_{n_{Nt}} \pi_{Nt} = p_{Nt}y_{Nt} - w_t n_{Nt}$$

subject to

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

3.5 Producers of final goods

A representative firm produces final goods y_t combining tradable goods q_{Tt} and non-tradable goods q_{Nt}. To produce final goods, 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.

Final goods are only sold to domestic households, who use them for consumption as

well as 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 both tradable and non-tradables as given and chooses q_{Tt} and q_{Nt} to maximize profits π_t. The firm's problem is given by:

$$\max \pi_t = p_t y_t - p_{Tt} q_{Tt} - p_{Nt} q_{Nt}$$

subject to

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

3.6 Global shipping firm

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

The global shipping firm sells global shipping services to producers of tradable goods from each country at price h_t per unit of shipping capacity. 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.

Then, we have that the global shipping firm is a necessary intermediary between producers of tradable varieties and their international buyers. Thus, 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 than or equal to the shipping capacity available in that period:

$$q_{Tt}^f + q_{Tt}^{h\,*} \leq g_t,$$

where q_{Tt}^f denotes the home country's imports of tradable varieties from the foreign country and $q_{Tt}^{h\,*}$ denotes the foreign country's imports of tradable varieties from the home country.[8]

The global shipping firm is owned by households in each of the countries. We assume

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[8]Note that this specification abstracts from the directional nature of shipping. In our model, a given shipping capacity can be used to ship all varieties in either direction or to equally split total shipments between the two possible directions. In reality, however, using a given shipping capacity to transport goods only in one direction means ships have to travel empty in the other direction, leaving room to expand the amount of goods shipped.

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 shipping capacity 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 investment 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 δ_G. Thus, the law of motion of shipping capacity is given by:

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

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 $\frac{\Phi_g}{2}\left(i_{Gt} - \delta \overline{g}\right)^2$, where Φ_g controls the magnitude of the adjustment costs and $\overline{g}$ denotes the steady-state level of shipping capacity. 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 lifetime expected profits Θ_t:

$$\max \mathbb{E}_0 \sum_{t=1}^{\infty} m_t \left\{ h_t g_t - [p_t \psi + (1 - \psi) p_t^*]\, i_{Gt} - [p_t \psi + (1 - \psi) p_t^*] \frac{\Phi_g}{2}\left(i_{Gt} - \frac{\delta_G}{a_G}\overline{g}\right)^2 \right\}$$

subject to

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

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

$$g_0 \text{ given},$$

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 $\left\{ w_t, w_t^*, p_t^*, p_{Tt}^h, p_{Tt}^f, p_{Tt}, p_{Tt}^*, p_{Nt}, p_{Nt}^*, r_{Kt}, r_{Kt}^*, r_t, h_t \right\}_{t=0}^{\infty}$,

- home country allocations

$$\left\{ c_t, n_t, i_t, b_{t+1}, k_{t+1}, \Pi_t, \pi_{Tt}^h, y_{Tt}, k_{Tt}, n_{Tt}, \pi_{Tt}, q_{Tt}^h, q_{Tt}^f, \pi_{Nt}, y_{Nt}, n_{Nt}, \pi_t, y_t, q_{Tt}, q_{Nt} \right\}_{t=0}^{\infty},$$

- foreign country allocations

$$\left\{ c_t^*, n_t^*, i_t^*, b_{t+1}^*, k_{t+1}^*, \Pi_t^*, \pi_{Tt}^f, y_{Tt}^*, k_{Tt}^*, n_{Tt}^*, \pi_{Tt}^*, q_{Tt}^{h\,*}, q_{Tt}^{f\,*}, \pi_{Nt}^*, y_{Nt}^*, n_{Nt}^*, \pi_t^*, y_t^*, q_{Tt}^*, q_{Nt}^* \right\}_{t=0}^{\infty},$$

- global shipping allocations $\{\Theta_t, i_{Gt}, g_{t+1}\}_{t=0}^{\infty}$,

such that the following conditions hold:

- Home country:

  1. Given prices, allocations solve household problem

  2. Given prices, allocations solve problem of producers of domestic tradable varieties

  3. Given prices, allocations solve problem of tradable goods producers

  4. Given prices, allocations solve problem of non-tradable goods producers

  5. Given prices, allocations solve problem of final goods producers

  6. Profits rebated back to households: $\Pi_t = pi_t + \pi_{Tt} + \pi_{Nt} + \pi_{Tt}^h$

  7. Labor market clears: $n_{Tt} + n_{Nt} = n_t \ \forall t$

  8. Capital market clears: $k_{Tt} = k_t \ \forall t$

  9. Domestic tradable varieties clear: $y_{Tt}^h = q_{Tt}^h + q_{Tt}^{h\,*}$

  10. Tradable goods clear: $y_{Tt} = q_{Tt}$

  11. Non-tradable goods clear: $y_{Nt} = q_{Nt}$

  12. Final goods clear:

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

- Foreign country:

    1. Given prices, allocations solve household problem

    2. Given prices, allocations solve problem of producers of domestic tradable varieties

    3. Given prices, allocations solve problem of tradable goods producers

    4. Given prices, allocations solve problem of non-tradable goods producers

    5. Given prices, allocations solve problem of final goods producers

    6. Profits rebated back to households: $\Pi_t^* = pi_t^* + \pi_{Tt}^* + \pi_{Nt}^* + \pi_{Tt}^{h\,*}$

    7. Labor market clears: $n_{Tt}^* + n_{Nt}^* = n_t^* \ \forall t$

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

    9. Domestic tradable varieties clear: $y_{Tt}^{f\,*} = q_{Tt}^f + q_{Tt}^{f\,*}$

    10. Tradable goods clear: $y_{Tt}^* = q_{Tt}^*$

    11. Non-tradable goods clear: $y_{Nt}^* = q_{Nt}^*$

    12. Final goods clear:

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

- Global shipping:

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

    2. Shipping services clear: $q_{Tt}^f + q_{Tt}^{h\,*} = g_t$

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

4 Quantification approach

In this section we 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 a key feature of the post-pandemic dynamics: the rapid increase in the demand and absorption of tradable goods. 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 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 following the pandemic. Given data limitations, 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.

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

4.1 Experiment

Motivated by the persistent increase in the demand for tradable goods observed in the data (see Figure 1), we study the impact of a persistent shock to the share of tradables χ in the production of final goods. We assume the economy is in its steady-state prior to the pandemic and that in the second quarter of 2020 the economy experiences an unexpected increase of χ from its baseline value to χ_H for 8 quarters. We let period 0 denote the initial steady state and assume that the full path of shocks is observed in period 1. Agents observe that the shock raises χ to χ_H for 8 periods, with its value reverting back to the initial steady-state level in period 9 — we study the perfect foresight solution of the model in response to this shock.

4.2 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 share θ, the capital depreciation rate δ, the elasticity of substitution between domestic and imported varieties ρ, the elasticity of substitution between tradable and nontradable goods η, the shipping capacity depreciation rate δ_G, and the shipping production lag J (that is, the number of periods between investment in and output of shipping capacity). We normalize the productivity of producers of tradable varieties a_T and the productivity

of producers of non-tradable goods a_N 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. Finally, without loss of generality we focus on an economy under international financial autarky ($\Phi_b = \infty$).

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 elasticity of substitution between domestic and imported varieties ρ to 1.50, the share of consumption μ in 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). For simplicity, we assume the elasticity of substitution between tradable and non-tradable goods is the same as the elasticity between domestic and imported tradables, $\eta = 1.50$.

We set the quarterly shipping depreciation rate δ_G to 0.03%, which is close to estimates from Tvedt (2003). 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 the changes in shipping capacity implied by the model are consistent with the ship production density observed in Clarkson's *Shipping Intelligence Network*.

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 tradable weight χ in the production of final goods, 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 prior to the onset of COVID-19: (*i*) the imports-to-output ratio in tradable goods, (*ii*) the share of tradables in aggregate GDP, and (*iii*) the share of shipping costs in the total cost of imports.

To compute empirical counterparts to these moments, we begin by classifying goods into tradable and non-tradable. We define tradable goods as those classified as goods in the aggregate output tables of the Bureau of Economic Analysis (BEA's). Non-tradable goods are defined as those classified as services in the BEA tables. For moment (*iii*), we target a ratio of shipping costs to imports equal to 5%, as documented in Clark et al. (2004).

The estimated parameters as well as the empirical targets and their model counter-

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
θ	0.36	Capital production share
δ	0.025	Capital depreciation rate
ρ	1.50	Elasticity between domestic and imported varieties
η	1.50	Elasticity between tradable and non-tradable goods
δ_G	0.03	Shipping capacity depreciation rate
J	6	Shipping production lag
a_N	1	Productivity of non-tradable goods
a_T	1	Productivity of tradable varieties
ψ	0.50	Share of shipping firm owned by home country
Φ_b	∞	Bond-holding cost

parts 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 absorption of tradable goods is imported. The model requires a relatively low share of tradables in the production of final goods χ to match the low share of imports in tradable GDP. Finally, the ratio between shipping costs and imports is determined by the steady-state level of shipping investment productivity a_G.

Parameters estimated to match dynamics following COVID-19 Given our approach to modeling the pandemic, we estimate the remaining parameters to match salient features of the dynamics following the onset of COVID-19: the higher weight on tradables χ_H during the pandemic, the capital adjustment cost ϕ_k, and the shipping adjustment cost ϕ.

We choose the three estimated parameters to match the following features of the data after the onset of COVID-19 relative to pre-pandemic levels: (*i*) the growth of the tradable share of aggregate GDP in the U.S., (*ii*) the growth of capital investment in the U.S, and (*iii*) the global change in the shipping investment rate.[9]

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[9]To isolate the impact of the increased demand for tradables we interpolate the values for 2020Q2. This

Table 2: Estimated parameters, pre-pandemic steady state

Parameter	Value	Description
τ	3.18	Iceberg trade cost
χ	0.22	Share of tradables in final goods
a_G	0.51	Shipping investment productivity
Moment	Data	Model
Imports / Tradable output	0.14	0.14
Tradable GDP / Aggregate GDP	0.23	0.23
Shipping costs / Imports	0.05	0.05

We compute empirical counterparts for these moments as follows: We compute moment (i) using tradable and aggregate output values from the BEA. We compute moment (ii) using data on investment from the BEA. For moment (iii), we use data on new ship orders and total fleet capacity from Clarksons *Shipping Intelligence Network*.

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 3 reports the estimated parameters as well as the empirical targets and their model counterparts. We find that the three estimated parameters match the target moments quite closely.

Figure 5 plots the estimated shock along with the dynamics of the tradable share of GDP in both the model and the data. We find that the estimated shock accounts well for the increase of the tradable share throughout the pandemic. In particular, note that the model matches the dynamics of the tradable share change fairly well despite our assumption that χ increases to a higher value that remains constant throughout the pandemic.

5   Quantitative results

We now investigate the impact of the increased demand for tradable goods during the outbreak of COVID-19.

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allows us to abstract from increases in the share of tradables driven solely by the decline of non-tradables.

Table 3: Estimated parameters, pandemic dynamics

Parameter	Value	Description	
χ_H	0.25	Tradables weight during pandemic	
ϕ_k	5.94	Capital adjustment cost	
ϕ	2178.95	Shipping adjustment cost	

Moment	Target value	Model
Tradable output / GDP, avg. log-change	0.13	0.13
Investment, avg. log-change	0.053	0.053
Shipping investment rate, avg. change	0.019	0.014

Note: The first two moments are computed as the average log-change over the period from 2020Q2 to 2022Q1 relative to their respective pre-pandemic values. The last moment is computed as the average change over the period 2020Q2 to 2021Q2 relative to its pre-pandemic value. We compute pre-pandemic values as the average over the period 2018Q1 to 2020Q1.
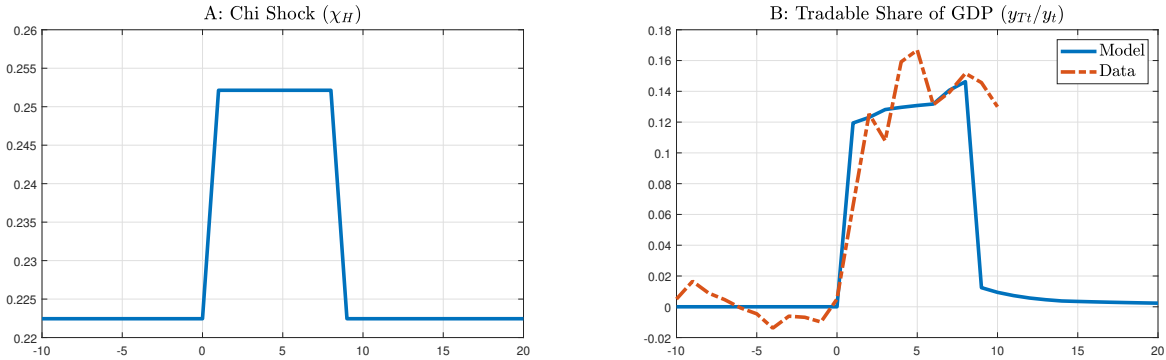
Figure 5: Shock to χ and implied dynamics

5.1 Aggregate dynamics following increased demand for tradables

We begin by examining the dynamics of key aggregate variables following the shock to χ presented in Figure 5. We plot the dynamics of key variables in Figure 6, expressed as log-deviations from their steady-state values, except for capital investment i which we express as the percent deviation from its steady-state value. We restrict attention to the dynamics over the five years (20 periods) following the onset of the pandemic.

The increase in the weight χ of tradables in the production of final goods has 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}).

These changes in the composition of aggregate absorption are identically mirrored by the dynamics of output of tradable and non-tradable varieties. While this need not
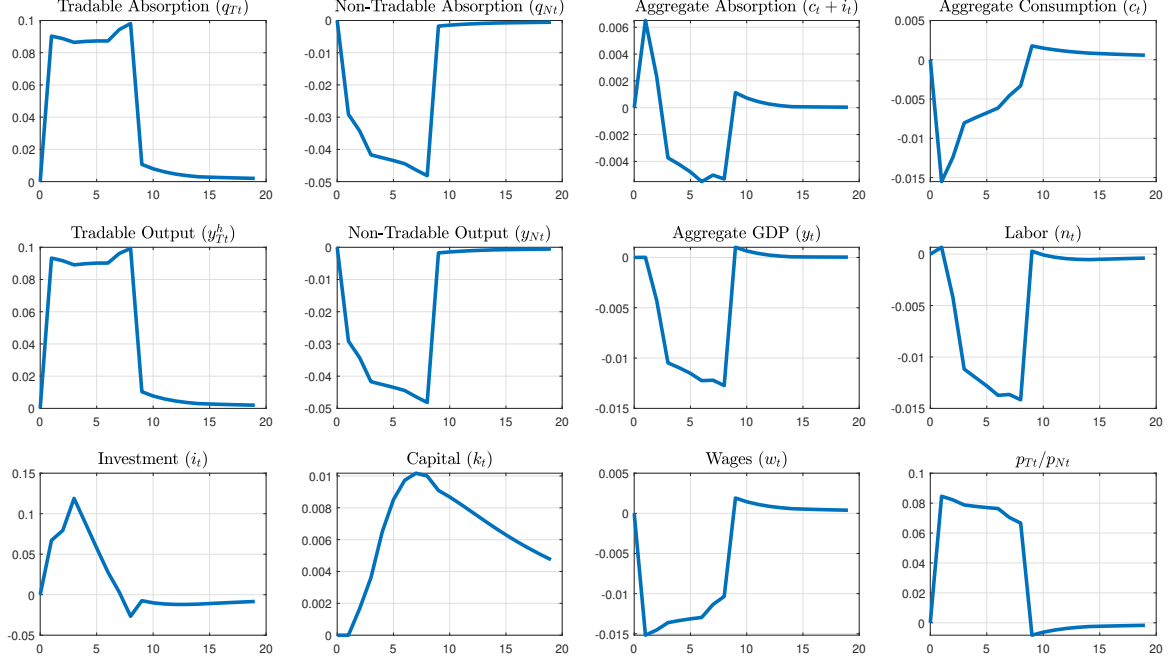
Figure 6: Aggregate dynamics following increased demand for tradables

generically be the case for tradable varieties, it is the case here given the global nature of the shock and our focus on symmetric countries. In contrast, this is trivially the case for non-tradables, given that absorption and output of these goods need to equal each other in equilibrium.

The change in the relative demand for tradable and non-tradable goods also affects the relative price between these goods (p_{Tt}/p_{Nt}). While output of tradable goods increases on impact as labor is reallocated across sectors, this sector is more capital-intensive than non-tradables, so increasing production scale requires capital investments that take time and are subject to adjustment costs. Thus, the transitory nature of the shock implies that production of these goods does not increase as much as desired, leading to an increase in their relative price.

In the aggregate, these effects lead to a decline in real GDP. While aggregate investment increases as producers of tradable goods demand a higher amount of capital to scale up production, production of these goods does not increase as much as desired given the short-lived nature of the shock. On the other hand, production and demand for non-tradables does decline in tandem with the decrease in demand for these goods. Thus, the net impact of the shock is to reduce real GDP and aggregate consumption. In contrast, aggregate absorption increases initially due to the investment spike, but declines thereafter as the investment boom subsides.

5.2 Shipping dynamics following increased demand for tradables

We now investigate the implications of our model for the dynamics of shipping and international trade following the increased demand for tradable goods. We report these dynamics in Figure 7. We ask: To what extent can the reallocation of demand toward tradable goods account for the dynamics of global shipping observed in the aftermath of COVID-19?

We find that, despite the sharp increase in the demand for domestic and imported tradable goods, real exports and real imports of these goods remain unchanged over the first 6 quarters. This is accounted by the short-run rigidity of shipping capacity: Investments to increase shipping capacity take several periods to become operational (6 quarters in our parametrization), thus limiting the amount of trade to the capacity installed prior to the shock. As a result, shipping prices (h_t) increase substantially to ration out the limited capacity across the increased demand for international shipments.

The higher shipping prices raise the returns to investments in shipping capacity, leading to an increase in the shipping investment rate over the first couple of periods after the shock is realized. The lengthy shipping production lag along with the transitory nature of the shock imply that shipping investments increase only over the first couple of periods, reverting thereafter. There are no incentives to invest after these first periods, since later investments would become operational after the shock dissipates.

As investments in shipping capacity become operational in period 7 (that is, 6 periods after the investments are made), we observe that real exports and real imports increase in tandem, and shipping prices 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.

After the shock expires, the world economy experiences a decline in the relative demand for tradable goods. However, the investments to increase shipping capacity during the shock along with the costs to adjust shipping capacity imply that there is now more supply of shipping capacity than in the initial steady state. This leads to a decline of shipping prices below their initial steady-state values and to levels of international trade flows higher than prior to the shock. Finally, note that net exports remain unchanged throughout, given our focus a global shock in a world economy with symmetric countries.

Model vs. data We find that these shipping dynamics are consistent with salient features of shipping dynamics observed in the data, even for variables not targeted in our estimation of the model.

Panel A of Figure 8 contrasts the dynamics of shipping prices (h_t) in the model
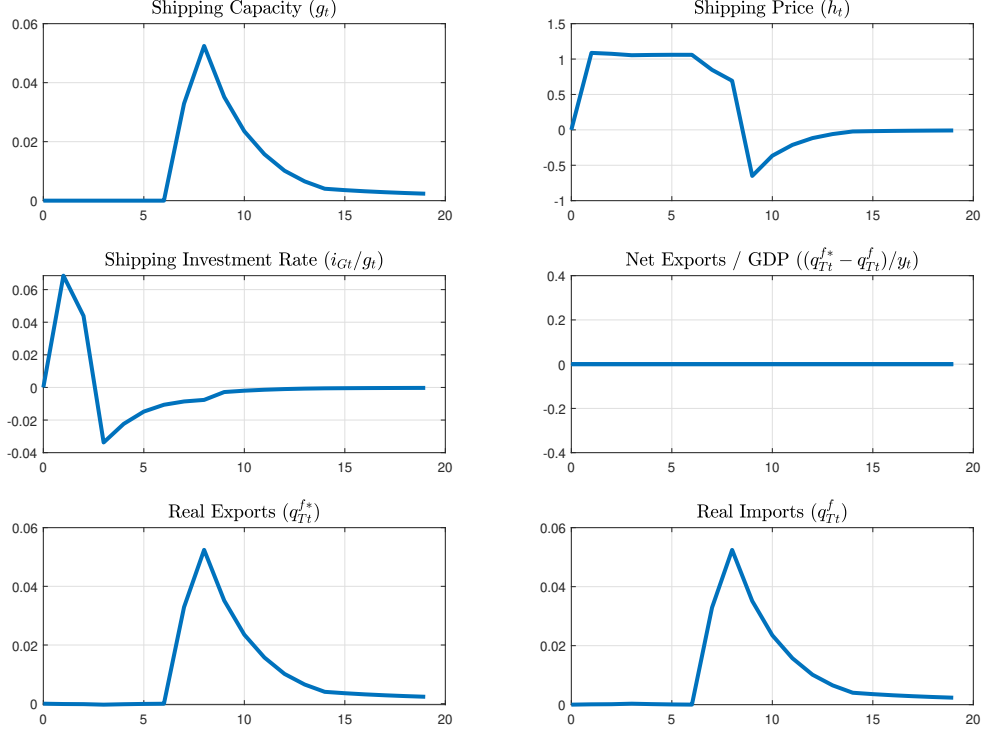
Figure 7: Shipping dynamics following increased demand for tradables

with their empirical counterpart. We find that the implications of the model mirror the dynamics observed in the data, accounting for approximately two thirds of the peak increase in shipping prices, while also exhibiting a decline around period 8.

Panel B of the figure contrasts the dynamics of shipping capacity in the model relative to the empirical distribution of shipping production lags. The latter captures the typical response of shipping capacity in response to investments made in period 0. This is akin to the dynamics of shipping capacity in our model, given that the model features a sharp spike in shipping investment in periods 1 and 2. We find that the model implies dynamics of shipping capacity in response to changes in shipping investment that are in line with the data. This finding provides evidence in support of the assumptions underlying shipping investments in the model.

5.3 Aggregate implications of shipping capacity

The previous findings show that the model implies realistic shipping dynamics in response to an increase in the demand for tradable goods, as observed in the aftermath of COVID-19. In particular, these findings show that rigid shipping capacity signficantly limited the adjustment of international trade flows, leading to a sharp increase in shipping costs.

We now investigate the extent to which the rigid short-run supply of shipping capacity
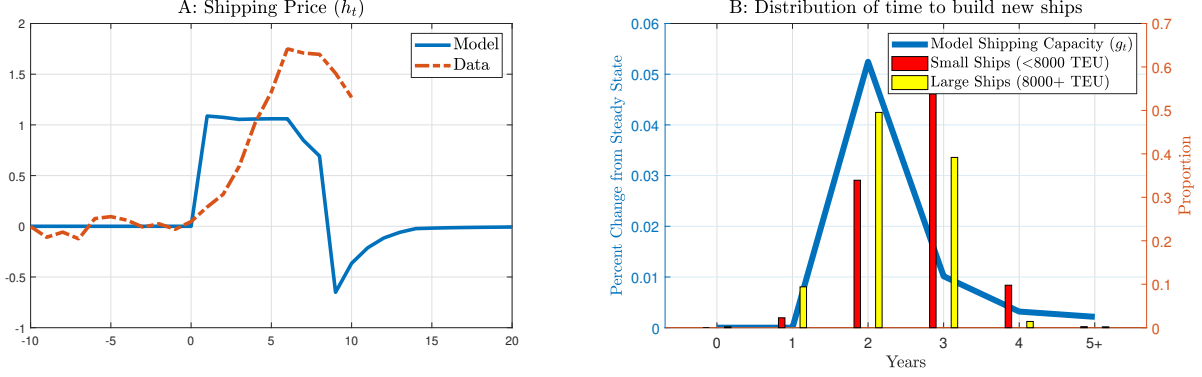
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Figure 8: Shipping dynamics: Model vs. data

affects the dynamics of key aggregate outcomes of the model. That is, we ask: To what extent does rigid shipping capacity affect the aggregate dynamics following an increase in the demand for tradable goods? To answer this question, we contrast the implications of our model with those of a counter factual economy with a perfectly elastic and costless supply of shipping capacity (referred to as Perfectly Elastic Shipping Supply [PESS] in Figure 9). This is implicitly the assumption in standard models of international trade and international business cycles (Backus et al. 1995; Heathcote and Perri 2002). We recalibrate the parameters from Table 2 to ensure both economies look identical in the pre-pandemic steady state. But we keep all the parameters estimated to pin down the dynamics implied by the model (Table 3) unchanged at their baseline values, avoiding differences in these from driving differences in the implied dynamics.

Figure 9 plots the dynamics of key aggregate variables following the same shock as in the baseline model, contrasting the baseline economy vis-a-vis the counterfactual with perfectly elastic and costless supply of shipping capacity. We interpret differences in the implied dynamics as accounted for by the different shipping technologies across the two models.

We find that tradable output and absorption increase relatively less in our baseline model than in the model with perfectly elastic shipping supply. In the baseline, demand for domestic and imported tradables increases, but the availability of imported tradables is limited by the pre-installed shipping capacity, which limits the extent to which producers increase output. In contrast, this is not a constraint in the model with perfectly elastic shipping capacity. In this model, production of tradables increases relatively more given that exports of these goods can increase more easily than in the baseline.

The differences in the shipping technology across the two models have important implications in the aggregate. For instance, real GDP decreases significantly more in the baseline than in the model with perfectly elastic shipping supply: the decline is 25% larger
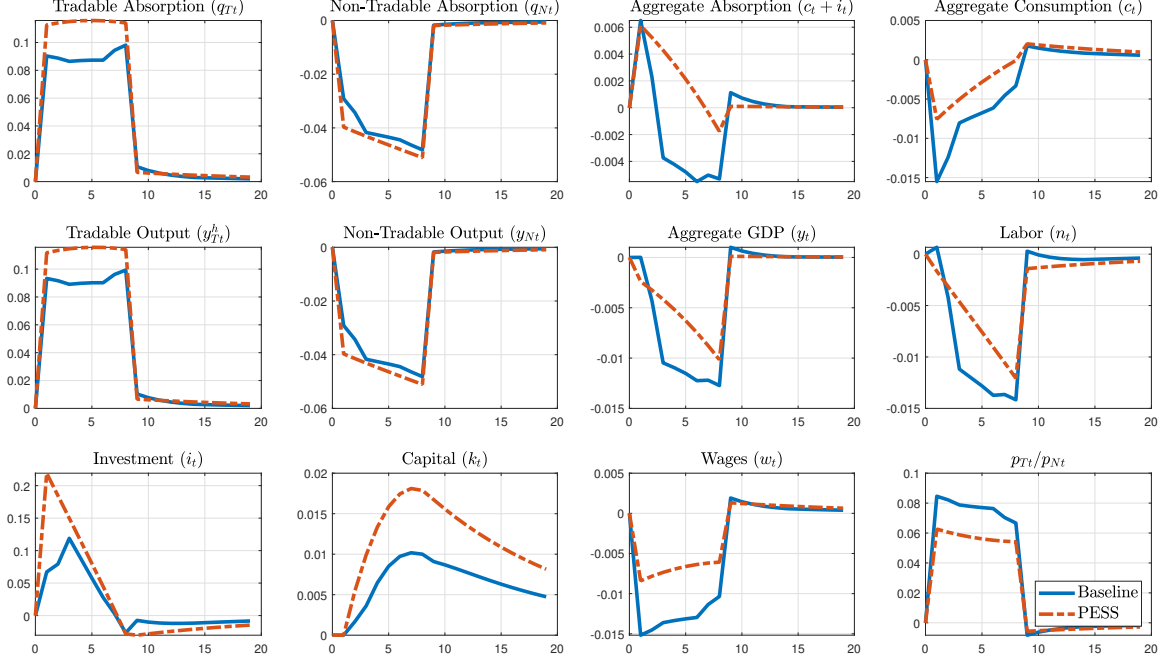
Figure 9: Aggregate implications of shipping capacity

at the trough in the former than in the latter. Similarly, we find significant quantitative differences in the dynamics of aggregate absorption, consumption, and investment between the two models. Thus, we conclude that differences in the shipping technology can have significant aggregate effects despite only affecting the tradable goods sector, which is only a fraction of all economic activity.

6   Concluding remarks

This paper studies the determinants and aggregate implications of global shipping dynamics. Motivated by salient features of the dynamics of global shipping that we document, we develop a multi-country dynamic model of international trade with endogenous global shipping supply. We find that the model can account for salient features of global shipping dynamics. In particular, the model accounts for a significant fraction of the unprecedented increase of international shipping costs observed in the aftermath of COVID-19. We find that accounting for these dynamics of global shipping have important implications for the dynamics of aggregate economic activity. Our findings can be important for shaping future policies in response to such developments, as well as evaluating the potential limitations of our state-of-the-art models of international trade and macroeconomic dynamics.

References

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

ALESSANDRIA, G., S. Y. KHAN, A. KHEDERLARIAN, C. MIX, AND K. J. RUHL (2022): "The Aggregate Effects of Global and Local Supply Chain Disruptions: 2020–2022," .

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

BACKUS, D., P. KEHOE, AND F. KYDLAND (1995): "International Business Cycles: Theory vs. Evidence," *Frontiers of Business Cycle Research*.

BEHRENS, K., C. GAIGNÉ, G. I. OTTAVIANO, AND J.-F. THISSE (2006): "How density economies in international transportation link the internal geography of trading partners," *Journal of Urban Economics*, 60, 248–263.

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

BRANCACCIO, G., M. KALOUPTSIDI, AND T. PAPAGEORGIOU (2020): "Geography, transportation, and endogenous trade costs," *Econometrica*, 88, 657–691.

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

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

CLARK, X., D. DOLLAR, AND A. MICCO (2004): "Port efficiency, maritime transport costs, and bilateral trade," *Journal of Development Economics*, 75, 417–450.

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

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

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

GANAPATI, S., W. F. WONG, AND O. ZIV (2021): "Entrepot: Hubs, scale, and trade costs," Tech. rep., National Bureau of Economic Research.

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

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

HEATHCOTE, J. AND F. PERRI (2002): "Financial autarky and international business cycles," *Journal of monetary Economics*, 49, 601–627.

HEILAND, I. AND K. H. ULLTVEIT-MOE (2020): "11 An unintended crisis is sea transportation due to COVID-19 restrictions," *COVID-19 and trade policy: Why turning inward won't work*, 151.

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

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

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

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

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

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

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

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

TVEDT, J. (2003): "Shipping market models and specification of freight rate processes," *Maritime Economics and Logistics*, 5, 327–346.

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