

# Trade Costs and Business Cycle Transmission in a Multi-country, Multi-sector Model

(Job Market Paper)

Hirokazu Ishise\*  
Boston University  
ishise@bu.edu

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## Abstract

This paper analyzes how trade contributes to the international business cycle transmission. I construct a multi-country, multi-sector real business cycle model that is a dynamic stochastic extension of the theoretical gravity equation model (Anderson, 1979). In the model, trade patterns are determined by Ricardian comparative advantage. A productivity shock is transmitted across countries through temporary changes in trade patterns, which are driven by temporary changes in the comparative advantage. Lower trade costs facilitate this transmission effect, leading in turn to higher business cycle comovement. By exploiting the model structure and trade flow data, I estimate exporter-importer- product- year-specific trade costs for 10 single-digit Standard International Trade Classification categories for 21 OECD countries from 1962 to 2000. The cross-sectional variation in the estimated trade costs generates cross-country variations in trade and fluctuations. The model accounts for the data better than typical models in the literature along several dimensions: the variation in bilateral trade, the correlations between output and trade flows, the business cycle comovement across countries, and the association between bilateral trade and comovement. The multiplicity of countries in the model affects the implication of the trade-comovement association. The parameterized model suggests a reduction in trade costs increases the magnitude of comovement, but does not greatly increase volatilities of output and consumption.

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\*Contact: Department of Economics, Boston University, 270 Bay State Road, Boston, MA 02215 USA. Tel.: (857)225-0865. The separate appendix is available at <http://people.bu.edu/ishise>

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# 1 Introduction

The rapid spread of the ongoing economic downturn raises the question of how international trade contributes to the transmission of business cycles across countries.<sup>1</sup> Cross-country regression studies introduced by Frankel and Rose (1998) show that high bilateral trade between two countries is robustly associated with more correlated business cycles. However, these regressions do not reveal the underlying mechanisms for this trade-comovement association. Meanwhile, potential candidates for analyzing the mechanism of the cross-country business cycle phenomena, international real business cycle (IRBC) models, have failed to reproduce important data facts of cross-country business cycles. The typical IRBC models cannot replicate positive cross-country correlations of output, investment, and labor, as well as a negative intra-country correlation between net exports and output.<sup>2</sup> In this paper, I construct an IRBC model that is consistent with these essential data facts. Then I use the model for understanding the mechanism how trade contributes to the international business cycle transmission.

Specifically, I construct an international real business cycle model, including the dynamics of multiple (more than two) countries and multiple intermediate products (more than one product per country) with capital accumulation and international assets trading. The multi-sector structure creates Ricardian comparative advantage in the model, and temporal changes in the comparative advantage are the central mechanism to generate international comovement. After a positive productivity shock in one of the sectors in one country, the country temporarily becomes more specialized in this sector. The country increases production of this intermediate product and increases imports of other intermediate products. The enlarged imports drive other countries' exports and aggregate output. Hence, a positive productivity shock in one country delivers world-wide economic booms through the expansion of trade. Moreover, if a pair of countries faces low trade costs, the pair more easily exploits the enlarged trade opportunity. A lower trade cost generates both higher bilateral trade on average and a higher comovement after the shock. Hence, a higher bilateral trade is positively associated with higher comovement.

For asking how much multi-country, multi-sector structure can explain the bilateral trade and the degree of comovement, the model trade costs are quantified based on the data. Exploiting the model structure and large dimensional international trade data (Feenstra et al., 2005), I estimate exporter- importer- product- year-specific trade costs for 10 single-digit Standard International Trade Classification categories for 21 OECD countries from 1962 to 2000. The estimation does not impose either country-by-country or period-by-period trade balance

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<sup>1</sup>“The downturn has been sharpest in countries that opened up most to world trade, especially East Asia’s tigers.... Is there a trade-off between taking advantage of good times and providing shock absorbers for bad ones?” (“Turning their backs on the world: Globalisation,” *The Economist*, February 21, 2009).

<sup>2</sup>e.g., Backus et al. (1994), Ambler et al. (2002) and Heathcote and Perri (2002). Baxter (1995) summarizes the literature in the early years. I review the performance of IRBC models further in Section 2.

assumptions. Contrary to the standard international trade studies, I use trade costs to quantify, not only cross-sectional variation in a point of time, but also the changes over time as well as the shock process of trade costs. The explicit consideration of time-series fluctuations in trade costs is important. I provide an evidence that there are sizable fluctuations in trade costs over time. In addition, the fluctuations in the trade costs affect model comovement properties because shocks in trade costs are determinants of the comparative advantage in the model.

The most important contribution of the paper is to provide evidence that a multi-sector structure, together with carefully estimated trade costs, quantitatively explains international business cycles in the data. Obstfeld and Rogoff (2000) illustrate the qualitative importance of including trade costs for explaining international macro data. However, the connection of the IRBC models to the empirically estimated trade costs is not straightforward, since most of the IRBC models are two-country, one-sector models. Ambler et al. (2002) and Arkolakis and Ramanarayanan (2009) suggest multi-sector models can explain comovement within a two-country framework. By expanding model to multi-country and multi-sector, the model in this paper has a tight link to empirically employed trade models. Then, I show that the heterogeneity in trade costs in multi-country, multi-sector structure can resolve the problems in the IRBC models: the cross-country correlations (Backus et al., 1992, 1994; Baxter, 1995), the variation in bilateral trade, and the association of trade and comovement (Kose and Yi, 2006).

Another important contribution of the paper is to show that the number of countries in the model has an important consequence on the trade-comovement association in the model. Contrary to two- or three-country models (Kose and Yi, 2006; Burstein et al., 2008; Arkolakis and Ramanarayanan, 2009), a multi-country model allows for direct comparison of empirical studies with the model, because the model generates cross-sectional variation of countries. A regression coefficient derived from a model explicitly including many countries is closer to the data than one obtained from a corresponding three-country model. This difference in the model coefficients suggests a potential bias of two- or three-country IRBC-based studies in the literature (e.g., Kose and Yi, 2006).

The parameterized model simultaneously accounts for data facts about the variation in bilateral trade, the correlations between output and trade flows, the business cycle correlations across countries, and the association between bilateral trade and comovement. I use the model to analyze international business cycle phenomena; how cross-country correlations are determined by the contributions of productivity shocks, trade cost shocks, transmission through trade, and transmission through financial connections. Changing the parameters has policy implications; how much can we reduce the size of the business cycles and their comovement by changing trade costs at the expense of long-run welfare. Decreasing trade costs raises output comovement because trade increases. On the one hand, a shock in one country easily transmits to another country. On the other hand, larger trade implies more diversification of

intermediate goods suppliers. By offsetting these two opposite effects, the standard deviations of output and consumption do not greatly increase. A policy implication is that raising tariffs does not significantly contribute to stabilizing an economy.

The rest of the paper is constructed as follows: In the following section, I summarize the data facts, with relation to problems in pertinent literature. Section 3 introduces the model. I explain the quantification methodology of the model, and present the estimated trade costs in Section 4. Section 5 presents the main results, including the explanation of the mechanism of the model and the examination of the effect of relevant policies. The final section presents my conclusion.

## 2 Business cycle correlations and trade

In this section, I discuss the data facts of international trade and business cycles. Relating the data, I suggest three potential problems in the previous research: (1) the model property of the typical international real business cycle (IRBC) models; (2) the specification of trade costs in IRBC models; and (3) the comparability of regression-based and model-based approaches. Then, I explain how I address these three problems using various modifications proposed in the literature.

There is accumulating evidence that a pair of countries with higher levels of bilateral trade are positively correlated with the degree of their output comovement. The basic setup of the regression is:

$$corr_{ij} = \alpha_0 + \alpha_1 trade_{ij} + \varepsilon_{ij} \quad (1)$$

where  $corr_{ij}$  is an output correlation measure between country  $i$  and country  $j$ , and  $trade_{ij}$  is a measure of bilateral trade intensity between  $i$  and  $j$ . Usually, the output correlation is measured by a cross-country correlation of output in the business cycle frequency.<sup>3</sup> The bilateral trade intensity is typically, and throughout this paper, defined as

$$trade_{ij} = \log \left( \frac{1}{T} \sum_{t=1}^T \frac{EX_{i,j,t} + EX_{j,i,t}}{Y_{i,t} + Y_{j,t}} \right). \quad (2)$$

where  $EX_{i,j,t}$  are total exports from  $i$  to  $j$  at  $t$ , and  $Y_{i,t}$  is GDP per capita. The sample is  $(i, j) \in N(N - 1)/2$  pair of countries among  $N$  countries. Frankel and Rose (1998) show the positive regression coefficient is robust among various measures of correlations and trade intensity measures. Imbs (2004) and Baxter and Kouparitsas (2005) further examine the robustness of the positive coefficient. Some other variables, such as similarity in sectoral composition and

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<sup>3</sup>I use BP-filter (Baxter and King, 1999) to calculate business cycle components. See the Appendix.

gravity variables (such as bilateral distance and sharing a border), are significantly associated with comovement. Yet, after controlling for a variety of variables, the trade intensity measure is found to positively correlate to comovement.<sup>4</sup> I calculate the coefficient based on the seven major OECD (G7) countries (Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States), which is the target of the comparison in this paper (Table 1). The business cycle moments are calculated based on the OECD quarterly national accounts from 1970–2006. The bilateral trade intensity is calculated using trade data set by Feenstra et al. (2005) and annual national accounts of the Penn World Table (Heston et al., 2008).<sup>5</sup> Table 2 shows the countries’ average of bilateral trade intensity. Table 2 also shows the standard deviations of output and consumption, and the trade-GDP ratio of the country, which is the combined mean of exports to GDP ratio and imports to GDP ratio. Note that there is no strong association between trade and output (or consumption) volatility among these countries, although seven observations are too few to reach a conclusion.

The top rows of Table 1 show estimated coefficients,  $\alpha_1$ , for the G7 observations.<sup>6</sup> Since the number of observations is limited in this sample, the standard error of the slope coefficient is large. Yet, a positive slope coefficient holds among the G7 countries. The upper-left panel of Figure 1 presents the scatter plot of the bilateral trade intensity and the business cycle comovement. As expected from a large standard error in the regression, there is a large variation in terms of output correlation across pairs of countries. The label of the pair in the figure suggests that the association is intuitive one. For example, the US and Canada pair shows a high bilateral trade intensity and a high comovement. A pair which consists of two separated countries, Japan and Italy, shows a low trade intensity and a low comovement.

A limitation of these regression studies is the difficulty in interpreting the underlying mechanism for this correlation. A growing literature (Kose and Yi, 2006; Burstein et al., 2008; Arkolakis and Ramanarayanan, 2009) asks whether versions of the international real business cycle (IRBC) models can generate this empirical correlation. Kose and Yi (2006) extend the models of Backus et al. (1994) and Heathcote and Perri (2002) to three countries, and they

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<sup>4</sup>Recently, di Giovanni and Levchenko (2008) examine trade intensity and comovement in disaggregate trade measures into the ISIC-3 digit level.

<sup>5</sup>I explain the details of the data and calculation in the Appendix.

<sup>6</sup>The standard errors are heteroskedasticity robust standard errors. The IV coefficients are obtained by two-step efficient linear generalized method of moments and the instruments are log of the bilateral distance, indicator of the sharing national border, indicator of the colonial relationship, and indicator of the common language. As mentioned by Frankel and Rose (1998), instrumental variable methods using gravity variables as instruments for the bilateral trade intensity imply larger coefficients. Yet Baxter and Kouparitsas (2005) show gravity variables are correlated with comovement even if bilateral trade is controlled (see also Clark and Wincoop, 2001). This direct effect of the gravity variables on comovement may be a result that the gravity variables proxy some other potential omitted variables. Regardless of the mechanism, the direct correlation of the gravity variables and comovement after controlling trade suggests gravity variables do not necessarily satisfy the orthogonality condition of the instrumental variable approach. Nevertheless, I use IV methodology in the model section following the literature, but OLS and IV give similar coefficients in the model (See Section 5).

find that the prototypical IRBC model (Backus et al., 1994) with the standard parameters is difficult to replicate variation in the bilateral trade intensity and the trade-comovement regression coefficient. If goods with different origins are assumed to be complements (instead of substitutes), the model shows empirically comparable numbers for both trade intensity and the trade-comovement coefficient. With a framework having vertical integration, Burstein et al. (2008) also suggest the importance of low substitutability between products produced in different countries for explaining observed trade-comovement correlation. These IRBC results, however, contradict the trade literature (for example, Broda and Weinstein, 2006), which suggests a relatively high substitutability between products produced in different countries.

There are at least three potential problems that may create the gaps between data and model: the performance of IRBC models for explaining international business cycles, the treatment of trade costs in the IRBC models, and the target of comparison. This paper addresses all of these potential problems.

The first potential problem concerns the results of the IRBC models. Typical IRBC models successfully explain intra-country business cycle phenomena, but have struggled to explain cross-country data (Backus et al., 1992; Baxter, 1995; Ambler et al., 2004; Ishise, 2009). I summarize the problem in Table 3. The left block of Table 3 contains the data moments. The right block of Table 3 includes corresponding moments obtained by various models. The model moments are obtained from my replications using a common set of parameters.<sup>7</sup> The mean cross-country correlations are the mean values of the correlations of 21 ( $= 7 \times 6/2$ ) pairs. The table also shows standard deviations across G7 countries. The data suggest the following: Output is positively correlated across countries; consumption’s cross-country correlation is as high as output’s; investment is positively correlated across countries; labor input is positively correlated across countries; net exports (divided by output) are weakly and negatively correlated across countries; both imports and exports are pro-cyclical and imports are more strongly correlated to output; and net exports (divided by output) are counter-cyclical. Typical IRBC models (e.g., “Mid TC” in Table 3) fail to replicate some of these data facts. Typically, consumption is more strongly correlated than output. Investment is negatively correlated across countries. Net exports are almost perfectly negatively correlated across countries. Typical models also suggest net exports are pro-cyclical. The gaps between data and model require some modifications to use IRBC models for explaining international business cycles.

One of the prominent modifications is including trade costs (Obstfeld and Rogoff, 2000),

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<sup>7</sup>The prototypical model (Backus et al., 1994) is a special case of my model. Most of the parameters are the same as those in Table 5. The exceptions are: I set the number of countries to two (three in the “three-country” case) and the number of sectors to one. Population weights are 1/2 (1/3 in the “three-country” case), the capital stock adjustment parameter to 0.0001 and the market assumption is a complete market. Since there is a single layer of CES aggregation, the elasticity parameter  $\rho$  is also set to 1/3. Trade costs are the same for all the potential external trade.

Two-sector model: the number of countries is two and the number of sectors is two. There is no heterogeneity in terms of population size and trade costs. Other parameters are the same as Table 5.

but how to include trade costs in IRBC models is the second problem potentially creating the gaps between data and model. Obstfeld and Rogoff (2000) suggest that a high trade cost prevents the reallocation of investment across countries, and hence the trade costs raises cross-country correlation of investment. For this reason, the IRBC models typically aim to replicate (or set parameters so as to be consistent with) trade facts: the trade-GDP ratio of the country, which is the combined mean of exports to GDP ratio and imports to GDP ratio, is around 5–25% in major developed economies (See Table 3. Also, Backus et al., 1994); the reduced form iceberg equivalent trade cost (the required amount of goods to deliver one unit of the good) is, at most, two units on average (Anderson and van Wincoop, 2004; Alvarez and Lucas, 2007). However, a problem is that typical IRBC models include extremely large trade costs for replicating the trade-GDP ratio. IRBC models are specified either by directly including trade costs or including a home bias in the final goods production, or both. Typically, final goods production uses both home and foreign countries’ intermediate goods. A home bias in the final goods production is a weight parameter to determine the home-foreign ratio of intermediate goods. If we try to replicate trade intensity only by trade costs (setting no home bias), the models require implausibly high trade costs (the “Mid TC” model in Table 3). If a typical model try to replicate a bilateral trade intensity, a required trade cost is extremely large (the “High TC” model in Table 3). Hence, what typically done is after setting the trade cost parameter to value implied in trade cost estimations, the home bias parameter is set so as to replicate steady state trade intensity. A problem is that because directly observing a home bias parameter is difficult, empirically estimated trade costs typically include the contribution of the home bias (Anderson and van Wincoop, 2004). But as shown in Table 3, reallocating home bias to trade costs greatly inflates model-embedded trade costs. Thus, the problem is how to reconcile low trade costs, low trade intensities, and (hopefully) significant contributions of trade costs on dynamic properties of models. A resolution is to take the empirical trade model structure seriously—including many goods as in the trade models.

The third potential problem of the IRBC-based approach for explaining trade-comovement regression is that experiments conducted by previous research is not necessarily an exact counterpart of the regression studies. A two-country framework is impossible to distinguish a bilateral trade intensity (which is a pairwise statistic) and trade-GDP ratio of a particular country, as shown in Table 3. The explanatory variable of the trade-comovement regression studies are bilateral trade intensity, but two-country models usually constructed so as to be consistent with the aggregate trade-GDP ratio (Backus et al., 1994). A possible way to separate the bilateral trade intensity and the aggregate trade-GDP ratio is to introduce a third country (“the rest of the world”) in the model. Yet, contrary to the regression studies exploiting cross-sectional variations in the observed bilateral trade intensity and the correlation of output, IRBC-based study (Kose and Yi, 2006) using three-country model cannot generate cross-sectional variation within the model. Instead, IRBC-based studies draw two sets of model-

implied values of trade intensity and comovement by changing parameters, and compare these numbers to the regression coefficient of the data. I show that a regression coefficient derived from the multi-country model is closer to the data than one obtained by three-country settings.

The model in this paper addresses three problems (the performance of the IRBC models for explaining international business cycle properties, the treatment of trade costs in the IRBC models, and the target of comparison) by employing three lines of modifications in international business cycle studies: the financial market assumption, multiplicity of countries, and the multiplicity of products.

First, I employ an incomplete market assumption (Arvanitis and Mikkola, 1996). Typically, a complete market assumption implies consumption's cross-country correlation is higher than output's (see, for example, the "Mid TC" case in Table 3). A comparison of "CM" and "IM" cases of the two-sector model in Table 3 suggests the importance of the incomplete market assumption. The "IM" model can reproduce the order of output and consumption cross-country correlation as well as positive cross-country correlations of input. An alternative method is to replace the market assumption with a "financial autarky" assumption (Heathcote and Perri, 2002; Kose and Yi, 2006).<sup>8</sup> Yet, a "financial autarky" assumption requires the countries always balance trade, meaning net exports (which are equal to the current account in typical IRBC models) are always zero. As a result, a "financial autarky" assumption cannot replicate facts associated with volatilities of trade variables. Hence, I use an incomplete market assumption.

Second, the model includes more than two countries. The empirical trade-comovement regressions are examined using a sample obtained from a world having more than two countries. A multi-country model allows for direct comparison of real data with the model. Three-country extensions are examined by Zimmermann (1997) and Kose and Yi (2006), in a specific context—two large countries and one small country, or one large country (the rest of the world) and two small countries. In the single-good international real business cycle framework (Backus et al., 1992; Baxter, 1995), Head (1995) examined consumption correlation implications of a five-country model. In a companion paper, I show that the cross-country moments of single-good international real business cycle models depend critically on the number of countries in the model (Ishise, 2009). Moreover, Ishise (2009) shows an inclusion of fictitious large "rest of the world" in a three-country model gives greatly different implications of cross-sectional correlations from a model in which the "rest of the world" is reasonably disaggregated. The model dynamics of the three-country model is mostly driven by the aggregate "rest of the world." In the real world, there is no such a large country. The aggregation of the "rest of the world" can cause bias in the model implications. Instead, an explicit treatment of multiplicity

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<sup>8</sup>As discussed in Section 3, "financial autarky" is a special case of incomplete market model if we employ the transaction cost of trading bond. The result obtained by a complete asset structure is included in the Appendix.

of countries enables more relevant comparison to the data. In addition, the multiplicity of countries is critical for my estimation strategy of trade costs, which exploits a variation across importers for a particular exporter, and a variation across exporters for a particular importer.

Third, this paper expands the number of products (sectors) in the model. The goods structure in the typical IRBC models is country-specific final goods and one intermediate good per country (Backus et al., 1994). In this case, the intermediate goods are differentiated only by origin of the goods. Ambler et al. (2002) increase the number of intermediate goods to two per country, within the two-country framework. Their model shows a better performance than the basic models do in some dimensions. Comparing “Mid TC” of “One-sector” and “CM” of “Two-sector” models in Table 3 indicates the two-sector model shows a higher cross-country correlation of investment and lower consumption correlation. Along the line, Arkolakis and Ramanarayanan (2009) suggest the importance of including a type of Ricardian force for explaining the association of trade and comovement. They show that a multi-sector structure having Ricardian trade endogenously generates cross-country productivity correlation, and helps to explain association of trade and comovement. I employ a different specification of the model from theirs. My model is more closely linked to the way I estimate the trade costs.

The multiplicity of goods in the international economy is mainly studied in the international trade literature. Usually, international trade models have large dimensions in goods and countries in a static world. Then, the static models are used for the trade cost estimations (Hummels, 1999; Baier and Bergstrand, 2001; Eaton and Kortum, 2002; Anderson and van Wincoop, 2003). Presumptions are made that there might be a long-run change in trade costs, but short-run fluctuation is not dominant; Also, agents’ intertemporal decisions do not significantly affect the results. Yet, these presumptions might not be true because of a high volatility in the indices representing trade costs, and the sizable temporal trade imbalance in the data.

A direct observation of the indices expressing trade costs indicates high volatility. Figure 2 and Figure 3 present the time series properties of shipping costs based on the market price indices. One of the indices is taken from Stopford (2009), who compiles long annual data of freight shipping cost. Another measure is the market price index calculated by the Baltic Exchange. These two measures are based on dry bulk shipping.<sup>9</sup> In both panels of Figure 2, these indices are normalized so that the values in 1985 are the same as the mean of my estimated values in Section 4. There is a long-run trend in declining trade costs until 2000 as suggested by Hummels (2007). At the same time, differences in the log series (left panel) and the trend series (right panel) suggest large fluctuations of these indices. Figure 3 presents the business cycle fluctuation of these indices (along with estimated trade costs). The standard deviations of these series are 0.23 (Stopford, 2009, , from 1962 to 2000) and 0.25 (BDI, from

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<sup>9</sup>I explain these measures in detail in the Appendix.

1985 to 2000), respectively. The fluctuation of these shipping costs is surprisingly large, since standard deviation in the business cycle series of US GDP is around 0.02. Note that these indices represent the equilibrium price of the shipping market, presumably reflecting both supply and demand effects, some of which are typically not explicitly modeled. For example, these indices are directly influenced by the price of oil, and also driven by capacity constraints, i.e., the construction of cargo ship takes time. Then, directly employing an observed series might create bias. Instead, I estimate trade costs using trade data.

When estimating the trade costs, a prevalent assumption caused by static setting of the models is a period-by-period trade balance. Recently, Dekle et al. (2007) have suggested the potential importance of considering intertemporal decision problems, because the temporal trade imbalance is sizable in the data. My model explicitly specifies a dynamic decision problem. A long-run (steady state) trade balance is imposed, but a period-by-period trade imbalance is allowed. Not surprisingly, the steady state of the model in this paper is similar to the models in the international trade literature. The model in this paper can be seen as a dynamic extension of the theoretical gravity equation model developed by Anderson (1979). As a natural consequence, the model implies a type of gravity equation. I exploit this gravity equation for quantifying trade costs in the model, and estimate detail trade costs without assuming either country-by-country or period-by-period trade balance assumptions. Contrary to standard international trade studies, I calculate trade costs to determine, not only cross-sectional variation in a point of time, but also the changes over time as well as the deviations from the trend. The cross-sectional variation in the estimated trade costs generates cross-sectional heterogeneity of the multiple countries in terms of bilateral trade intensity, and then, the dynamics of the model countries. Moreover, since trade costs are one of the key determinants of comparative advantages, not only the level of trade costs but also the shocks of trade costs critically alter the model comovement properties. Exploiting the model structure and obtained trade costs help to explain observed international trade and business cycle properties.

### **3 The model**

This section presents the model. After specifying the environment of the model, I show households', final goods producers' and intermediate goods producers' problems. Then, the equilibrium of the model is defined. Finally, I explain how to calculate the model numerically.

#### **3.1 Environment**

The model is a dynamic stochastic general equilibrium of multiple countries and multiple goods. The model is a nested version of Backus et al. (1994) and Anderson (1979). Time is discrete,

$t = 0, 1, \dots$ . There are exogenous shocks, following a Markov process. The state of the world is expressed by  $s_t \in S$ , the history is expressed by  $s^t = \{s_0, s_1, \dots, s_t\} \in \mathbf{S}$ , and the probability of realizing a particular history  $s^t$  is expressed by  $\Pr(s^t)$ . There are  $i, j = 1, \dots, N$  countries, living representative households with population measure  $\pi_i$ . The population measure of a country  $i$  is constant over time. The total mass of the population is normalized to unity  $\sum_i \pi_i = 1$ .

In each period of each state, there are  $N \times M + N$  types of goods in the economy.  $N \times M$  goods are intermediate goods indicated by a pair indices  $(i, m)$ . Intermediate goods are differentiated by origin and category of the products.  $i$  is the country index and  $m = 1, \dots, M$  is the product index. For example, French wine and Italian wine are differentiated by origin but they are classified in the same category; French wine and French automobile are differentiated because they are in different categories of the products.<sup>10</sup> The production of an intermediate good uses constant returns to scale production technology, using capital and labor as input. Intermediate goods producers face perfect competition in both input and output markets. All the intermediate goods are tradeable and traded.  $z_{j,i,m,t}(s^t)$  is quantity of the intermediate product  $m$  produced in country  $j$  used in country  $i$  at period  $t$ . Transporting one unit of  $z_{j,i,m,t}(s^t)$  from country  $j$  to country  $i$  requires shipping more than one unit of the product because of iceberg transportation cost  $\tau_{j,i,m,t}(s^t) \geq 1$ . The lowest possible iceberg trade cost is unity (no trade cost) and the internal shipment (shipping from  $j$  to  $j$ ) incurs no trade cost for all  $(m, t, s^t)$ , i.e.,  $\tau_{j,j,m,t}(s^t) = 1$ .

Using all  $N \times M$  intermediate products, each country  $i$  produces its own final product,  $Z_{i,t}$ . The final goods are made only from intermediate products. In other words, capital stock and labor are not used.<sup>11</sup> The final goods production uses constant returns to scale technology, and both input and output markets are perfectly competitive. The final goods produced in country  $i$  are different from the ones produced in country  $j$  because the combination of the intermediate products are different. Hence, there are  $N$  different final goods, and final goods produced in country  $i$  are exclusively used for the internal absorption—consumption and investment—of country  $i$ . The investment is distributed to  $m = 1, \dots, M$  intermediate goods productions in country  $i$ .

Although there is no nominal friction, I introduce a world common currency for the purpose of accounting and indexation of the world assets (Ghironi and Melitz, 2005). The only available assets are non-state contingent claims. The representative households internationally transact these non-state contingent claims.

Table 4 is a list of the variables. In this paper, most of the variables express amounts (values) per capita, regardless of upper or lower case letters. The upper case letters are used

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<sup>10</sup>Note that I use broader classification (single digit Standard international trade classification) of the products in the empirical section.

<sup>11</sup>Ambler et al. (2002) and Arkolakis and Ramanarayanan (2009) employ a final goods production function using intermediate goods, capital and labor. I do not include capital stock and labor in the final goods production to follow the theoretical gravity equation of Anderson (1979).

for the country level aggregate variables (e.g.,  $X_{i,t}(s^t)$  is the aggregate investment per capita in country  $i$  at period  $t$ ), and the lower case letters are the sector level variables (e.g.,  $x_{i,m,t}(s^t)$  is the investment per capita to  $m$  intermediate good production of country  $i$  at period  $t$ ).

## 3.2 Households

Households have standard utility functions over consumption ( $C_{i,t}(s^t)$ ) and leisure ( $1 - L_{i,t}(s^t)$ ) of the history and time. Total time is normalized to unity, and  $L_{i,t}(s^t)$  is total labor supply. Total labor is distributed to intermediate productions ( $l_{i,m,t}(s^t)$ ). Households hold capital stock of the own country's productions. Total investment of the households is distributed to investment ( $x_{i,m,t}(s^t)$ ) for accumulating capital stock of the countries' intermediate productions.

### 3.2.1 Households problem

The objective function of each representative household living in  $i$  is

$$\max \sum_{t=0}^{\infty} \sum_{s^t} \beta^t \Pr(s^t) u(C_{i,t}(s^t), L_{i,t}(s^t)), \quad (3)$$

where

$$u(C_{i,t}(s^t), L_{i,t}(s^t)) = \frac{(C_{i,t}(s^t)^\psi (1 - L_{i,t}(s^t))^{1-\psi})^{1-\gamma}}{1 - \gamma}. \quad (4)$$

The subjective discount factor  $\beta$ , the relative risk aversion/ the intertemporal elasticity of substitution parameter  $\gamma$ , and the utility consumption share parameter  $\psi$  satisfy standard assumptions (e.g., Backus et al., 1992). The household faces following constraints. Total labor supply is equalized to sum of the labor used in the own country's productions:

$$\sum_{m=1}^M l_{i,m,t}(s^t) = L_{i,t}(s^t) \quad \text{for all } (t, s^t). \quad (5)$$

Capital stock is specific to each product:

$$k_{i,m,t+1}(s^t) = (1 - \delta)k_{i,m,t}(s^{t-1}) + \phi \left( \frac{x_{i,m,t}(s^t)}{k_{i,m,t}(s^{t-1})} \right) k_{i,m,t}(s^{t-1}) \quad \text{for all } (m, t, s^t), \quad (6)$$

where  $\phi$  is a capital adjustment friction function (Baxter, 1995).<sup>12</sup> The depreciation rate  $\delta$  is common across category and country. This simplification assumption helps to calculate the

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<sup>12</sup>The function  $\phi$  satisfies the following properties:

$$\phi(\bar{x}/\bar{k}) = \bar{x}/\bar{k}, \quad \phi'(\bar{x}/\bar{k}) = 1, \quad -\frac{\bar{x}_{i,m}\bar{\phi}_{i,m}''}{\bar{k}_{i,m}\bar{\phi}_{i,m}'} = \eta_\phi, \quad \text{constant}, \quad (7)$$

model. A household budget constraint is, for all  $s^t$ ,

$$\begin{aligned}
& P_{i,t}(s^t) \left[ C_{i,t}(s^t) + \sum_{m=1}^M x_{i,m,t}(s^t) \right] + P_t^b(s^t) B_{i,t}(s^t) + \frac{\eta_t^b}{2} P_t^b(s^t) (B_{i,t}(s^t))^2 \\
= & B_{i,t-1}(s^{t-1}) + T_{i,t}^b(s^t) + P_{i,t}(s^t) \left[ W_{i,t} \sum_{m=1}^M l_{i,m,t} + \sum_{m=1}^M R_{i,m,t}(s^t) k_{i,m,t}(s^{t-1}) \right], \quad (8)
\end{aligned}$$

and an appropriate transversality condition is also imposed.<sup>13</sup>  $P_{i,t}(s^t)$  is the price of the final goods in country  $i$ ,  $C_{i,t}(s^t)$  is consumption, and  $x_{i,m,t}(s^t)$  is investment to intermediate product  $m$ . The households have access to the non-state contingent bonds.  $P_t^b$  is world price of non-state contingent bond,  $B_{i,t}$  is amount of bond holdings,  $\eta_t^b$  is a parameter associated with cost (tax) of adjusting bond holdings,<sup>14</sup> and  $T_{i,t}^b$  is a lump-sum transfer financed by the tax of adjusting bond holdings. Using this set of transaction cost (tax) and transfer follows Ghironi and Melitz (2005) for uniquely determining steady state bond holdings to zero. Moreover, if  $\eta^b$  is large, the transaction cost effectively excludes the possibility of temporal financial imbalance because deviating from steady state bond holdings (which is zero) is too costly. A high adjusting cost for bond holding leads to a period-by-period trade balance of the country. Such a period-by-period trade balance is equivalent to a straightforward multi-country extension of “financial autarky” assumption proposed by Heathcote and Perri (2002).

### 3.3 Final goods producers

There is a unit mass of the final goods producers in each country. Both input and output markets are perfectly competitive; the final goods producers maximize their profit taking intermediate goods and final goods prices as given.

#### 3.3.1 Final goods producers problem

Final goods producer in  $i$  solves

$$\max P_{i,t}(s^t) Z_{i,t}(s^t) - \sum_{m=1}^M \sum_{j=1}^N p_{j,i,m,t}(s^t) z_{j,i,m,t}(s^t) \quad (9)$$

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where variables with bar are their steady state values.

<sup>13</sup>The transversality condition is:

$$0 = E_0 \lim_{t \rightarrow \infty} \prod_{k=0}^t P_k^b(s^k) B_{i,t}(s^t).$$

<sup>14</sup> $\eta_t^b$  consists of constant part  $\eta^b$  and trend component. After removing trend from the model,  $\eta^b$  is constant.

subject to

$$Z_{i,t}(s^t) = \left[ \sum_{m=1}^M \left[ \sum_{j=1}^N v_{j,i}^\rho z_{j,i,m,t}(s^t)^\rho \right]^{\frac{\theta}{\rho}} \right]^{\frac{1}{\theta}}, \quad (10)$$

where  $P_{i,t}(s^t)$  is the price of the final good  $Z_{i,t}$ , and  $p_{j,i,m,t}(s^t)$  is the price of an intermediate product  $z_{j,i,m,t}(s^t)$  in country  $j$ . The production function is two-level constant elasticity of substitution (CES) function (Sato, 1967). The inner parentheses correspond to the aggregation of intermediate goods from different origins, for a particular product category  $m$ . Outer parentheses are the aggregation of different categories. Notice that the elasticity of substitution within the category but different origin,  $1/(1-\rho)$ , may be different from the elasticity of substitution across category of goods  $1/(1-\theta)$ .<sup>15</sup> An implicit restriction here is that cross-origin substitutability is the same for any categories. Although this simplification does not agree with recent empirical trade studies (e.g., Feenstra, 1994; Hummels and Klenow, 2005; Broda and Weinstein, 2006), this assumption is helpful for model calculations. In the model section, the weight parameter  $v$  is allowed to be general positive constant. In the quantitative sections,  $v$  is set to unity for all  $(i, j)$  because  $v$  is captured by  $\tau$  and  $a$  (trade cost and productivity parameters) as long as steady state values are considered. In addition, the empirical strategy is impossible to separately identify  $\tau$  and  $v$ .

### 3.3.2 Final goods producers' maximization

The final good producer maximization condition yields an inverse demand function

$$p_{j,i,m,t}(s^t) = P_{i,t}(s^t) Z_{i,t}(s^t)^{1-\theta} \left( \sum_{h=1}^N v_{h,i} z_{h,i,m,t}(s^t)^\rho \right)^{\frac{\theta-\rho}{\rho}} v_{j,i}^\rho z_{j,i,m,t}(s^t)^{\rho-1}. \quad (11)$$

The implied currency unit total value (not per capita) of trade flow is expressed as:

$$\begin{aligned} ex_{j,i,m,t}(s^t) &\equiv \pi_i p_{j,i,m,t}(s^t) z_{j,i,m,t}(s^t) \\ &= \pi_i P_{i,t}^{\frac{1}{1-\theta}} Z_{i,t}^{\frac{-\rho}{1-\rho}} \left( \sum_{h=1}^N p_{h,m,t}^{\frac{-\rho}{1-\rho}} (v_{h,i}^{-1} \tau_{h,i,m,t})^{\frac{-\rho}{1-\rho}} \right)^{\frac{\theta-\rho}{\rho(1-\theta)}} (v_{j,i}^{-1} \tau_{j,i,m,t})^{\frac{-\rho}{1-\rho}}. \end{aligned} \quad (12)$$

This trade flow expression plays a key role in the empirical estimation. This type of the trade flow expression holds in a wide class of the trade models (Anderson, 1979; Hummels and Levinsohn, 1995; Alvarez and Lucas, 2007). In static models, combining (12) with aggregate trade balance condition gives a classical gravity equation (Anderson, 1979). The period-by-

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<sup>15</sup>Sato (1967) shows the detail about the elasticity and other properties of the two-level CES function.

period trade balance does not necessarily hold in a dynamic setting. I use (12) in the empirical part instead of deriving the classical gravity equation.

### 3.4 Intermediate goods producers and trade cost

There is a mass of intermediate goods producers producing an intermediate product  $z_{i,m,t}(s^t)$ , who maximizes profits by purchasing labor ( $l_{i,m,t}(s^t)$ ) and capital services ( $k_{i,m,t}(s^t)$ ). The production technology is a constant returns to scale Cobb=Douglas function. The share parameter  $\alpha$  is constant across products and countries. The problem is

$$\max p_{i,m,t}(s^t)z_{i,m,t}(s^t) - P_{i,t}(s^t)W_{i,t}(s^t)l_{i,m,t}(s^t) - P_{i,t}(s^t)R_{i,m,t}(s^t)k_{i,m,t}(s^t) \quad (13)$$

subject to

$$z_{i,m,t}(s^t) = a_{i,m,t}(s^t)k_{i,m,t}(s^t)^\alpha l_{i,m,t}(s^t)^{1-\alpha}. \quad (14)$$

where  $p_{i,m,t}(s^t)$  is the price of  $z_{i,m,t}(s^t)$  in country  $i$ ,  $P_{i,t}(s^t)$  is the price of the final goods in country  $i$ , and  $a_{i,m,t}(s^t)$  is the sector specific total factor productivity. There is a pool of producers for each  $(i, m)$  goods. The goods are sold to any country subject to iceberg trade costs,  $\tau_{j,i,m,t}(s^t)$ . To deliver one unit of goods requires to ship  $\tau$  units of goods. No trade cost for internal distribution is assumed:  $\tau_{i,i,m,t} = 1$ . Hence, by arbitrage, price is equalized across destinations after deducting trade costs:

$$\frac{p_{i,j,m,t}(s^t)}{\tau_{i,j,m,t}(s^t)} = \frac{p_{i,h,m,t}(s^t)}{\tau_{i,h,m,t}(s^t)} = p_{i,i,m,t}(s^t) = p_{i,m,t}(s^t). \quad (15)$$

### 3.5 Market clearing, shocks and the equilibrium

#### 3.5.1 Market clearing

Followings are market clearing conditions of the economy. Total investment in each country is financed by total investment of the residents:

$$\forall(i, t, s^t) \quad \sum_{m=1}^M x_{i,m,t}(s^t) = X_{i,t}(s^t). \quad (16)$$

Sum of the demand of the intermediate goods and the iceberg loss is equalized to the total supply of the intermediate goods:

$$\forall(i, m, t, s^t) \quad \sum_{j=1}^N \pi_j \tau_{i,j,m,t} z_{i,j,m,t}(s^t) = \pi_i z_{i,m,t}(s^t). \quad (17)$$

A country's resource constraint:

$$\forall(i, t, s^t) \quad C_{i,t}(s^t) + X_{i,t}(s^t) = Z_{i,t}(s^t), \quad (18)$$

hence, the final goods production per capita in country  $i$ ,  $Z_{i,t}(s^t)$ , corresponds to the absorption per capita, not gross domestic products per capita. The total net supply of the assets is zero:

$$\forall(t, s^t) \quad 0 = \sum_{i=1}^N \pi_i B_{i,t}(s^t). \quad (19)$$

The lump-sum transfer is financed by the bond holding adjustment tax:

$$\forall(t, s^t) \quad \frac{\eta_t^b}{2} P_t^b(s^t) (B_{i,t}(s^t))^2 = T_{i,t}^b(s^t). \quad (20)$$

### 3.5.2 Other variables

The value of total exports per capita in country  $i$  is

$$EX_{i,t}(s^t) \equiv \frac{1}{\pi_i P_{i,t}} \sum_m \sum_{j \neq i} \pi_j p_{i,j,m,t}(s^t) z_{i,j,m,t}(s^t). \quad (21)$$

Similarly, the value of total imports in country  $i$  is

$$IM_{i,t}(s^t) \equiv \frac{1}{\pi_i P_{i,t}} \sum_m \sum_{j \neq i} \pi_j p_{j,i,m,t}(s^t) z_{j,i,m,t}(s^t). \quad (22)$$

Net exports per capita are defined as:

$$NX_{i,t}(s^t) \equiv EX_{i,t}(s^t) - IM_{i,t}(s^t). \quad (23)$$

The gross domestic products (GDP) per capita of the model economy,  $Y_{i,t}$ , is sum of the absorption per capita  $Z_{i,t}$  and net exports per capita:<sup>16</sup>

$$Y_{i,t} \equiv Z_{i,t} + NX_{i,t}. \quad (24)$$

In standard macro models, the total factor productivity (TFP) of the aggregate production function plays a central role in determining model properties (e.g., Backus et al., 1992). If we postulate an aggregate production function in the model economy, the implied TFP of the

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<sup>16</sup>I explain the national accounting of the model in detail in the Appendix.

aggregate production function is expressed as:

$$TFP_{i,t} \equiv Y_{i,t} \left( \sum_{m=1}^M k_{i,m,t} \right)^{-\alpha} L_{i,t}^{-(1-\alpha)}. \quad (25)$$

This aggregate TFP fundamentally depends on TFPs of intermediate productions and trade costs. The mapping from sector TFPs and trade costs to the aggregate TFP is a complicated non-linear function because of the constant elasticity of substitution aggregation and the sector specific capital accumulation.

### 3.5.3 Trend and exogenous shocks

The sources of the shocks in the economies are productivity  $a_{i,m,t}(s^t)$  and trade cost  $\tau_{j,i,m,t}$ .<sup>17</sup> The sector level productivity consists of a common trend component  $g_a$ , a specific steady state value  $\bar{a}_{i,m}$  and a deviation  $\hat{a}_{i,m,t}$ . Similarly, the trade cost consists of a common trend component  $g_\tau$ , a specific steady state value  $\bar{\tau}_{j,i,m}$ , and a deviation  $\hat{\tau}_{j,i,m,t}$ .

$$a_{i,m,t} = g_a^t \bar{a}_{i,m} \exp(\hat{a}_{i,m,t}) \quad (26)$$

$$\tau_{j,i,m,t} = g_\tau^t \bar{\tau}_{j,i,m} \exp(\hat{\tau}_{j,i,m,t}). \quad (27)$$

The literature (Hummels, 1999, 2007; Baier and Bergstrand, 2001; Anderson and van Wincoop, 2004; Stopford, 2009) suggests trend reduction in trade costs ( $g_\tau < 1$ ). Based on the estimation in Section 4, I assume the cross-sector/ cross-country diffusion of the productivity shock is zero, and the shock follows an univariate AR1 process. Similarly, the trade cost shock follow an univariate AR1 process:

$$\hat{a}_{i,m,t} = \rho_a \hat{a}_{i,m,t-1} + \hat{\varepsilon}_{i,m,t}, \quad (28)$$

$$\hat{\tau}_{j,i,m,t} = \rho_\tau \hat{\tau}_{j,i,m,t-1} + \hat{u}_{j,i,m,t}. \quad (29)$$

The innovation in productivity shock  $\hat{\varepsilon}_{i,m,t}$  follows multivariate ( $N \times M$ ) normal distribution.  $\hat{u}_{j,i,m,t}$  follows multivariate ( $N \times (N - 1) \times M$ ) normal distribution. Innovations in the trade cost shocks and the productivity shocks are not correlated.

### 3.5.4 Equilibrium

**Definition:** The **competitive equilibrium** of the economy, given exogenous shocks of technology, trade costs and government spending, is a sequence of quantities and prices listed in the Table 4 which are consistent with (1) household maximization problem, (2) final goods

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<sup>17</sup>A government spending shock can be included. See the Appendix.

producer maximization problem, (3) intermediate goods producer maximization problem, (4) trade arbitrage conditions, and (5) market clearing conditions.

### 3.6 Computational strategy

The computation of the model dynamics is to solve the rational expectation equilibrium of the log-linearized model around the non-stochastic steady state. First I detrend the economy by trend growth rates of productivity and trade cost (trade cost has trend reduction). Then I calculate the steady state of the detrended economy. In the rest of the paper, I drop explicit history dependence from the notation.

**Definition:** The **non-stochastic steady state** of the economy is a competitive equilibrium in which there is no shock, and all detrended variables stay at some constant values.

In this economy, variables in the steady state are not necessarily equalized across countries. This heterogeneity is caused by the differences in the productivity, the population and the trade costs the countries face. Moreover, the trade pattern in the steady state has complicated structure because of the multiplicity of the country and the multiplicity of the intermediate goods. The calculation of the steady state exploits two properties embedded in the model.

First, the model has “the return of Ricardo” (Baxter, 1992) property; although there are two fundamental input (capital stock and labor), the steady state trade pattern is explained by Ricardo, not Heckscher=Ohlin. The return to investment in the steady state is determined only by the subjective discounting factor, degree of capital depreciation and trend growth rates. Given return to the investment, capital stock of each intermediate production is adjusted to be consistent with the product’s steady state labor productivity. Moreover, Cobb=Douglas assumption of the intermediate production implies that the total factor productivity is the same as labor productivity, after adjusting capital stock. As a result, the only production decision problem in the steady state is allocation of labor facing production technologies, which are linear in labor. Hence, the steady state of the model is regarded as an equilibrium of a static version of a Ricardian type general equilibrium model. In addition, the CES production function of the final goods leads to no perfect specialization of the intermediate productions, and hence, the possibility of corner solutions in solving the labor allocation problem is excluded.<sup>18</sup>

Second, the equilibrium conditions characterizing a class of the Ricardian models can be reduced to a system of excess demand functions. Wilson (1980) established this excess demand approach to characterize the equilibrium of a multi-country version of the Dornbusch et al. (1977) model. Recently, Alvarez and Lucas (2007) applied this method to the Eaton and

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<sup>18</sup>Nevertheless, the equations obtained here are similar to the Ricardian problems with perfect specialization (Eaton and Kortum, 2002; Alvarez and Lucas, 2007).

Kortum (2002) model. The corresponding excess demand approach is used to calculate steady state values of the model economy. The steady state conditions and the exact calculation equations are explained in the Appendix.

Once the steady state values are calculated, the standard macroeconomic method, which solve rational expectation equilibrium of log-linearized system, is used to analyze dynamic property of the model. The Appendix presents these log-linearized equations. Note that there are a large number of state variables: capital stock and productivity of each intermediate in each country. I use AIM implementation of the Anderson-Moore algorithm (Anderson, 2008) with MATLAB.

## 4 Model parameterization

There are a large number of parameters in the model. I exploit a trade flow expression (12) and international trade data for quantifying trade cost parameters. I follow the literature for setting other parameters (Backus et al., 1994; Baxter, 1995; Ambler et al., 2002).

### 4.1 Calibrated parameters

Table 5 lists of the baseline parameters. The model period is quarter of a year. The parameters of the utility function and production function are set to standard values (see, for example, Baxter, 1995). The subjective discounting factor  $\beta$  is 0.988. The parameter controlling relative risk aversion/ intertemporal elasticity of substitution  $\gamma$  is set to 1.50, and the utility consumption share parameter,  $\psi$ , is 0.34. The capital share of the Cobb=Douglas production function of intermediate goods production  $\alpha$  is 1/3. This capital share is common for any intermediate production and any country. Similarly, the capital depreciation rate,  $\delta = 0.025$ , is homogeneous across categories and countries. The capital stock adjustment friction parameter,  $\eta_\phi$  is set to 0.2 for removing a large volatility in investment (Baxter, 1995). I impose the common capital share, the depreciation rate and the adjustment friction parameter for the tractability of the model calculations. The parameter of financial market cost  $\eta^b$  is set to 0.0001. Ghironi and Melitz (2005) use a different number but as long as it is small, the exact value does not drastically change the results. Parameters associated with utility functions and production functions are fixed throughout the paper.

Two important parameters in the model are  $\theta$  and  $\rho$ . They are associated with final goods aggregation. The elasticity of substitution between two intermediate products from different countries is controlled by  $\rho$ . The elasticity of substitution between two different products is determined by  $\theta$ . The values,  $\theta = 1/3$  and  $\rho = 0.9$  are taken from Whalley (1985) and Ambler et al. (2002). There are range of estimated values for these parameters, based on different

types of production functions.<sup>19</sup>

The steady state productivity of intermediate productions,  $\bar{a}_{i,m}$ , is uniformly set to unity. An international comparison of the sector level productivity is not straightforward (see, for example, Feenstra and Kee, 2008). Also, since the target of this paper is the G7 countries, I expect that a common productivity level assumption is a plausible first step. The exercise of the paper, therefore, is to determine how much the difference in trade costs (together with population size) can explain the variations in trade intensity and comovement.

The shock process of sectoral productivity is based on the observation of aggregate TFP processes and sector level labor productivity processes. Using sector level productivity indices and sector level employment data, I calculate sector level labor productivities for three sectors (general manufacturing, manufacturing of agricultural products, and mining), in six countries (seven countries of the G7 minus Italy, because sector level labor data of Italy is not included in the data).<sup>20</sup> The overall average within-country correlation of sector level productivities is 0.15. This value is similar to that obtained by Ambler et al. (2002) in their estimate of a two-country (US and Europe) two-sector model (manufacturing and non-manufacturing). The diffusion parameters are uniformly set to 0, because Ambler et al. (2002) and my estimate suggest no coherent pattern of the diffusion parameters. The estimated autocorrelation is around 0.9 for the manufacturing sector, and 0.6 for other sectors. However, employing such a low autocorrelation in the model implies low autocorrelation of aggregate TFP. To be consistent with a high autocorrelation in aggregate TFP (Baxter, 1995), the autocorrelation of technology is set to  $\rho_a = 0.995$ . The estimated cross-country correlation of sector level TFP shock ( $\sigma(\hat{\varepsilon}_{i,m}, \hat{\varepsilon}_{j,m})$ ) is around 0.2 for manufacturing and 0 for other sectors. However, the

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<sup>19</sup>These values are exactly opposite to the values used by Chari et al. (2002). They pick  $\theta = 0.9$  and  $\rho = 1/3$ . However, the order of production aggregation is also exactly opposite. The inner layer aggregates products from same country (controlled by  $\theta$ ), and the outer layer aggregates the products from different countries (controlled by  $\rho$ ). They choose  $\theta$  based on the markup ratio of monopolistically competitive firms. Although I assume a perfect competition, the corresponding parameter controlling (hypothetical) markup is  $\rho$ , because the inner layer of the aggregation mainly determines the markup. Hence, the parameterization of Chari et al. (2002) is consistent with mine. The aggregation employed in this paper is the same as Ambler et al. (2002), and hence I follow the parameterization of Ambler et al. (2002).

Ruhl (2008) summarizes the result obtained from two-country, continuum of products models. The value  $\theta = 1/3$  is a standard setting in the one intermediate good per country model (Backus et al., 1994). The implied elasticity of substitution between two products from different countries is 1.5. Yet, Heathcote and Perri (2002) and Kose and Yi (2006) prefer to use negative number,  $-1/9$ , for explaining IRBC facts. The implied elasticity is less than unity, meaning two goods from different countries are complement. Trade literature suggests larger elasticity. For example, theoretically, the pure Ricardian model is a situation in which  $\rho$  is unity. Broda and Weinstein (2006) estimate elasticities of substitution across different origin goods using US import data. The mean values of elasticity in the samples from 1972 to 1988 are 17.3 for 7-digit, 7.5 for 5-digit, 6.8 for 3-digit levels. The implied  $\rho$  are 0.94, 0.87, and 0.85 respectively. This conversion ignores the fact that they employ a different CES aggregator. The layers specified in Broda and Weinstein (2006) are aggregation of the imports from different origin, the aggregation of categories, and the aggregation of the composite domestic products and the composite imports. Anderson and van Wincoop (2004) summarize that  $\rho$  is in the range of 0.75 to 0.95. Hence,  $\rho = 0.9$  is in a range of the trade literature.

<sup>20</sup>The industry level data is taken from OECD database. See the Appendix for the detail.

observed cross-country aggregate TFP shock correlation is 0.2 (Ishise, 2009). I set sector level TFP shock correlation to be roughly consistent with this number. To preview the robustness results, the trade-comovement implication does not critically depend on this correlation.

The subjective production weight parameter is set to unity,  $v_{j,i} = 1$ , throughout the paper because the estimated trade costs effectively include the contribution of  $v_{j,i}$ . This point becomes more clear from the estimation equation.

## 4.2 Estimation of trade costs

I exploit a trade flow expression (12) and international trade data for quantifying trade cost parameters. The estimation methodology itself is a version of traditional gravity equation estimations (e.g., Anderson and van Wincoop, 2004). Contrary to standard international trade researches, I calculate trade costs to investigate not only cross-sectional variation at a point of time, but also the changes over time as well as the deviations from trend movements.

### 4.2.1 Data

The national accounting data employed in the estimation is Penn World Table mark 6.2 (Heston et al., 2008). Trade data is NBER-UN world trade data (Feenstra et al., 2005). The trade data spans all the world countries, four-digit Standard International Trade Classification (SITC, revision 2), from 1962 to 2000. I compress this data into 21 OECD countries, single-digit SITC (10 categories) from 1962 to 2000. As a result, 163,800 ( $= 21 \times 20 \times 10 \times 39$ ) observations are used. This data is enumerated using destination country record, in CIF (cost, insurance, freight), not FOB (free on board). Hence, the value of trade flow conceptually includes trade costs. If the value is smaller than \$100,000 US dollar (in current value), the data set records this entry as missing (Feenstra et al., 2005). By aggregating into single digit SITC and focusing only on major OECD countries, many of the missing values are eliminated. Yet 3,935 (2.4%) observations are missing values. I replace these missing observations with \$50,000 in current value. The exact number of the replaced value does not significantly affect the estimated trade costs.<sup>21</sup> Before using the estimation, the original data variables are converted into model concept (e.g., the model does not have inflation). The details of the data conversion are explained in the Appendix.

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<sup>21</sup>I examine the other values {100, 1000, 100000}. The obtained estimation coefficients and trade costs are almost identical to the baseline case. Helpman et al. (2008) exploits structural model in a version of gravity equation to create exclusion variable of Tobit type estimation. Their result suggests replacement of missing values does not significantly cause the estimation bias.

## 4.2.2 Trade flow expression

The trade flow equation (12) can be written as:

$$ex_{j,i,m,t} = \underbrace{P_{i,t}^{\frac{1}{1-\theta}}}_{\text{importer income}} \underbrace{\pi_i}_{\text{population}} \underbrace{Z_{i,t}}_{\text{real absorption per capita}} \underbrace{p_{j,m,t}^{\frac{-\rho}{1-\rho}}}_{\text{exporter price}} \underbrace{\left( \sum_{h=1}^N p_{h,m,t}^{\frac{-\rho}{1-\rho}} (v_{h,i}^{-1} \tau_{h,i,m,t})^{\frac{-\rho}{1-\rho}} \right)^{\frac{\theta-\rho}{\rho(1-\theta)}}}_{\text{substitution of different origin}} \underbrace{(v_{j,i}^{-1} \tau_{j,i,m,t})^{\frac{-\rho}{1-\rho}}}_{\text{trade cost}}. \quad (30)$$

Here,  $ex_{j,i,m,t}$  is the total (not per capita) value of trade flow of product  $m$  from country  $j$  to country  $i$  at period  $t$ . The flow can be decomposed into the contribution of (1) the economic size of the destination (importing) country, which is captured by  $P_{i,t}$  (aggregate price),  $\pi_i$  (population) and  $Z_{i,t}$  (real absorption per capita); (2) the price of the goods in the origin (exporting) country  $p_{j,m,t}$ ; (3) the substitution between the same intermediate products from different origins (the term in the parentheses); and (4) the trade costs  $\tau_{j,i,m,t}$ , which will be captured by traditional gravity variables. The substitution term makes a country difficult to export to another country who can purchase the same category of intermediate products from different origins with low costs.<sup>22</sup>

The expression shows that the subjective production weight  $v_{j,i}$  and trade costs  $\tau_{j,i,m,t}$  are not separately identified, unless plausible proxies for these two variables are available. Therefore, most of the trade literature set  $v_{i,j}$  as 1 for all  $(i, j)$  (Anderson and van Wincoop, 2004). That is, the estimated trade cost based on the gravity equation include this subjective weight component.

I use a two-step procedure to quantify  $\tau_{j,i,m,t}$ . The first step is to exploit the fact that the price of intermediate product is origin-specific, and the substitution term is destination specific. The first step gives the relative size of the trade costs. The second step exploits the model assumption that internal shipments incur no trade costs in order to quantify the level of trade costs. It should be noted that if the trade costs are captured by gravity variables, the gravity variables vary with the  $(j, i)$  pair and  $t$  (e.g., period with or without regional trade agreement), but no variation is observed across  $m$ . A plausible assumption is each category has different trade cost and hence different coefficients (Hummels, 1999). Moreover, significant time variation is also expected. The following estimation is thus made for each product and time pair  $(m, t)$  samples. For each  $(m, t)$  pair, there are  $N(N-1) = 21 \times 20 = 420$  observations. For simplicity in presentation, the following section drops the subscripts  $(m, t)$ .

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<sup>22</sup>This substitution term looks similar to “multilateral resistance” term appeared in Anderson and van Wincoop (2003). The role played by this term is essentially same. Yet, the reason that the term appears is different. Anderson and van Wincoop (2003) impose standard single layer CES assumption ( $\rho = \theta$ ). If  $\rho = \theta$  is imposed in (30), the substitution term disappears. The exact reason that they have “multilateral resistance” term is they impose period-by-period trade balance condition and use it to eliminate origin specific price term.

### 4.2.3 Estimation

I calculate the trade costs based on trade flow expression (30). First, the trade flow (exports) is normalized by economic size of the importer:

$$y_{j,i} \equiv \log \left( ex_{j,i} / \left( P_i^{\frac{1}{1-\theta}} Z_i \pi_i \right) \right). \quad (31)$$

Then, I estimate a fixed effect model:

$$y_{j,i} = \Gamma_j + \Lambda_i + \nu + \mathbf{x}'_{j,i} \boldsymbol{\beta} + \varepsilon_{j,i} \quad (32)$$

where  $\Gamma_j$  is the indicator of fixed effect for  $j$ ,  $\Lambda_i$  is the indicator of fixed effect for  $i$ ,  $\nu$  is the level of trade costs (which will be dropped based on the fixed effect estimation strategy),  $\mathbf{x}_{j,i}$  is a vector of the set of gravity variables as log of the physical distance and border dummy.  $\varepsilon_{j,i}$  is the error term orthogonal to the observable explanatory variables:

$$E(\varepsilon_{j,i} \mathbf{x}_{g,h}) = \mathbf{0} \quad \text{for all } (j, i, g, h) \in N^4. \quad (33)$$

The error term assumption is based on the model setting. By the model construction, the trade costs consist of the steady state component and the shock component. The estimation error comes from this shock component of the trade cost. The orthogonality condition is potentially invalid, for example, by the treatment of missing observations. Namely, if distance variables predict the missing values, the error and distance variables are not orthogonal. For minimizing the possibility of this missing observation problem, I focus my sample on 21 OECD economies.

The gravity variables are taken from Glick and Rose (2002) and Rose (2005). The variables included in the estimation are log of the bilateral distance, square of the log of the distance ( $\ln(\text{distance})^2$ ), cube of the log distance ( $\ln(\text{distance})^3$ ), indicator of the sharing national border, indicator of the colonial relationship, indicator of the common language, and indicator for being in the same regional trade agreement.<sup>23</sup> The inclusion of the square and the cube terms aims to capture potential non-linearity in the distance coefficient suggested by, Eaton and Kortum (2002) and Anderson and van Wincoop (2004), for example. As the result, the component of the exogenous explanatory variables is expressed as

$$\begin{aligned} \mathbf{x}'_{j,i} \boldsymbol{\beta} &= \beta_1 \ln \text{dist}_{j,i} + \beta_2 (\ln \text{dist}_{j,i})^2 + \beta_3 (\ln \text{dist}_{j,i})^3 + \beta_4 \text{border}_{j,i} \\ &+ \beta_5 \text{Lang}_{j,i} + \beta_6 \text{Colony}_{j,i} + \beta_7 \text{FTA}_{j,i,t}. \end{aligned} \quad (34)$$

The estimation strategy exploits a variation across different exporters for a particular im-

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<sup>23</sup>Other common “distance” variables, e.g., the generalized system of preference, do not have enough variations across these OECD countries.

porter, and a variation across different importers for a particular exporter. After controlling the importers' size, the difference in trade flow for a different destination is attributed to the difference in trade costs. The fixed effect  $\Gamma_j$  captures the contribution of the exporter-product-year-specific price (which then captures the exporter-product-year-specific productivity). That is, anything exporter-specific is attributed to the price of the goods at the origin. Anything importer-specific is attributed to the substitution effect. Then, the estimation gives the trade costs as the residual from the actual trade flow and potential explanatory variables. The strategy of obtaining trade costs as the residual is similar to Hummels (1999) and Gervais and Jensen (2009).

A two-way fixed effect estimation gives  $\hat{\beta}$  and fixed effects as deviations from the means ( $\hat{\Gamma}_j, \hat{\Lambda}_i$ ). That is, the estimation does not give  $\bar{\Gamma} = \Gamma_j - \ddot{\Gamma}_j$ ,  $\bar{\Lambda} = \Lambda_i - \ddot{\Lambda}_i$  and  $\nu$  (a potential constant term in the true trade cost). Yet, there are  $N$  additional structural assumptions: intra-country trade costs are all unity. The basic idea of the second step is to set these three parameters so as to minimize a loss function summing the deviations of  $N$  conditions by non-linear least squares. The loss function is given by

$$V(\bar{\Gamma}, \bar{\Lambda}) = \frac{1}{2} \sum_{i=1}^N \left( \sum_{h \neq i} \exp(y_{h,i}) + \exp(\hat{\Gamma}_i + \bar{\Gamma} + \hat{\Lambda}_i + \bar{\Lambda}) - \exp\left(\frac{\theta(1-\rho)}{\theta-\rho} (\hat{\Lambda}_i + \bar{\Lambda})\right) \right)^2. \quad (35)$$

The derivation of this loss function is shown in the Appendix. This two-step estimation is done separately for each  $(m, t)$ , and hence, the estimated coefficients indeed depend on  $(m, t)$ :  $\hat{\beta}_{m,t}, \hat{\Gamma}_{j,m,t}, \hat{\Lambda}_{i,m,t}, \hat{\nu}_{m,t}$ . Using estimated coefficients, the trade cost is calculated by:

$$\hat{\tau}_{j,i,m,t} = \exp\left(\frac{\rho-1}{\rho} (\hat{\nu}_{m,t} + \mathbf{x}'_{j,i,t} \hat{\beta}_{m,t} + \hat{\varepsilon}_{j,i,m,t})\right). \quad (36)$$

After calculating the exporter-importer-product-year-specific trade costs, the trend component of the trade costs is calculated as the mean of all of the trade costs in each period.<sup>24</sup> Then, the steady state trade costs, specific to  $(j, i, m)$ , are calculated by taking a time series average.<sup>25</sup>

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$$(\hat{g}_\tau)^4 = \frac{1}{T-1} \sum_{t=1}^{T-1} \left( \left( \frac{1}{N(N-1)M} \sum_{i=1}^N \sum_{j \neq i} \sum_{m=1}^M \hat{\tau}_{j,i,m,t+1} \right) / \left( \frac{1}{N(N-1)M} \sum_{i=1}^N \sum_{j \neq i} \sum_{m=1}^M \hat{\tau}_{j,i,m,t} \right) \right). \quad (37)$$

Fourth power term is to adjust model (quarterly) and data (annual) time periods.

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$$\hat{\tau}_{j,i,m} = \frac{1}{T} \sum_{t=1}^T \hat{\tau}_{j,i,m,t} / (\hat{g}_\tau)^{4t}. \quad (38)$$

### 4.3 Estimation result

Table 7 presents the summary result of the first step estimations. Here, the mean coefficients are the mean of the coefficients over 390 (10 single-digit classifications  $\times$  39 years) different estimations. The standard deviations are variations over 390 different estimations. There are some variations in the point estimates of the gravity variables for each  $(m, t)$ , suggesting variations of trade costs across categories and time.<sup>26</sup>

The estimated trade costs are mainly explained by the gravity variables. For decomposing the estimated trade costs into the contribution of gravity variables and other terms, I calculate a reduced form regression:

$$\exp\left(\frac{\rho}{\rho-1}\hat{\tau}_{j,i,m,t}\right) = \alpha_0 + \alpha_1\left(\mathbf{x}'_{j,i,t}\hat{\boldsymbol{\beta}}_{m,t}\right) + \alpha_2(\hat{\varepsilon}_{j,i,m,t}) + u_{j,i}, \quad (39)$$

for each  $(m, t)$  of 390 different estimations. If I could quantify the trade costs only by the first step, and conduct this regression, then  $R^2$  of this regression would be unity because trade costs are exclusively constructed by the gravity variables. The second step introduces contributions of additional terms through estimated values of the error terms. The mean of  $R^2$ s of this estimation is 0.86. If I drop  $\hat{\varepsilon}_{j,i,m,t}$  term from the regression, the mean of  $R^2$ s is 0.77. If I drop  $\mathbf{x}'_{j,i,t}\hat{\boldsymbol{\beta}}_{m,t}$  term from the regression, the mean of  $R^2$ s is 0.08. Thus, the gravity variables determine a large fraction of the estimated trade costs, but not all.

According to the mean of the estimated coefficients in Table 7, the trade flow increases if two countries share the border, or it suggests that sharing a border decreases trade costs. Two countries sharing a border have 0.04 points lower trade costs than countries do not share a border. Other gravity variables also show some effects on trade cost. Inclusion of the quadratic and cubic terms in (34) prevents a direct interpretation of the coefficient of the distance as the elasticity. The average elasticity of the distance is calculated by

$$\frac{\partial \tau_{j,i,m,t} \text{ dist}_{j,i}}{\partial \text{dist}_{j,i} \tau_{j,i,m,t}} = \frac{\rho-1}{\rho} (\beta_1 + 2\beta_2(\ln \text{dist}_{j,i}) + 3\beta_3(\ln \text{dist}_{j,i})^2). \quad (40)$$

where I substitute averages of the estimated  $\beta$ s in Table 7. Figure 4 plots the implied distance elasticity of the trade costs. The distance elasticity increases in distance. The percentage increment of trade costs is higher the further the two countries are. The effect increases sharply within 2,000 kilometers—covering most pairs of European countries (e.g., the distance between Spain and Finland is 2,050 km). Within relatively near countries, additional distances increase trade costs rapidly. A reason of non-linearity is that with this range, an additional increment of distance leads to switch of transportation mode. On the contrary, the curve

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<sup>26</sup>In the Appendix, I present estimation results obtained from standard gravity equations with several specifications.

becomes flat beyond 6,000 km (e.g., US-Japan distance is 6,225 km). In this range, trade costs increase linearly with respect to distance. For this length of separation, the trade is almost entirely done through ships (Stopford, 2009). Hence, an additional distance does affect the cost level, but does not have acceleration effects.

The implied trade costs are summarized in Figures 2–3 and Tables 8–9. First, there is a significant reduction in the trade costs over time. Figure 2 compares the estimated trade costs and shipping costs based on the market price indices (Stopford, 2009, and the Baltic Exchange). The trend of estimated trade costs tracks trend movements of price indices (right panel of Figure 2), although I do not use any information of these price indices to estimate trade costs. Based on the average trade costs, the estimated trend reduction rate in trade cost is  $g_\tau = 0.9992$ . In this model, the trend growth rate of GDP is composite of the trend reduction of trade costs and the trend growth rate of intermediate goods productivity,  $g_a$ . That is, the trend growth rate of GDP is  $g_1 = (g_a/g_\tau)^{1/(1-\alpha)}$ . Setting  $g_1$  as 1.004 as in the standard IRBC model (Ishise, 2009), together with  $g_\tau = 0.9992$ , implies that the trend productivity growth is  $g_a = 1.0018$ . Since  $1/g_\tau = 1.0008$ , the contribution of the productivity growth is around twice that of the trade cost reduction. In other words, this imputation suggests about 30% of the world income growth is contributed by reduction of trade costs.

After removing common trend components, exporter- importer- product-specific steady state trade costs are calculated by taking the time series average. The basis year of detrending is 1985, since this year is in the middle of the sample for the business cycle calculations. Tables 8 and 9 present the results. Trade costs are higher in agricultural products whereas lower in fuels, which is consistent with the estimation of Hummels (1999). Table 9 shows the exporter- importer-specific trade costs, which are the averages of the categories. The countries are roughly ordered by proximity in the table. As a natural consequence, the trade costs near the diagonal are small. Isolated countries in the sample such as Japan and New Zealand generally face high trade costs whereas most of the European countries face low trade costs on average. A pair of countries separated by larger distances, as France and Australia, suffers from high trade costs.

There are some differences in trade costs depending on the direction. For example, trade costs from Canada to US is smaller (1.44) than the cost from US to Canada (1.55). A potential reason is Canadian economic activities are concentrated in the US border area whereas US economic activities are scattered across countries. If Canadian exports were mainly shipped to closer areas, and Canadian imports came from all over the US, then the average trade costs would be lower for Canadian exporting.

The overall average of the estimated steady state trade costs is 1.73 (1.74 among G7 countries). The number is slightly higher than that suggested in trade literature (Anderson and van Wincoop, 2004), but not greatly different (Alvarez and Lucas (2007) use 1.5 as their baseline, which includes tariffs).

Comparing the left and right panels of Figure 2 suggests large volatilities in trade costs over time. The mean of the standard deviations of HP-filtered estimated trade costs is 0.023. This size of the volatility is approximately the same as that of US GDP (right panel of Figure 3). Yet, the estimated volatility is much smaller than the standard deviations of the shipping costs indices (left panel of Figure 3). As a result, the estimated trade costs track the average behavior of the shipping cost index; however, the estimated trade costs are more smooth (left panel of Figure 2). This is because the market price, for example, does not necessarily reflect the shipping costs of long-term contracts. I assume trade cost shock follow AR1 process, and I assume no diffusions in the shock process of trade costs. The standard deviation of the innovation is not necessarily the same as that of the standard deviation of the shock itself, but the standard deviation of the innovation depends on the autocorrelation parameter. The mean of the (quarterly) autocorrelation of the estimated trade costs is slightly negative ( $-0.1$ ). The autocorrelation based on BDI (using observations from 1985 to 2000) is 0.956 and (Stopford, 2009) (from 1962 to 2000) is 0.59. I employ high autocorrelation based on BDI because BDI has more precise monthly observations. The baseline parameter of the standard deviation of innovation in the trade cost shock is 0.0485, which is calculated based on high (0.956) autocorrelation. I will also examine various volatility in trade cost shocks.<sup>27</sup>

The correlation matrix of the innovation of the estimated HP-filtered trade costs is large (since time dimension is used to calculate covariance, the size of the matrix is  $21 \times 20 \times 10$ ). The model calculation in the next section uses three parameters for summarizing this correlation matrix. First, if two trade costs are in the same product, the correlation is set to 0.63 based on the corresponding data average ( $\sigma(\hat{u}_{j,i,m,t}, \hat{u}_{h,k,m,t}) = 0.63$ ). This high correlation potentially reflects my calculation methodology where the estimation is conducted for each  $(m, t)$  pair. Second, if two trade costs share an origin and destination, the correlation is 0.08 ( $\sigma(\hat{u}_{j,i,m,t}, \hat{u}_{j,i,l,t}) = 0.08$ ). This value is also based on the corresponding data average. Third, the rest of the off-diagonal terms of the correlation matrix are set to 0.03 ( $\sigma(\hat{u}_{j,i,m,t}, \hat{u}_{h,k,l,t}) = 0.03$ ), so that the overall average of off-diagonal terms is the same as that of the data correlation matrix.

## 5 Results and mechanisms

In this section, I present the results of the baseline parameterization and explain the basic mechanisms in the model using a simplified example. After discussing the difference between the multi-country model and the three-country models, I examine the effects of some of the model parameters. These investigations are relevant to the potential policy implications.

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<sup>27</sup>The Appendix includes more discussion on the autocorrelation and standard deviation of the trade cost shock.

## 5.1 Baseline results

Adding to the parameters specified in Section 4, I specify the number of countries and sectors in the model. In the baseline specification, the number of countries is 13 ( $N = 13$ ), which corresponds to the G7 countries and six small symmetric “rest of the world.” The computational limitation restricts the number of the “rest of the world” countries. Each of the six countries has one-sixth of the remaining fraction of the population of the model economy.<sup>28</sup> The number of products is three ( $M = 3$ ), as in the productivity process estimations. Ten products in the trade costs estimation are aggregated to three products. One of these products is an agricultural product (constructed by products classified as 0, 1 and 4 of SITC1). For each exporter-importer pair, I take the average of trade costs for these three classifications. Similarly, I construct materials (2 and 3 of SITC1) and manufacturing products (5–9 of SITC1). The trade costs associated with the “rest of the world” are the average over all potential origins and destinations in 21 countries for each aggregated category. Using these trade costs, population weights, and baseline parameters, the model values for bilateral trade intensity and business cycle statistics are calculated. Note that all the parameters excluding steady state trade costs, and the population weights are uniform across any pair of countries. Hence, the cross-sectional variation in the statistics of the model is driven by the difference in trade costs and population size.

The last two columns of Table 3 show the international business cycle statistics of the model. The cross-country correlations of the model US economy are the average of the US and the other six countries of the G7. The G7 column presents the overall average of 21 cross-country correlations. The correlations of output and trade variables in the G7 column are the average of seven countries. The model replicates all the international business cycle moments in the data. The output, consumption, investment, and labor are positively correlated across countries, and the output shows a higher correlation than the consumption. The strong cross-country correlation of net exports, which is typically observed in two-country models, disappears in the model. Both exports and imports are positively correlated with the output, and the net exports are negatively correlated with the output. The model bilateral trade intensity is obtained from the steady state value. The average bilateral trade intensity of the model US economy is 0.46%, and the G7 average is 1.35%. The model predicts a large variation in bilateral trade intensity, contrary to Kose and Yi (2006) who faced the difficulties of replicating variations in the bilateral trade intensity by using the prototypical model. The

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<sup>28</sup>The size of the rest of the world is determined in the following way. Based on Penn World Table 6.2., the fraction of the US total GDP to the world total GDP was 24% in 1985. I set the population size parameter of the US to be 0.24. I then set the population size parameters of the other six G7 countries to be consistent with the ratio of the US to the other country’s population size. Since the total population size is normalized to unity, the population size of the aggregate of the “rest of the world” is the residual of the sum of G7 countries. I use total GDP instead of the population size to quantify the size of the rest of the world because I would like to eliminate largely populated developing economies.

estimated trade costs explain a large fraction of variation in the trade intensity. The upper-left panel of Figure 5 illustrates the relationship between average (of the three products for imports and exports) trade costs and the bilateral trade intensity. The relationship is almost linear, although there are some deviations because of the variation in trade costs across products. Then, the average trade costs predict cross-country correlation of output, as shown in the upper-right panel of Figure 5. Moreover, as shown in the lower-left panel of Figure 5, the average trade costs are associated with the correlations of the implied aggregate TFP. As a consequence, the aggregate TFP is a strong predictor of the output comovement, as shown in the lower-right panel of Figure 5.<sup>29</sup>

The second and sixth rows of Table 1 compare the data and model slope coefficients of the Frankel and Rose (1998) regression (predicted value of  $\alpha_1$  in (1)). The model explains approximately 75% of the data coefficient, even though the trade costs and population size are the only drivers to create cross-sectional variation in the model. The gap between the OLS coefficient and the IV coefficient in the model is smaller than the one in the data. The smaller gap is not surprising because the model trade costs are determined by the gravity variables. The upper-right panel of Figure 1 shows the corresponding scatter plots. The horizontal axis is the log trade intensity and the vertical axis shows the output correlations. The model and data regression lines are almost parallel within the range of observed bilateral trade intensity. A problem of the baseline model is that it cannot replicate the average level of cross-country output correlations. Yet, the level of correlation critically depends on various parameters in the model (see Section 5.4). Another remark is that the model cannot predict a large variation in the cross-country output correlations. That is, the model suggests that the value of output correlations are clustered around the regression line. This is not surprising since both the steady state trade costs and the population size can produce variations in the steady states, but not deviations from the steady state. We will see that a larger size of the shock produces larger deviations.

## 5.2 Model mechanisms

I explain the mechanisms behind the quantitative results using impulse response functions. For simplification of the explanation, I squeeze the model into three countries ( $N = 3$ ) and two intermediate goods per country ( $M = 2$ ). Populations are the same across countries ( $\pi_i = 1/3$  for all  $i \in N$ ). Other parameters are set to the baseline parameters, excluding trade costs.

Let the three countries be labeled as “France”, “Germany” and the “United Kingdom” and the two intermediate inputs as “wine” and “cloth”. The trade costs faced by these countries are different across pairs. The same trade costs are applied for exporting and importing, and

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<sup>29</sup>Arkolakis and Ramanarayanan (2009) showed that fluctuations in the implied TFP are not correlated to trade. Their result is obtained under the complete market assumption. Also, the sector level capital stock can spontaneously move across sectors.

both of the intermediate goods. The trade costs are listed in Table 10. The incurred trade costs are lower for France-Germany trade than for Germany-UK trade and UK-France trade. Since the steady state productivities are the same across countries for all the products, the only reason to create country heterogeneity is trade costs. In the following figures, the impulse is a one percent positive productivity shock to French wine production. Since autocorrelation of the productivity is high (0.995), a one time positive shock lasts for a long period.

Figure 6 shows the impulse response functions of aggregate variables. The upper panel shows the impulse response functions of French aggregate variables, the lower-left panel shows the German, and the lower-right panel shows the British aggregate variables. A positive productivity shock in France stimulates French investment, financed largely by the importing of intermediate products. The one percent positive productivity shock in one of the intermediate goods production leads to a rise in consumption and GDP of around a half percent. These positive responses are usually expected in real business cycle models. As time passes, France starts to export more than before. This is because a higher productivity of wine continues (because of high autocorrelation), and the capital stock of wine production is accumulated. Also, imports decrease gradually since the return to investment becomes lower.

The shock leads to a sector reallocation in France. Table 11 shows the cumulative impulse responses of trade flows after four periods. For example, the first row in the second column of the left matrix shows trade flow (the amount of the destination's usage of the product) of wine from France to Germany. The numbers show how much trade flows has increased within four periods (one year) after the shock, compared with the steady state. The trade flow of French wine increases. After a one percent shock in French wine productivity, the cumulative consumption of French wine in France increases five percent, or on average, by more than one percent increment in each quarter. The flow of French wine to the other countries also drastically increases. A higher productivity of French wine attracts investment and labor from the cloth production industry. As a result, the production of French cloth decreases. A reduction in cloth production potentially decreases a reduction in the final goods production, —if trade is prohibited. What actually happens is France increases cloth imports. The lower production in cloth is substituted by imported cloth. As shown in the right matrix of Table 11, French imports of cloth from Germany and the United Kingdom increase by more than ten percent.

Germany and the United Kingdom experience temporal and minor economic booms (lower panels of Figure 6). The main driver of the boom is a large jump in exports. Both Germany and UK export cloth to France, leading to more production of cloth. Moreover, they can produce final goods more efficiently, because they can access cheaper wine produced in France. During these boom periods, investments decrease, and this lower investment delays capital accumulation in these countries. After a while, the German and United Kingdom economies go into minor slumps because of the lower capital accumulation.

The main mechanism so far is in perfect parallel to the main mechanisms of textbook Ricardian trade theory. Trade is beneficial because trade allows specialization, and the trade pattern is determined by comparative advantage. After the shock, France has the comparative advantage to produce wine whereas Germany and the United Kingdom have the comparative advantage to produce cloth. A key ingredient in the model to generate the Ricardian mechanism is the multiplicity of the goods produced within country. If a country produces a single tradable good, an intra-country production shift does not occur. In the one good per country framework, a similar mechanism can be achieved by specifying a large complementarity of goods from different origins. After a positive shock in one country, the other country's product comes into demand because the other country's product is the complement to produce the final goods (Heathcote and Perri, 2002).

The impulse responses are different for German and the United Kingdom, reflecting their trade costs with France. Compared with the steady states, expansion in cloth exports is larger for the United Kingdom than for Germany (Table 11). At the absolute level, however, German exports are larger than the United Kingdom's (because of the difference in the steady state). The enlarged trade opportunity is beneficial for a pair of countries facing low trade costs. A lower trade cost both generates higher bilateral trade on average and a higher comovement after the shock. Hence, higher bilateral trade is positively associated with higher comovement. A difference in the impulse response functions for two different countries suggests the importance of treating heterogeneity of countries explicitly in the model.

### 5.3 Multi-country model and two- or three-country model

Table 1 compares the slope coefficient of Frankel and Rose (1998) regressions under various conditions. The first to fourth rows include the data values. The fifth and sixth rows are the coefficients obtained by the baseline parameterization. The remaining rows compare the effects of the number of countries in the model.

The existence of a fictitious large country affects the comovement implication of the interested countries. The coefficient in the seventh row is obtained by the model in which I aggregate the six "rest of the world" countries into a single aggregate "rest of the world." This aggregation weakens the implied coefficient. The lower-left panel in Figure 5 shows the corresponding scatter plot. This effect of the existence of a large economy is much more serious if we reduce the number of countries in the model.

The eighth row ("Rec. of 3-country") shows the coefficient drawn by 21 recursions of the three-country, three-sector models. That is, in the three-country model, I pick up a particular pair of countries from the G7, and map them to the first two countries of the three-country model. The third country is always considered to be the "rest of the world." The trade costs between the first two countries are the same as that used in the baseline parameterization.

The trade costs involving the “rest of the world” are the same as the baseline case. Using this three-country model, I can calculate the bilateral trade intensity and cross-country correlation of output for the pair of the two countries. I then pick up another pair of countries from seven countries. Since there are 21 possible pairs of countries among the seven countries, I calculate 21 different model statistics. Finally, I calculate the slope coefficient using these 21 different sets of trade intensity and output correlation as observations. This methodology is similar to one employed by Kose and Yi (2006). A difference is that they repeat the step only twice. They focus only on a pair of countries, comparing a case with plausible trade costs and a case with no trade cost. In any case, the number of recursion is not critical. As shown in the lower-right panel of Figure 5, the calculated output correlations are placed almost exactly on the regression line. Picking up any pair of the countries does not greatly change the implied coefficient.

The implied coefficient is less than the one obtained by the baseline model. A cross-sectional variation of trade costs allows a country to switch the trade partner according to the realization of the shock. Of course, mutual dependence is stronger if trade costs are lower. Hence, cross-sectional variation of the degree of comovement arises. In a three-country model, the interested pair is much smaller than the third country (“rest of the world”). As a result, all the variation in the model is largely driven by the shocks to this third country, and the response of the large country attenuates potential variations caused by the difference in trade costs in the interested two countries. Then, these two countries show a similar level of comovement, regardless of trade costs. The problem is that there is no such large economy in the real world.

Admittedly, the baseline model also aggregates potential effects of more than a hundred economies into some number of “rest of the world” countries. For examining the potential problems caused by limiting the number of model economies to seven, the last line in Table 1 shows a result obtained by an expanded model. Here, I include other OECD economies that are relatively large: Australia, Belgium, the Netherlands, and Spain. A cost is that the inclusion of the additional four countries limits the number of the countries as rest of the world to three because of the computational problem. The other parameterization strategy is exactly the same as the baseline model. Although there are more than seven countries in the model, the regression is based on the observation from seven countries as in the data. The obtained regression coefficient is 7.62, which is close to the data value.<sup>30</sup> This is because the inclusion of additional countries generates further variations in the trade intensity and the correlation of output. Hence, even with seven countries, quantitative implication might be biased to some extent.

The number of countries and their sizes are important model parameters. In the companion paper I suggest the number of countries and their sizes are important factors for explaining the

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<sup>30</sup>Business cycle properties of the model are not drastically changed from the baseline model.

level of the cross-country business cycle statistics (Ishise, 2009). The above examination suggests the variation (slope) of the correlation also critically depends on the number of countries and their sizes in the model.

## 5.4 Further examinations

Some of the model parameters affect the implications of the model. Here, I examine the effects of changing parameters associated with trade costs, shock process, and financial frictions. The main purpose of the examination is a robustness check of the main implications. At the same time, the examination associated with the steady state level of trade costs, volatility of trade costs, and financial friction is relevant for the potential policies.

### 5.4.1 Standard deviation of productivity shock

The left panel of Figure 7 shows the effect of changing the standard deviation of the productivity shocks ( $\sigma(\hat{\varepsilon}_{i,m,t})$ ). The figure illustrates the slope coefficient of trade-comovement regression, output and consumption volatilities, and cross-country correlations of output and consumption for various sizes of productivity shock, while other parameters are fixed.

The volatilities of the aggregate output and consumption critically depend on the size of the shock. The magnitude of cross-country correlations is not affected by varying the size of the productivity shock. Yet, when the standard deviation approaches zero, the cross-country correlations increase. Also, the slope coefficient increases dramatically when the standard deviation decreases. Since the model has two types (productivity and trade costs) of shocks, the cross-sectional variation of the model economy is driven by the trade cost shock if the productivity shock is extremely small. The relative size of the shock is an important determinant of the cross-sectional variation of the model economy. Finally, the slope coefficient becomes small if the shock is extremely small, because temporal changes in comparative advantage are small.

### 5.4.2 Cross-country correlation of productivity shock

The right panel of Figure 7 illustrates the effects of changing the cross-country correlation of the productivity shock ( $\sigma(\hat{\varepsilon}_{i,m,t}, \hat{\varepsilon}_{j,m,t})$ ). IRBC literature (for example, Baxter, 1995) suggests that the cross-country correlation of productivity shock directly affects the cross-country correlations of variables. As expected, a higher productivity correlation implies higher output and consumption correlations (they almost perfectly overlap each other). In contrast, standard deviations of output and consumption do not drastically change. Therefore, a higher degree of comovement does not necessarily imply higher volatilities of the countries.

Even in the case that there is almost no cross-country correlation in productivity, the slope

coefficient is positive. Hence, the model cross-sectional variation does not depend exclusively on the degree of cross-country correlation of productivity shock. This result is consistent with the finding by Arkolakis and Ramanarayanan (2009), who examined a multi-sector international real business cycle model including Ricardian trade structure, and showed that their model can generate a positive aggregate output correlation and a positive slope coefficient without imposing a positive productivity correlation.

### 5.4.3 Steady state trade cost

A worst scenario in the world-wide economic slump is emergence of trade blocks.<sup>31</sup> Obviously, in this model, a lower trade cost is beneficial in the steady state. A lower trade cost implies higher output and consumption. Moreover, a low trade cost implies a high trade intensity, which then implies a high comovement. The problem is, then, how does a change in trade costs affect volatility of the economy. Since the trade costs in this model include tariffs, an examination of trade costs also corresponds to a policy question: Can introduction of a tariff reduce the volatility of the output and consumption?

Admittedly, the welfare gain of eliminating the entire business cycle is tiny, since the model economy satisfies the standard property suggested by Lucas (1987). Instead, I calculate percentage changes in the volatilities, cross-country correlations, and the steady state values of output per capita and consumption per capita of the model US economy for four different scenarios. Table 12 presents the results of the examination for the case of (1) 5% lower trade costs for all the world trade, (2) 5% lower trade costs in imports of the model US economy, (3) 5% higher trade costs in imports of the model US economy, and (4) 5% higher trade costs for all the world trade. Note that a 5% change in steady state trade costs is sizable. An introduction of an FTA reduces trade costs by 0.02 points (see Table 7), which is approximately 1.15% (= 0.02/1.75) of trade costs. A 5% change also corresponds to the magnitude of trend reduction for 15 years ( $g_{\tau}^{4 \times 15} \approx 0.95$ ).

If trade costs associated with US imports (trade costs from other countries to US) increase by 5% from the baseline parameterization, then the steady state GDP and consumption decrease by 0.25%. At the same time, the volatility of output decreases only by 0.02%. The reason is that in this economy the US needs to import other countries' intermediate products to produce final goods. A higher trade cost makes it difficult for the US to stably import the intermediate goods. Hence, output volatility does not dramatically decrease. Yet, by substitution of intermediate goods, the US now relies more on internally produced intermediate products. Hence, the US becomes more isolated from other economies. As a result, the cross-country correlation of output decreases. The volatility of consumption decreases to a

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<sup>31</sup>Trade protection is not a past story, but an important issue even in the current downturn. "According to the World Bank, 17 members of the group have taken a total of 47 trade-restricting steps since November." ("The nuts and bolts come apart; Globalization and trade," *The Economist*, March 28, 2009)

larger extent than output, and the cross-country correlation of consumption also decreases. A consumption smoothing motive induces households to hold internationally traded assets more by sacrificing the steady state level of investment and consumption for stabilizing the consumption path. The impact of changing trade costs is larger if trade cost change is done only for US imports. A world simultaneous change does not fundamentally change the world trade pattern, and hence the impact is weaker. There is an asymmetric response between rise or fall in trade costs. Figure 8 shows this asymmetric pattern.

Figure 8 illustrates the effect of changing all the world steady state trade costs to a larger extent. Compared with baseline trade costs, higher trade costs do not greatly change the statistics whereas lower trade costs raise the correlations, volatilities, and slope. A low steady state trade cost implies a smaller magnitude of the trade cost shock since trade cost shocks are percentage deviations from the steady state. On the one hand, lower trade costs induce more dependence on the foreign intermediate products, implying higher comovement and higher volatility. On the other hand, lower trade costs can generate a smaller shock in absolute terms, implying lower comovement and lower volatility. The magnitude of change in the output volatility depends on which effect dominates. At the same time, lower trade costs imply that production of the intermediate goods is more affected by the neighboring countries' demands. Hence, the cross-country correlation of output increases. Moreover, a shock in productivity or trade costs influences the a pair of countries that are closely located. As a result, the cross-country correlation of output is more correlated to a country that trades more. The slope coefficient becomes larger, and the consumption becomes more correlated. Nevertheless, the volatilities of output and consumption are not greatly altered. Hence, higher trade costs do not contribute stabilizing the economy.

#### 5.4.4 Standard deviation of trade cost shock

The two panels of Figure 9 show the effect of changing the standard deviation of trade cost shock. In the baseline parameterization, I set the standard deviation of trade cost shock to 0.0485. This value is based on the estimated trade costs in Section 4. Yet, as shown in Figures 2 and 3, the shipping cost indices based on the market price show substantially larger standard deviations. Using this level of large standard deviation significantly alters model properties. The left panel of Figure 9 displays the slope coefficient, the standard deviation of output, and the standard deviation of consumption for various standard deviations of trade cost shock. A real world interpretation of high standard deviation is that a high standard deviation represents the period of a more volatile oil price, because the shipping costs critically depend on the oil price (Stopford, 2009).

The baseline parameterization is located at around 0.05. Even if trade cost volatility is set to 0.2, the standard deviation of output is still less than two, which is in the range of corresponding

data from developed countries (Backus et al., 1994). The volatility of consumption increases to a smaller extent, suggesting the effect of consumption smoothing mechanisms. The cross-country correlation of output and consumption increases to some degree (right panel of Figure 9). In contrast, the slope coefficient sharply increases because a high volatility of trade cost shock reduces trade with remote countries and increases trade with neighboring countries. This is because the shock is a percentage deviation from the steady state, meaning the absolute changes in trade costs are larger if steady state trade costs are larger. A high volatility of trade cost shock then generates a larger comovement in the neighboring countries. As a result, the average correlation also increases. An implication is that the slope coefficient depends on the timing of the sample period. If the sample comes from a relatively volatile trade costs period (1970s and 2000s, see Figure 3), then the slope coefficient is expected to be high.

#### 5.4.5 Cross-country correlation of trade cost shock

Given the significant role played by the size of a trade shock, a natural question is whether the assumption on the correlation matrix of trade cost shock also significantly alters the model statistics. The answer is no, except for the slope coefficient. For examining the effect of changing parameters in the correlation matrix of the trade cost shock while maintaining tractability, I set all the off-diagonal terms of the correlation matrix to specific values. I then vary the value from zero to one. Figure 10 shows the model statistics for various correlations of trade cost shocks. The slope coefficient changes, but the other statistics do not change. Hence, varying the correlation of trade cost shock does not change the volatilities and cross-country correlations of output and consumption.

#### 5.4.6 Role of the financial market

Figure 11 shows the effects of changing the asset trading cost parameter,  $\eta^b$ . The horizontal axis is  $\eta^b$  in log scale. The original motivation to introduce the asset trading cost parameter is to allow the model to have a unique steady state of the amount of asset holdings to be zero in the incomplete market setting (Ghironi and Melitz, 2005). Effectively, the parameter controls the transaction costs of asset trading. A low parameter value suggests low costs in international trade of assets. A high  $\eta^b$  reduces the incentive to change the amount of assets. At the extreme, a high enough  $\eta^b$  is equivalent to the “financial autarky” assumption proposed by Heathcote and Perri (2002) because agents in the model do not have incentive to change the amount of assets from the steady state value (which is zero). Since the “financial autarky” model excludes the possibility of asset trading, an interpretation of the parameter is the degree of restriction imposed on the international financial trading.

Tightening the financial transactions (for a high  $\eta^b$ ) does not reduce the degree of volatility, which is consistent with the results obtained by Heathcote and Perri (2002). They found that

the financial autarky assumption (which corresponds to an extremely high financial transaction cost in my model) does not significantly alter intra-country business cycle properties. They also show that the financial autarky assumption reproduces empirically comparable magnitude of output and consumption cross-country correlations. Along with their findings, Figure 11 shows that the cross-country correlations of output and consumption are not responsive to the financial friction parameter. Reducing the financial friction does not drastically change the volatilities and cross-country correlations. The size of the financial friction influences the slope coefficient, but the absolute change is not large. A policy implication based on the model is that tightening the international financial transaction does not eliminate the magnitude of business cycle volatilities, as well as the degree of cross-country comovement.

## 6 Conclusion

This paper presents a multi-country, multi-sector international real business cycle model. A multi-sector structure produces a mechanism such that a productivity shock is transmitted across countries through changes in trade patterns, which are driven by changes in Ricardian comparative advantage. I estimate exporter- importer- product- year-specific trade costs by exploiting the model structure and trade flow data. The cross-sectional variations in the estimated trade costs generate heterogeneity in bilateral trade and the dynamics of the multiple countries. The parameterized model simultaneously accounts for data facts about the variation in bilateral trade, the correlations between output and trade flows, the business cycle correlations across countries, and the association between bilateral trade and comovement. I show that the trade-comovement regression coefficient depends critically on the number of countries and their sizes in the model. The model confirms lower trade costs are associated with higher comovement. At the same time, low trade costs do not greatly increase the output volatility.

## Appendix

The separate appendix is available at <http://people.bu.edu/ishise>

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Table 1: Data and model trade-comovement regression coefficients

		Obs.	Slope ×100	S.E. ×100	Reference
Data (G7)	OLS	21	2.39	(5.05)	Section 2
Data (G7)	IV	21	7.02	(5.93)	Section 2
Data (21 OECD)	OLS		5.0	–	Kose and Yi (2006)
Data (21 OECD)	IV		9.1	(2.2)	Kose and Yi (2006)
Baseline (7+6ROW)	OLS	21	4.84	(0.99)	Section 5.1
Baseline (7+6ROW)	IV	21	5.18	(0.58)	Section 5.1
7+1ROW	IV	21	4.16	(0.34)	Section 5.3
Rec. of 3-country	IV	21	1.25	(0.15)	Section 5.3
7+4+3ROW	IV	21	7.26	(0.05)	Section 5.3

Slope coefficient of Frankel and Rose (1998) regressions, (1).

See corresponding section for the calculation method of the model values.

Table 2: Standard deviation of output and consumption, average bilateral trade intensity, and aggregate trade-to-GDP ratio (Data)

	CAN	FRA	DEU	ITA	JPN	GBR	USA
Output (GDP) standard deviation (%)	1.44	0.90	1.27	1.37	1.34	1.45	1.57
Consumption standard deviation (%)	1.22	0.89	1.27	1.26	1.20	1.69	1.25
Average bilateral trade intensity (%)	0.74	1.18	1.36	0.95	0.58	0.93	1.04
Aggregate Trade-GDP ratio	0.30	0.25	0.23	0.20	0.09	0.20	0.09

Standard deviations: Based on  $BP_{12}(6, 32)$  filtered GDP and consumption series.

Original data: OECD quarterly national account, 1970–2006.

Average bilateral trade intensity: average of bilateral trade intensities with other 6 countries.

The bilateral trade intensity is sum of exports and imports of two countries divided by sum of GDPs.

Original data: Heston et al. (2008) and Feenstra et al. (2005), average of 1970–2000.

Aggregate Trade-GDP ratio: the combined mean of exports to GDP ratio and imports to GDP ratio.

Original data: OECD quarterly national account, average of 1970–2006.

Table 3: Data and model international business cycle moments

	Data (G7)		One-sector				Two-sector		Baseline model		
	USA	Mean	SD	Low TC	Mid TC	High TC	Three	CM	IM	US	G7
Cross country correl.											
Output ( $Y$ )	0.51	0.41	0.19	0.72	0.35	0.19	0.55	0.05	0.17	0.20	0.28
Consumption ( $C$ )	0.36	0.21	0.29	0.58	0.56	0.23	0.66	0.34	0.14	0.16	0.22
Investment ( $X$ )	0.30	0.23	0.23	-0.71	-0.07	0.16	0.10	-0.01	0.10	0.14	0.22
Labor ( $L$ )	0.26	0.23	0.30	0.78	0.08	0.11	0.43	-0.71	0.12	0.25	0.33
Net exports ( $NX$ )	-0.08	-0.02	0.22	-0.99	-0.96	-0.84	-0.50	-0.92	-0.97	-0.17	-0.11
Aggregate TFP shock	0.15	0.10	0.21	-0.71	-0.09	0.14	0.08	-0.02	0.08	0.14	0.23
Correl. to output											
Exports ( $EX$ )	0.41	0.42	0.22	0.91	0.93	0.87	0.96	0.98	0.11	0.28	0.32
Imports ( $IM$ )	0.83	0.72	0.12	0.88	0.73	0.54	0.80	0.89	0.04	0.29	0.32
Net exports ( $NX$ )	-0.46	-0.32	0.17	0.01	0.43	0.57	0.43	0.22	0.11	-0.05	-0.01
Ave. bilat. trade int. (%)	1.04	0.97	0.86	43	15	1.04	15	0.61	0.61	0.46	1.35
Agg. Trade-GDP ratio	0.09	0.19	0.08	0.43	0.15	0.01	0.15	0.006	0.006	0.04	0.14
Trade cost	$\approx 1.5$	-	-	1.76	30	9000	20	1.76	1.76	1.76	1.74

Business cycle moments are  $BP_{12}(6, 32)$  filtered data. Original data: OECD quarterly national account. See the Appendix for the detail.

Cross-country correlation of US is mean of correlations of US and 6 other G7 countries.

Cross-country correlation of G7 is mean (and standard deviation) of 21 ( $= 7 \times 6/2$ ) pairs.

Average bilateral trade intensity and aggregate Trade-GDP ratios: see note for Table 2.

Trade cost is iceberg equivalent trade cost. Data trade costs are from Anderson and van Wincoop (2004).

Model values are based on my replication using common parameters (See footnote 7).

One-sector: Backus et al. (1994) model. Two-sector: Two-country, two-sector model, similar to Ambler et al. (2002).

“Low TC”: using baseline trade cost estimation. “Mid TC”: to replicate aggregate Trade-GDP ratio to 0.15.

“High TC”: to replicate average bilateral trade intensity to 1.04.

“Three”: three-country model as Kose and Yi (2006). “CM”: complete market model. “IM”: incomplete market model.

Table 4: Variables and indices

Variable	Description
Indices	
$i, j \in \{1, \dots, N\}$	Country index
$m \in \{1, \dots, M\}$	Product (sector) index
$t = 0, 1, \dots$	Time index
$s_t \in S$	State of the world at $t$
$s^t \in \mathbf{S}$	History upto $t$
$\Pr(s^t)$	Probability realizing history $s^t$
Quantities (per capita values)	
$C_{i,t}(s^t)$	Consumption of final goods
$L_{i,t}(s^t)$	Total labor supply
$l_{i,m,t}(s^t)$	Labor supply for sector $m$
$X_{i,t}(s^t)$	Total investment
$x_{i,m,t}(s^t)$	Investment for sector $m$
$k_{i,m,t}(s^{t-1})$	Capital stock of sector $m$
$Z_{i,t}(s^t)$	Total final goods production = Absorption per capita
$z_{j,i,m,t}(s^t)$	Int. goods $m$ produced in $j$ used in $i$
$B_{i,t}(s^t)$	Risk free bond holdings
$T_{i,t}^b(s^t)$	Transfer financed by bond adjustment tax
Prices	
$P_{i,t}(s^t)$	Final goods price
$W_{i,t}(s^t)$	Real wage
$R_{i,m,t}(s^t)$	Real rental rate
$P_t^b(s^t)$	Price of risk free bond
$p_{j,i,m,t}(s^t)$	Price of $(j, m)$ products in $i$
Exogenous shock variables	
$a_{i,m,t}(s^t)$	Productivity of intermediate product
$\tau_{j,i,m,t}(s^t)$	Trade cost of product $m$ from $j$ to $i$
Functions and constant	
$u(C, L)$	Time separable period utility function
$\phi(x/k)$	Capital adjustment friction function
$\eta_t^b$	Bond adjustment tax rate
Additional variables	
$ex_{j,i,m,t}(s^t)$	Total flow value of product $m$ from $j$ to $i$
$Y_{i,t}$	GDP per capita
$EX_{i,t}$	Total exports per capita
$IM_{i,t}$	Total imports per capita
$NX_{i,t}$	Net exports per capita

Table 5: Baseline parameters

	Value	Explanation	Reference
$\beta$	0.988	Subjective discount factor	
$\gamma$	2.00	Controlling IES and RRA	
$\psi$	0.34	Utility share of consumption	
$\eta_\phi$	0.3	Adjustment function elasticity	
$\alpha$	1/3	Capital share in production	
$\delta$	0.025	Capital depreciation	
$\rho$	0.9	Elast. subst. across origin	Whalley (1985)
$\theta$	1/3	Elast. subst. across product	Whalley (1985)
$\eta^b$	0.0001	Incomplete market adjustment cost	Small cost
$v_{i,j}$	1.00	Production weight	Assumption
$g_a$	1.0018	Trend productivity growth	Estimated
$g_\tau$	0.9992	Trend trade cost reduction	Estimated
$\bar{a}_{i,m}$	1	Steady state productivity	Assumption
$\bar{\tau}_{i,j,m}$	various	Steady state trade costs	Estimated
$\rho_a$	0.995	Autocorrelation of the productivity	Aggregate TFP
–	0	Diffusion of productivity	Ambler et al. (2002)
$\rho_\tau$	0.956	Autocorrelation of trade cost shock	Estimated
–	0	Diffusion of trade cost	Estimated
$\sigma(\hat{\varepsilon}_{i,m,t})$	0.015	Standard deviation of productivity shock	Aggregate TFP
$\sigma(\hat{\varepsilon}_{i,m}, \hat{\varepsilon}_{j,m})$	0.2	Cross-country shock correlations	Aggregate TFP
$\sigma(\hat{\varepsilon}_{i,m}, \hat{\varepsilon}_{i,l})$	0.15	Within country shock correlations	Estimated
$\sigma(\hat{u}_{j,i,m,t})$	0.0485	Standard deviation of trade cost shock	Estimated
$\sigma(\hat{u}_{j,i,m,t}, \hat{\tau}_{h,k,m,t})$	0.63	TC shock correl. for same $m$	Estimated
$\sigma(\hat{u}_{j,i,m,t}, \hat{\tau}_{j,i,l,t})$	0.08	TC shock correl. for same $(j, i)$	Estimated
$\sigma(\hat{u}_{j,i,m,t}, \hat{\tau}_{h,k,l,t})$	0.03	TC shock correl. general	Estimated
$\sigma(\hat{\varepsilon}_{i,m}, \hat{\tau}_{j,h,l})$	0	Correlation of prod. and TC shock	Assumption
$N$	13	Number of countries	
$M$	3	Number of products (sectors)	

Table 6: List of empirical variables

Notation	Explanation	Data source
$j$	Exporter country index	
$i$	Importer country index	
$m$	Product (sector) index	
$t$	Year index	
$ex_{j,i,m,t}$	Trade flow from $j$ to $i$ of category $m$ at $t$	Feenstra et al. (2005)
$Z_{i,t}$	Absorption per capita	PWT6.2.
$P_{i,t}$	PPP price	PWT6.2.
$\pi_i$	Population	PWT6.2.
$\ln\text{Dist}_{j,i}$	Bilateral log distance	Rose (2005)
$\text{Border}_{j,i}$	Sharing a border dummy	Rose (2005)
$\text{Lang}_{j,i}$	Common language dummy	Rose (2005)
$\text{Colony}_{j,i}$	Formal colonial relationship dummy	Rose (2005)
$\text{FTA}_{j,i,t}$	Indicator of $j$ and $i$ are in the same FTA at $t$	Rose (2005)

See Section 4 and the Appendix for the detail of variable construction.

Table 7: Average and standard deviations of 390 first stage fixed effects estimations

	Mean	SD	Implied effect
$\ln\text{Dist}_{j,i}$	9.21	8.92	
$(\ln\text{Dist}_{j,i})^2$	-1.27	1.33	
$(\ln\text{Dist}_{j,i})^3$	0.05	0.06	
$\text{Border}_{j,i}$	0.36	0.22	-0.04
$\text{Lang}_{j,i}$	0.87	0.32	-0.10
$\text{Colony}_{j,i}$	0.15	0.21	-0.02
$\text{FTA}_{j,i,t}$	0.15	0.33	-0.02

There are 390 category-time specific fixed effects estimations. Mean and SD are mean and standard deviations of 390 different estimations. “Implied elast.” is implied trade cost elasticity with respect to the variables. For the distance, see Figure 4. The implied effect shows how much trade cost decreases. Sharing a border, for example, makes 0.04 points lower iceberg trade costs.

Table 8: Estimated steady state trade costs (category specific, average over exporter-importer)

SITC1	Description	Mean	SD
0	Food and live animals chiefly for food	2.24	0.48
1	Beverages and tobacco	1.72	0.26
2	Crude materials, inedible, except fuels	1.61	0.30
3	Mineral fuels, lubricants and related materials	1.59	0.35
4	Animals and vegetable oils, fats and waxes	1.72	0.37
5	Chemicals and related products, N.E.S.	1.78	0.30
6	Manufactured goods classified chiefly by material	1.77	0.30
7	Machinery and transport equipment	1.68	0.32
8	Miscellaneous manufactured articles	1.49	0.33
9	Commodities and trans.	1.67	0.27

Iceberg (the required units of goods to deliver one unit of the good) trade cost.

See the estimation method in Section 4.

The steady state costs are average (1962–2000), after adjusting common growth component.

Basis year is 1985.

Table 9: Estimated steady state trade cost (exporter- importer-specific, average over category)

	I M P O R T E R																					
	USA	CAN	GBR	IRL	FRA	BEL	NLD	DEU	ITA	ESP	PRT	GRC	AUT	CHE	DNK	NOR	SWE	FIN	AUS	NZL	JPN	
United States	1.55	1.85	1.78	1.85	1.85	1.83	1.90	1.92	1.88	2.11	2.12	1.99	1.88	1.96	2.04	1.99	2.10	2.20	2.32	1.90		
Canada	1.44		1.63	1.73	1.81	1.78	1.79	1.82	1.82	1.91	2.05	2.06	1.95	1.93	1.99	1.91	1.98	2.01	2.06	2.06	1.81	
United Kingdom	1.82	1.66		1.17	1.48	1.42	1.43	1.54	1.56	1.52	1.50	1.59	1.56	1.49	1.44	1.47	1.49	1.52	1.84	1.82	1.95	
Ireland	1.70	1.79	1.16		1.42	1.40	1.40	1.43	1.54	1.51	1.71	1.70	1.59	1.49	1.57	1.60	1.57	1.68	2.10	2.23	1.98	
France	1.88	1.83	1.49	1.50		1.26	1.40	1.38	1.34	1.39	1.46	1.49	1.50	1.33	1.53	1.62	1.60	1.64	2.17	2.30	1.99	
Belgium	1.90	1.87	1.44	1.47	1.24		1.16	1.31	1.39	1.50	1.50	1.50	1.44	1.40	1.44	1.52	1.51	1.57	2.18	2.23	2.03	
E Netherlands	1.96	1.90	1.41	1.43	1.36	1.17		1.30	1.41	1.50	1.50	1.49	1.42	1.41	1.41	1.52	1.50	1.56	2.15	2.18	2.06	
X Germany	1.91	1.86	1.56	1.51	1.40	1.32	1.31		1.42	1.50	1.51	1.49	1.23	1.30	1.39	1.52	1.48	1.51	2.07	2.20	1.97	
P Italy	1.91	1.83	1.57	1.60	1.37	1.45	1.50	1.41		1.47	1.54	1.42	1.35	1.35	1.57	1.67	1.64	1.67	2.10	2.22	2.06	
O Spain	1.90	1.89	1.51	1.55	1.35	1.48	1.48	1.47	1.47		1.26	1.58	1.60	1.52	1.59	1.67	1.67	1.70	2.25	2.37	2.09	
R Portugal	1.96	1.91	1.47	1.58	1.46	1.48	1.52	1.51	1.61	1.37		1.73	1.50	1.57	1.49	1.59	1.55	1.62	2.44	2.44	2.22	
T Greece	1.91	1.91	1.57	1.74	1.47	1.49	1.50	1.37	1.32	1.59	1.75		1.49	1.60	1.71	1.78	1.70	1.77	2.25	2.45	2.12	
E Austria	1.97	1.83	1.53	1.64	1.52	1.49	1.47	1.27	1.34	1.56	1.56	1.49		1.22	1.44	1.49	1.45	1.49	2.16	2.30	2.05	
R Switzerland	1.89	1.79	1.49	1.63	1.41	1.44	1.47	1.37	1.40	1.51	1.52	1.62	1.25		1.47	1.56	1.54	1.55	2.04	2.13	1.83	
Denmark	1.95	1.89	1.43	1.48	1.55	1.54	1.44	1.39	1.57	1.60	1.58	1.60	1.45	1.43		1.23	1.24	1.36	2.19	2.23	2.02	
Norway	1.97	1.85	1.39	1.63	1.57	1.58	1.47	1.46	1.71	1.65	1.63	1.76	1.59	1.60	1.23		1.23	1.38	2.23	2.32	2.03	
Sweden	1.99	1.85	1.54	1.60	1.61	1.56	1.51	1.53	1.65	1.63	1.65	1.74	1.49	1.52	1.25	1.26		1.30	2.05	2.21	2.09	
Finland	2.02	1.95	1.49	1.64	1.63	1.61	1.53	1.50	1.68	1.72	1.70	1.74	1.52	1.59	1.32	1.33	1.24		2.23	2.42	2.18	
Australia	2.09	2.05	1.78	2.24	2.07	2.07	2.12	2.02	2.02	2.24	2.36	2.34	2.29	2.26	2.42	2.28	2.30	2.38		1.60	1.71	
New Zealand	2.09	2.18	1.81	2.03	2.26	2.22	2.17	2.23	2.34	2.32	2.30	2.31	2.20	2.30	2.21	2.40	2.48	2.31	1.72		1.86	
Japan	1.94	1.92	1.93	1.95	1.98	2.01	1.97	1.92	2.11	2.03	2.20	2.04	2.00	1.94	2.01	2.01	2.06	2.05	2.10	2.20		

Iceberg (the required units of goods to deliver one unit of the good) trade cost, based on the estimation in Section 4. Internal trade costs are unity.

Steady state costs are calculated by taking time series average (1962–2000) after adjusting common growth component, in which 1985 is set to basis.

Table 10: Trade cost matrix (simplified example)

Exporter	Importer		
	FRA	DEU	GER
France	1	1.4	1.5
Germany	1.4	1	1.5
United Kingdom	1.5	1.5	1

Trade costs used in Section 5.2.

Table 11: Cumulative impulse of trade flows (simplified example)

Exporter	Importer					
	Wine			Cloth		
	FRA	DEU	GBR	FRA	DEU	GBR
France	5.08	11.28	11.88	-0.45	-11.76	-12.71
Germany	-6.40	-0.20	0.40	11.34	0.03	-0.92
United Kingdom	-6.91	-0.71	-0.12	12.28	0.97	0.02

Cumulative impulses (%) after 4 periods of the shock. See Section 5.2.

Table 12: Effects of changes in steady state trade costs

	5% low	5% low	5% high	5% high
	All world TC <sup>†</sup>	US imports <sup>‡</sup>	US imports <sup>‡</sup>	All world TC <sup>†</sup>
Steady state GDP	+0.20%	+0.39%	-0.25%	-0.15%
Steady state consumption	+0.20%	+0.39%	-0.25%	-0.15%
Output volatility	+0.20%	+0.39%	-0.02%	-0.06%
Consumption volatility	+0.62%	+1.14%	-0.85%	-0.49%
Output XC correl.	+6.48%	+15.04%	-8.66%	-4.96%
Consumption XC correl.	+4.26%	+13.43%	-5.98%	-2.93%

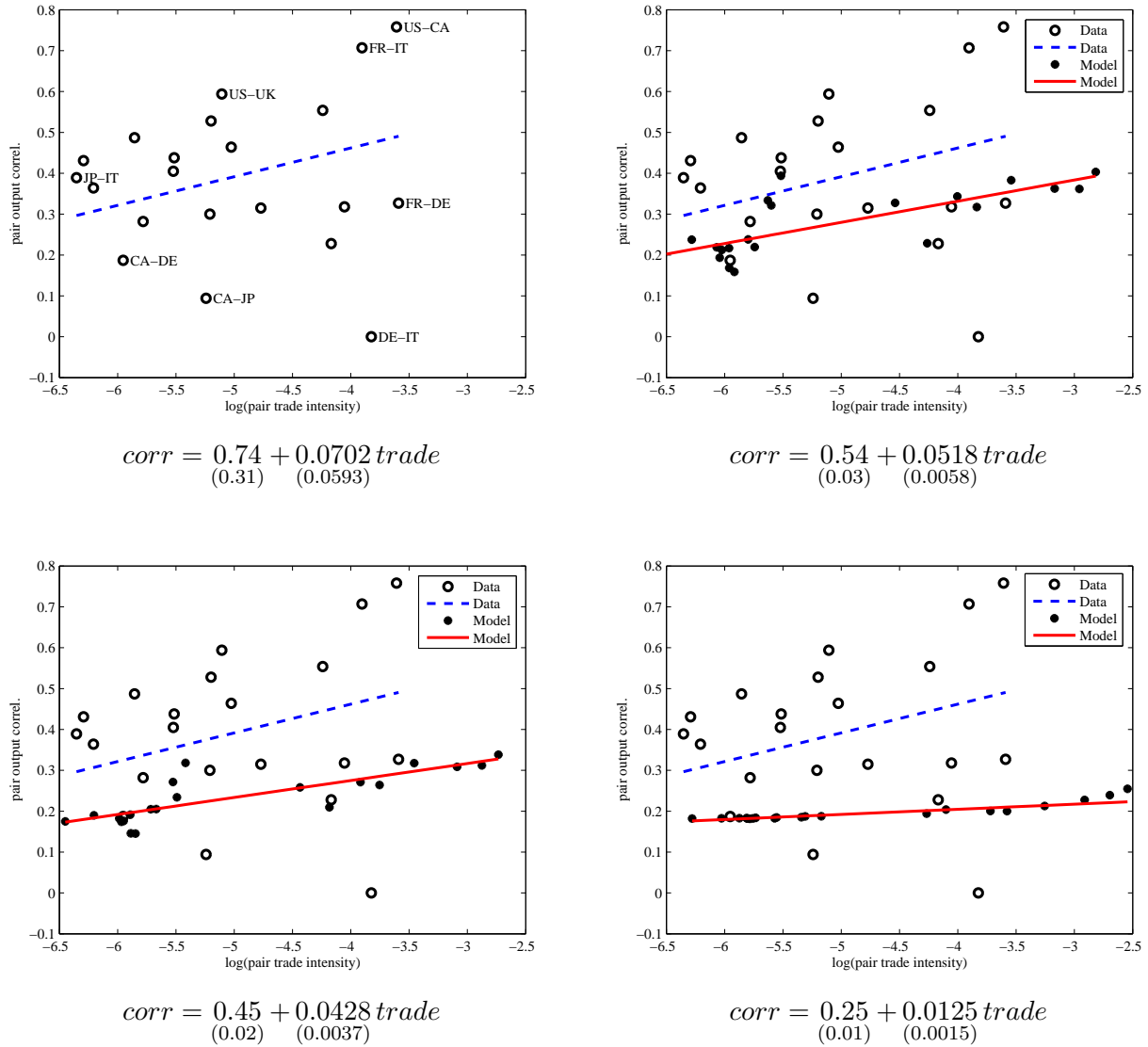
Comparison to baseline trade costs. The outcomes are of US values. See Section 5.4.3.

<sup>†</sup> All the world trade costs are lower (higher) by 5%.

<sup>‡</sup> All the trade costs associated with US imports are lower (higher) by 5%.

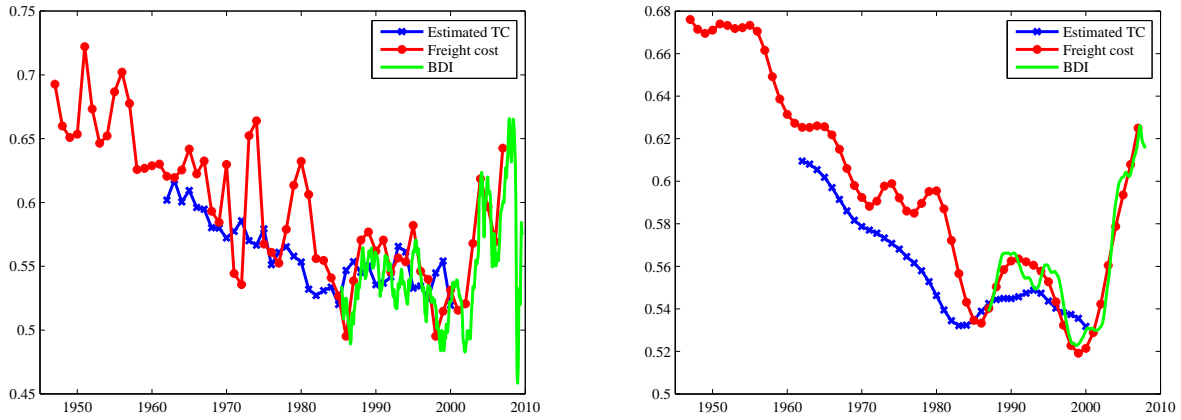
XC correl. is cross-country correlation, average of US and other six G7 countries' correlation.

Figure 1: G7 bilateral trade and output correlations



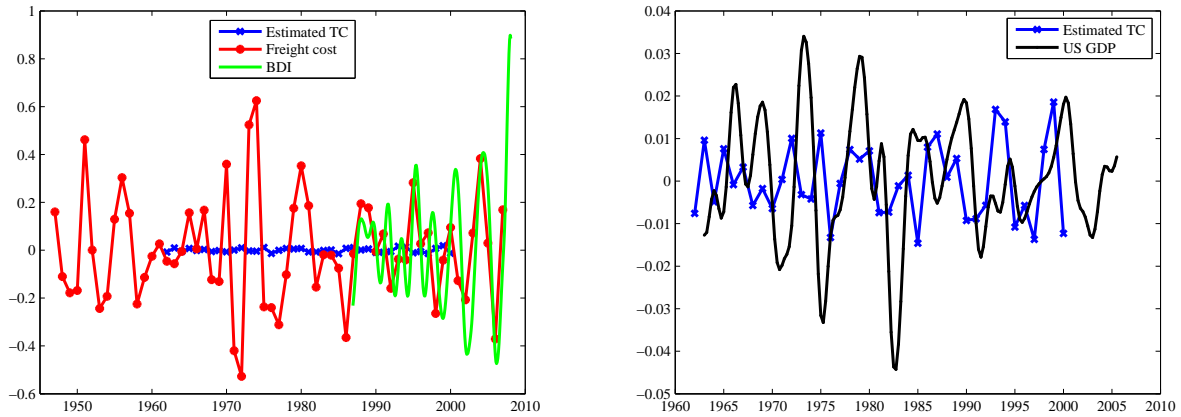
Upper-left panel: Log bilateral trade intensities and BP-filtered output correlations among G7 countries (Data). Upper-right panel: data and the baseline model (G7 countries and 6 other countries). Lower-left panel: G7 countries and single “rest of the world.” Lower-right panel: 21 recursion of three-country (interested pair and single “rest of the world”) models. The equations show corresponding IV regressions. Numbers in parentheses are robust standard errors. Instruments: log of the bilateral distance, indicator of sharing a border, indicator of colonial relationship, indicator of common language.

Figure 2: Log and trend of the estimated trade cost and shipping costs



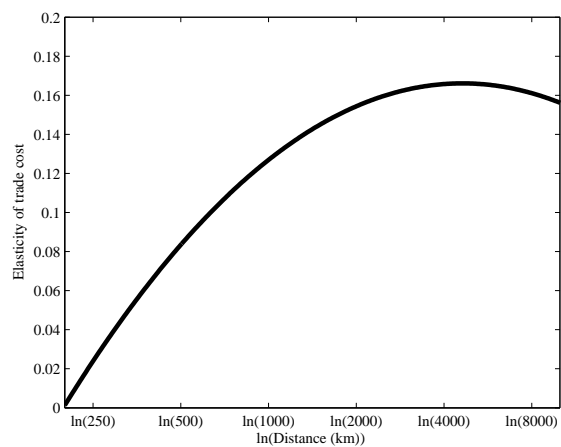
Left panel is log series. Right panel is trend series. The estimated trade cost is the average over countries and categories for each year. “Freight cost” is the price index of Stopford (2009). “BDI” is the Baltic exchange dry index. Trend values are residuals of filtered series. Trade cost and freight cost are annual and HP filtered ( $\lambda = 6.25$ ). BDI is a monthly average of daily data, and  $BP_{18}(2, 96)$  filtered. In both panels, the values are normalized to 1985 value of trend of estimated trade costs. See the Appendix for the detail of shipping cost indices.

Figure 3: Business cycle components of the estimated trade cost, shipping costs and US GDP



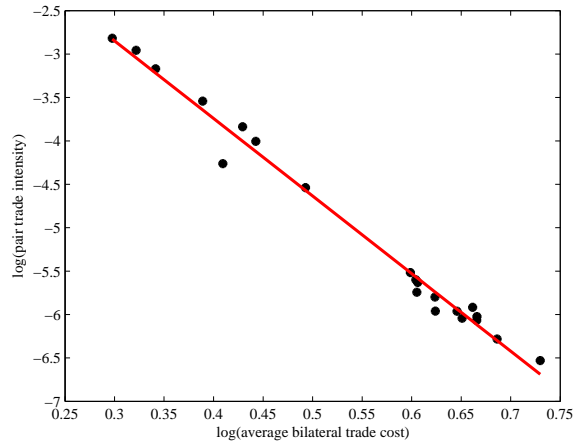
The estimated trade cost is the average over countries and categories for each year. “Freight cost” is the price index of Stopford (2009). “BDI” is the Baltic exchange dry index. Trade cost and freight cost are annual and HP filtered ( $\lambda = 6.25$ ). BDI is a monthly average of daily data, and  $BP_{18}(18, 96)$  filtered. US GDP is US quarterly real GDP per capita, and  $BP_{12}(6, 32)$  filtered. See the Appendix for the detail about shipping cost indices.

Figure 4: Estimated distance elasticity of trade cost



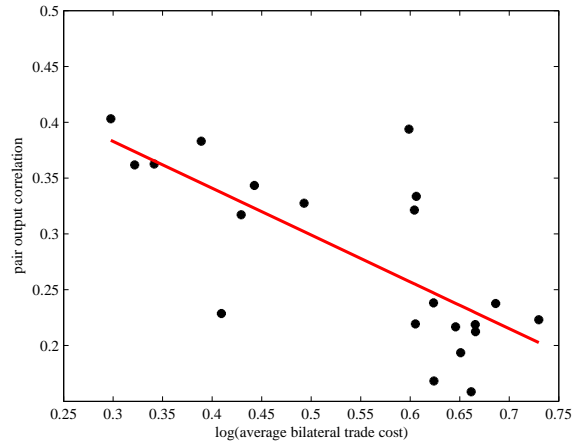
From trade cost estimations, average of the estimated coefficients are obtained. Then, based on these coefficients, implied distance dependent distance elasticity is calculated. See Section 4 for the detail.

Figure 5: Average trade costs, bilateral trade, implied TFP and output correlations



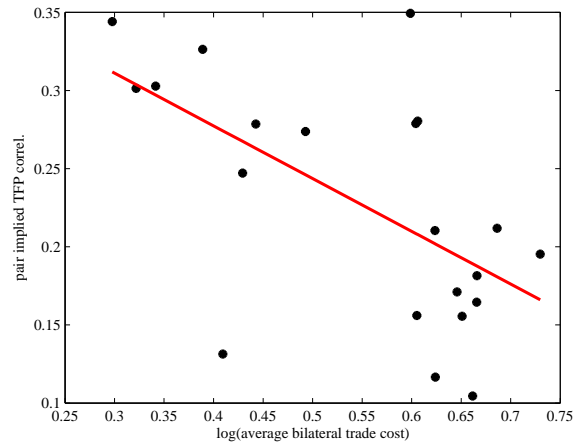
$$trade = -0.17 - 8.93 TC, R^2 = 0.99.$$

(0.14) (0.22)



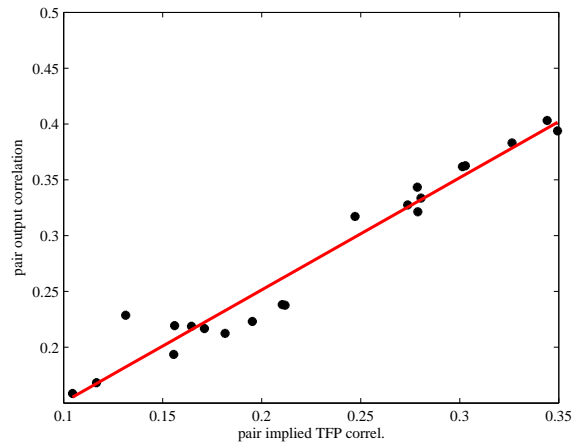
$$corr = 0.51 - 0.42 TC, R^2 = 0.52.$$

(0.03) (0.06)



$$TFP = 0.41 - 0.34 TC, R^2 = 0.35.$$

(0.04) (0.08)

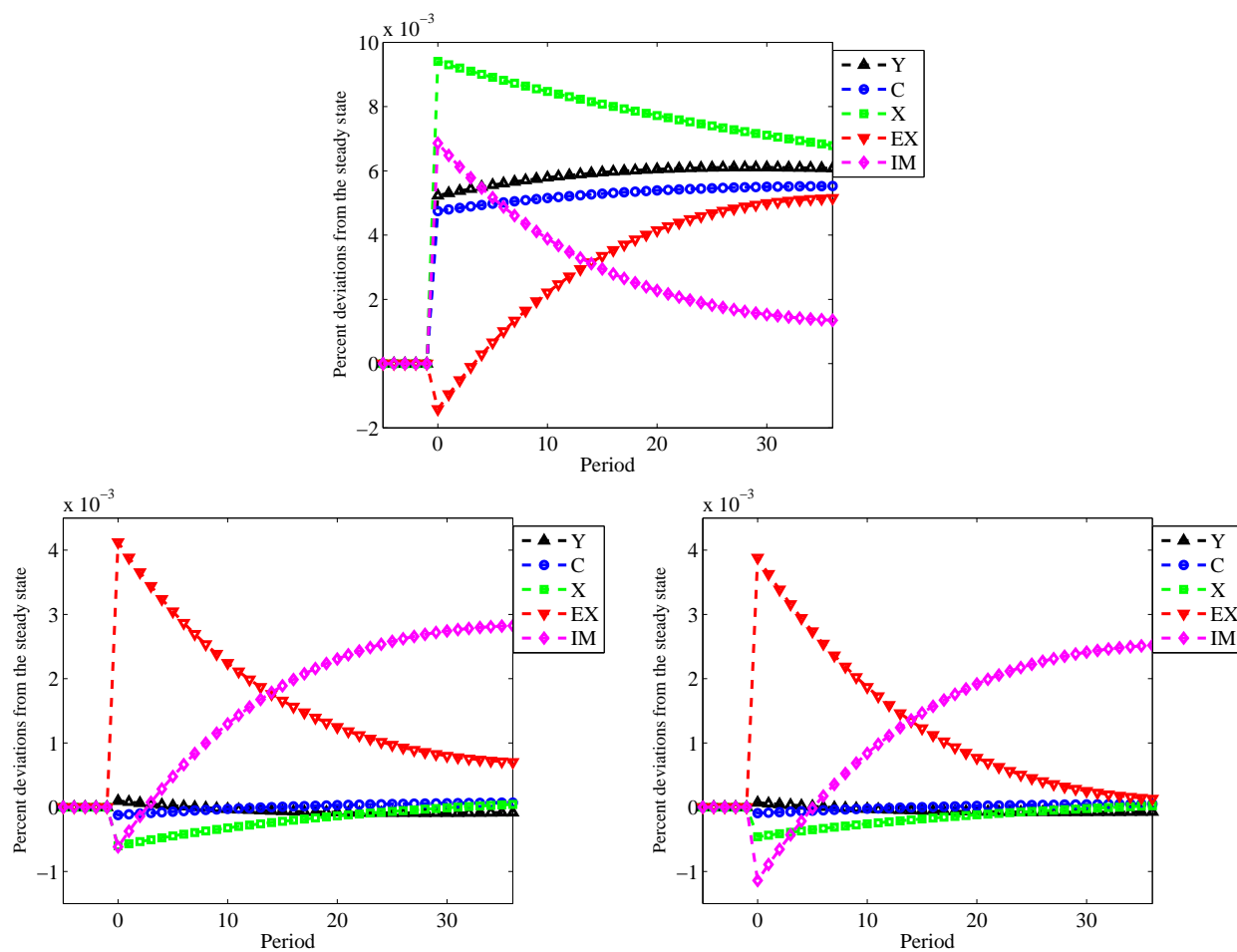


$$corr = 0.05 + 1.01 TFP, R^2 = 0.96.$$

(0.01) (0.04)

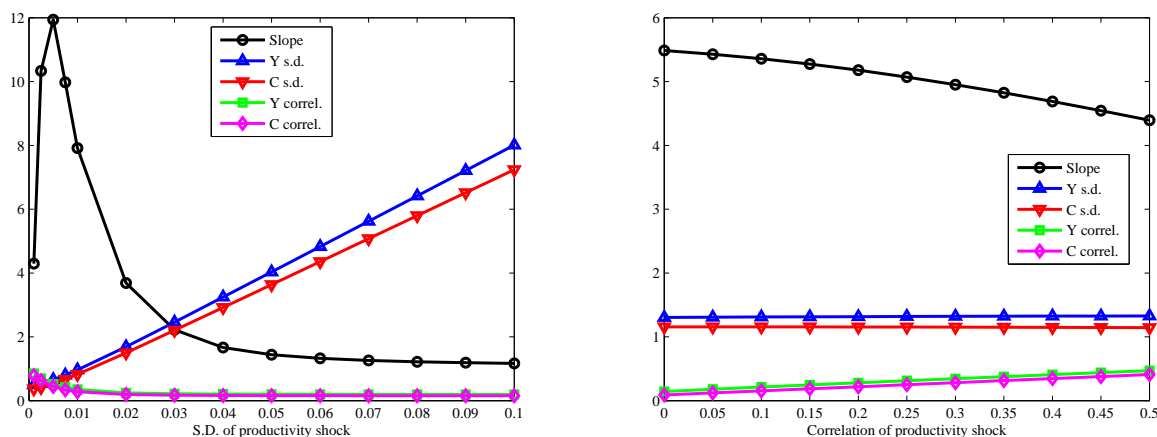
Upper-left panel: Log average trade costs and bilateral trade intensities. Upper-right panel: Log average trade costs and BP-filtered output correlations. Lower-left panel: Log average trade costs and BP-filtered implied aggregate TFP correlations. Upper-right panel: BP-filtered implied aggregate TFP correlations and BP-filtered output correlations. All panels are taken from the baseline model. The equations show corresponding OLS regressions. Numbers in parentheses are robust standard errors.

Figure 6: Impulse response functions (simplified example)



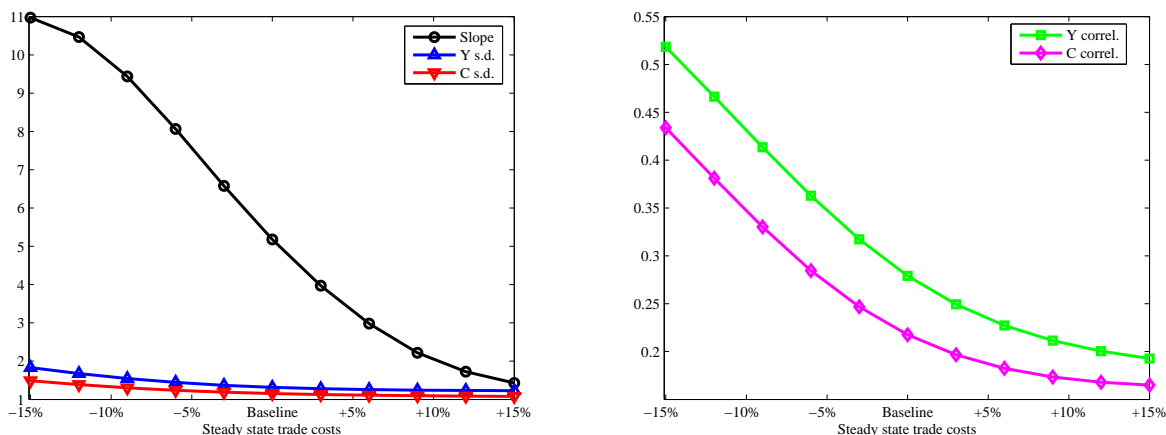
Impulse response functions of aggregate variables, for the simplified example in Section 5.2. Upper panel: France. Lower left panel: Germany. Lower right panel: United Kingdom.

Figure 7: Varying productivity shock



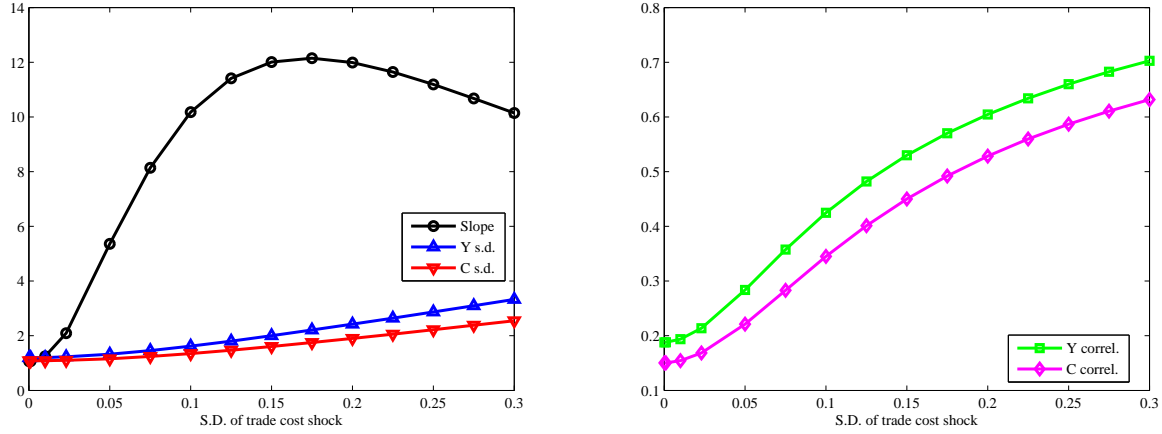
Left panel: baseline parameterization, with varying standard deviation of productivity shock. Right panel: baseline parameterization, with varying cross-country correlation of productivity shock. “Slope” is the slope coefficient ( $\times 100$ ) of trade-comovement regression (1). “Y s.d.” and “C s.d.” are standard deviations of model GDP and consumption (mean of model G7 countries), respectively. “Y correl.” and “C correl.” are cross-country correlations of model GDP and consumption, among G7 countries, respectively.

Figure 8: Varying steady state trade costs



Baseline parameterization, with varying all the steady state trade costs. “Slope” is the slope coefficient ( $\times 100$ ) of trade-comovement regression (1). “Y s.d.” and “C s.d.” are standard deviations of model GDP and consumption (mean of model G7 countries), respectively. “Y correl.” and “C correl.” are cross-country correlations of model GDP and consumption, among G7 countries, respectively.

Figure 9: Varying standard deviation of trade cost shock



Baseline parameterization, with varying correlation of technology shock. “Slope” is the slope coefficient ( $\times 100$ ) of trade-comovement regression (1). “Y s.d.” and “C s.d.” are standard deviations of model GDP and consumption (mean of model G7 countries), respectively. “Y correl.” and “C correl.” are cross-country correlations of model GDP and consumption, among G7 countries, respectively.

Figure 10: Varying correl. of trade cost shock

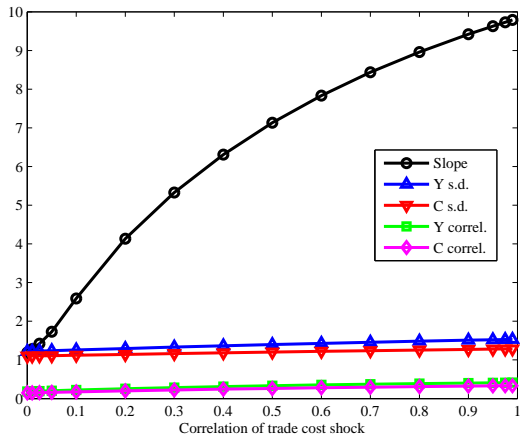
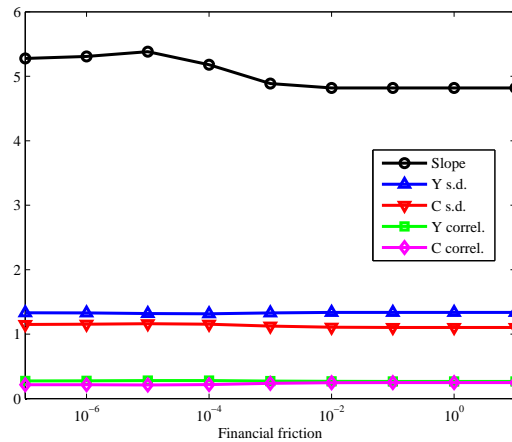


Figure 11: Varying financial friction



Left panel: baseline parameterization, with varying correlation of trade cost shock. Right panel: baseline parameterization, with varying financial friction parameter. “Slope” is the slope coefficient ( $\times 100$ ) of trade-comovement regression (1). “Y s.d.” and “C s.d.” are standard deviations of model GDP and consumption (mean of model G7 countries), respectively. “Y correl.” and “C correl.” are cross-country correlations of model GDP and consumption, among G7 countries, respectively.