Volatility, Intermediaries, and Exchange Rates

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Abstract

This paper studies how time-varying volatility drives exchange rates through financial intermediaries' risk management. We propose a model where currency market participants are levered intermediaries subject to value-at-risk constraints. Higher volatility translates into tighter financial constraints. Therefore, intermediaries require higher returns to hold foreign assets, and the foreign currency is expected to appreciate. Estimated by the simulated method of moments, our model quantitatively resolves the Backus-Smith puzzle, the forward premium puzzle, the exchange rate volatility puzzle, and generate deviations from covered interest rate parity. Our empirical tests verify model implications that volatility and financial constraint tightness predict exchange rates.

Keywords: Volatility, Financial Intermediaries, Exchange Rates, Currency Risk Premium, Value-at-Risk

JEL classification: G15, G20, F31

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1 Introduction

Exchange rates are puzzling in many aspects. First, exchange rates are disconnected from economic fundamentals, especially relative consumption growth rate, which is in sharp contrast to implications of most international macro-finance models (Backus and Smith, 1993). Second, high-interest-rate currencies do not depreciate as the uncovered interest parity suggests. On the contrary, they often appreciate in subsequent periods (Hansen and Hodrick, 1980; Fama, 1984), known as the "forward premium puzzle". As a result, excess returns of currency investment can be predicted by interest rate differentials. Third, it is hard to obtain exchange rate volatility close to data in standard international macro-finance models (Chari et al., 2002; Brandt et al., 2006). Lastly, covered interest rate parity, a classic no-arbitrage condition in the currency market, is violated for a decade after the global financial crisis (Du et al., 2018). In this paper, we attempt to resolve these puzzles by focusing on the role of leveraged financial intermediaries in exchange rate determination.

Financial intermediaries are major participants in the foreign exchange (FX) market. More than 85% of turnovers in the FX market have financial institutions involved, according to the recent BIS triennial surveys. Moreover, non-dealer financial institutions account for more than half of turnovers. With respect to aggregate portfolio holding, the BIS reporting banks hold about half of the countries' total external claims and more than 40% of total external liabilities in 21 OECD countries[1].

The recent intermediary asset pricing literature has shown the importance of intermediaries on a broad class of asset returns (for example, Brunnermeier and Pedersen, 2009; Adrian et al., 2014; He and Krishnamurthy, 2013; He et al., 2017). It is natural to study exchange rates through the lens of an intermediary-based model. An essential feature of financial intermediaries is the constraint on taking leverage. The financial constraint is tightly linked to the volatility in the economy because of the value-at-risk (VaR) rule adopted by major financial institutions (Adrian and Shin, 2014). The VaR rule states that the size of the balance sheet shrinks with the rise of volatility in the economy.

[1] Details will be shown in section 2.

In light of the dominance of intermediaries in the FX market and the constraints they are facing, we introduce these features into an otherwise standard international asset pricing model. The model has two ex-ante identical countries, home and foreign. Both countries have a continuum of homogeneous households and intermediaries. Households only have access to a risk-free money market account in local intermediaries. Intermediaries take deposits and invest in the local risky asset and the international bond. Both intermediaries face value-at-risk induced financial constraints, such that the size of the balance sheet cannot exceed a fraction of their market values (Gertler and Kiyotaki, 2010). The fraction increases with the volatility in the economy. In equilibrium, constrained from taking leverage, intermediaries' marginal value of assets is higher than that of their liabilities. Since intermediaries are the only traders on intermediated assets including the local risky asset and the international bond, they require an excess return on those assets. The exchange rate change is a large component in international bond returns, so exchange rate dynamics are driven by the financial constraint. A higher volatility in the home country tightens its intermediaries' constraint and increases the difference between the two marginal values, and thus leads to an expected foreign appreciation.

We estimate the model using the simulated method of moments (SMM), and show that the model can resolve the four exchange rate puzzles quantitatively. We resolve the Backus-Smith puzzle by replacing the standard consumption Euler equation with an intermediary Euler equation, so that consumption and exchange rates are disconnected. As for the forward premium puzzle, when volatility increases in the home country, its interest rate declines. Meanwhile, because of a higher excess return required by home intermediaries, there is an expected foreign appreciation. The exchange rate volatility is closer to data, as the financial constraint amplifies the shocks in the economy. Finally, the tightened banking regulations after the global financial crises constrain the intermediaries from making arbitrage in the currency forward market and generate deviations from covered interest rate parity. Moreover, the model generates the cyclicality of CIP deviations consistent with empirical evidence documented by Avdjiev et al. (2016). The deviations are large when home currency is strong, and when volatility is large.

We examine additional empirical implications of our model. First, we link exchange rates to the most direct measure of value-at-risk for currency traders, the exchange rate volatility. We find that a higher dollar exchange rate volatility predicts an appreciation of foreign currencies, and a higher currency return borrowing dollar and investing in foreign currencies. Second, as a more direct test on the channel of intermediaries and financial constraint, we measure the tightness of financial constraint in the US using the annual growth rate of US financial commercial paper outstanding. An increase in commercial paper is associated with looser financial conditions. We show that a higher amount of US financial commercial paper outstanding predicts a foreign depreciation and a lower foreign currency return. The predictability is preserved after controlling for other predictors in the literature. Third, when we include the commercial paper and exchange rate volatility in the standard regression of currency returns on interest rate differentials, the coefficient on interest rate becomes smaller, and less significant. It indicates that our mechanism is supported by data in resolving the forward premium puzzle.

Related Literature

A vast literature resolves the exchange rate puzzles in complete market settings. The leading models include habit formation (Verdelhan, 2010; Stathopoulos, 2016), long run risks (Colacito and Croce, 2011, 2013; Bansal and Shaliastovich, 2013), disaster risks (Farhi and Gabaix, 2016), etc. There are also various attempts to explain these puzzles in incomplete market models, including Corsetti et al. (2008), Maurer and Tran (2016) and Favilukis et al. (2015). Lustig and Verdelhan (2016) shows that standard models with only financial market incompleteness cannot resolve multiple exchange rate puzzles simultaneously. Additional frictions are added into standard models to account for these puzzles: market segmentation (Alvarez et al., 2002, 2009 and Chien et al., 2015), nominal rigidity (Chari et al., 2002), search frictions (Bai and Ríos-Rull, 2015), infrequent portfolio decisions (Bacchetta and Van Wincoop, 2010). Itskhoki and Mukhin (2017) show the key friction to explaining exchange rate puzzles is the financial shock.

The literature of financial frictions emphasizes several types of constraints faced by capital market participants. Bernanke et al. (1999), Kiyotaki and Moore (1997), Gertler and Kiyotaki (2010), and Brunnermeier and Sannikov (2014) study the amplification effect of financial frictions on the macroeconomy. Jermann and Quadrini (2012) uncover that the time variation of financial constraint is an important source of aggregate fluctuations and financial flows. In the asset pricing literature, theoretical models show the importance of intermediaries in asset returns (Brunnermeier and Pedersen, 2009; He and Krishnamurthy, 2013; Li, 2013). Adrian et al. (2014), He et al. (2017), and Haddad and Muir (2017) find strong supportive evidence for a broad class of asset returns including stocks, bonds, and more complex securities such as mortgage-backed securities and derivatives. In international finance, Mendoza (2010) and Perri and Quadrini (2018) show that real shocks are amplified by financial frictions, leading to financial crisis. Dedola et al. (2013) studies the transmission of shocks to financial constraints across countries.

Recently, the role of financial intermediation in exchange rate determination is emphasized by Gabaix and Maggiori (2015). They propose a theory with imperfect intermediation in the international financial market. Exchange rates are determined jointly by capital flows and intermediary balance sheet. Malamud and Schrimpf (2018) develop a theoretical model in which intermediaries exploit their market power to seek rent, and explain the safe haven properties of exchange rates and CIP deviation. Our paper is different from them in several aspects. First of all, they provide theoretical frameworks while we bring the model to data and resolve the four puzzles in a quantitative manner. Second, we highlight the link between stochastic volatility and financial constraint fluctuations through VaR. Third, their model has a single global intermediary that intermediates capital flows, while our model studies risk sharing across countries of intermediaries with different financial constraints. Lastly, we provide supportive empirical evidence on our mechanism. Sandulescu et al. (2017) use a model-free approach to estimate international SDFs, and show strong links between model-free international SDFs and intermediary balance sheets as well as volatility.

The rest of the paper is organized as follows. Section 2 lays out some institutional features of the foreign exchange market and shows the preeminent role of leveraged financial institutions in exchange rate determination. Section 3 presents the model and section 4 illustrates how this model can qualitatively resolve the four exchange rate puzzles. In section 5 we estimate our model and show that the model can resolve the four exchange rate puzzles quantitatively. Empirical implications of the model are tested in section 6. Section 7 concludes the paper.

2 The Relevance of Financial Institutions

This section sketches the basic structure of the foreign exchange market. We show that financial institutions play a major role in the foreign exchange market, and thus exchange rate determination [2].

The foreign exchange market is the largest financial market in the world, with daily trading volume exceeding five trillion dollars in 2016, according to the BIS triennial survey. The structure of the foreign exchange market is two-tier: the inter-dealer market and dealer-customer market. Most inter-dealer transactions are high-frequency market-making transactions. These high-frequency transactions are not our considerations, as the half-life of inventory for dealers is only between 1 to 30 minutes, and dealers usually end the day with a small amount of inventories (Bjønnes and Rime, 2005). There are several exceptions, according to Sager and Taylor (2006), that dealers take speculative positions in propriety trading with horizons from one day to three months. These longer horizon speculations are within our consideration in the paper.

Behaviors in the dealer-customer market are important determinants of exchange rates at monthly, quarterly, or annual frequencies. Main categories of customers include financial customers, corporate customers[3], and retail customers[4]. Financial customers can be divided into two groups: real money investors and levered investors. Real money investors include mutual funds, pensions funds, endowments, and so on, which do not take leverage and infrequently adjust their portfolios.

[2]Though there have been tremendous changes in the foreign exchange market in the recent decades, we describe the common features of the market across time. The new changes include the use of electronic trading systems, the increase of foreign exchange transactions between financial institutions, etc. For more institutional details of the foreign exchange market, see Osler (2008) and King et al. (2011).

[3]Corporate customers trade for real purposes, such as production, investment, and dividend payout. The size of corporate transactions is small relative to financial transactions.

[4]Retail customers, accounting for a very small fraction, are not studied in this paper.

Levered investors include non-dealer commercial banks, hedge funds, and commodity trading advisors, and so on. They take high leverages and actively manage their portfolios.

We show that levered investors account for a substantial portion of turnovers in the FX market in Table 1 and Figure 1. Table 1 shows the fraction of FX turnovers by different entities from 1998 to 2016. Turnovers associated with nondealer financial institutions keep increasing and rise to 51% in 2016. Starting from 2013, the BIS triennial survey makes a detailed split of nondealer financial institutions into nonreporting banks (24%, 22%[5]), institutional investors (11%, 16%), hedge funds and, PTFs (11%, 8%), official sector (1%, 1%), and other institutions (6%, 4%). Nonreporting banks, hedge funds and PTFs, and part of institutional investors are considered as levered investors. Meanwhile, nonfinancial transactions account for no more than 20% of all turnovers, and it has been declining in the recent decades. These facts motivate us to focus on the behavior of levered institutions to study exchange rates.

Besides looking at turnovers in the FX market, we also show the important role of banks in holding cross-border claims and liabilities using aggregate banking data. Figure 1 plots the time series weighted average of the ratio of banking claims (liabilities) over total claims (liabilities) from 1977 to 2014[6]. In the late 1970s and early 1980s, banks account for about half of external claims and 40 percent of external liabilities. This number declined substantially in the late 1990s, to 40 percent (claims) and 30 percent (liabilities) at the trough, possibly due to the global stock market boom. It rebounded back quickly in the 2000s until the global financial crisis in 2007.

Generally, levered financial intermediaries are constrained in taking leverage, so do the FX market participants. Speculative positions are constrained for various reasons, such as regulation, risk management and avoidance of excess risk taking for each trader. Banks in different countries are subject to the Basel regulatory capital adequacy framework with a minimal risk-weighted capital ratio of 8 percent and non-risk-weighted leverage ratio of 3 percent. Beyond regulation, FX market participants face market disciplines in balance sheet management, usually in the form of value-at-

[5] Numbers in 2013 and 2016, respectively.

[6] Countries include Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Japan, Netherlands, New Zealand, Norway, Portugal, South Korea, Spain, Sweden, Switzerland, UK, and US.

risk (VaR) constraint (Sager and Taylor, 2006). In practice, most intermediaries adopt VaR as their portfolio risk management model. It calculates the worst possible loss that will not exceed a given probability over a period. Intermediaries collect data on portfolio positions and market conditions to calculate their value-at-risk. They use different models to derive time variation in risk, such as ARCH, GARCH, and exponentially-weighted moving average models. When the Basel Committee on Banking Supervision allowed commercial banks to use their internal VaR model as the basis for market risk charge in 1998, the VaR model is widely accepted by the industry (Jorion, 2010). Usually, position limits are imposed on traders to avoid individual excess risk taking (Osler, 2008). Therefore, we argue that the variation in intermediaries' financial constraint is the distinct feature of levered institutions that bring us new insights into exchange rate studies.

To sum up, we provide descriptive evidence on the preeminent role financial institutions (banks) play in the international financial market and their distinct feature of facing leverage constraints. In the next sections, we incorporate these features into an otherwise standard international asset pricing model and show these features help us resolve the exchange rate puzzles documented in the literature.

3 The Model

There are two ex-ante identical countries in the economy, home and foreign, each populated with a unit measure of households and endowed with a Lucas tree. The home tree delivers good X, and the foreign tree delivers good Y, both of which are tradable. In both countries, each household owns an intermediary and sends out a manager to operate it. Households make deposits in local intermediaries. Intermediaries combine deposits and their own net worth to invest in risky assets. There are two available risky assets, a claim to the local Lucas tree and an international bond. Intermediation is imperfect, in the form that the intermediaries in each country face a financial constraint, whose tightness is determined by the volatility in the local economy. Every period, a fixed fraction of intermediaries exit the market and rebate back their net worth to their owners, while the same measure of new intermediaries is set up with some initial funds to keep the measure of intermediaries stationary. The structure of the economy in each country is similar to Gertler and Kiyotaki (2010).

We describe the behavior of households and intermediaries in detail in the following subsections.

3.1 Households

Households in the home and foreign countries are endowed with a Lucas tree with different goods, X for home and Y for foreign. They follow cointegrated processes:

$$\log X_{t+1} - \log X_t = \mu + \tau(\log Y_t - \log X_t) + \sigma_{X,t}\varepsilon_{X,t+1}$$

$$\log Y_{t+1} - \log Y = \mu - \tau(\log Y_t - \log X_t) + \sigma_{Y,t}\varepsilon_{Y,t+1} \tag{1}$$

Volatilities are stochastic, following:

$$\log(\sigma_{X,t+1}) = (1-\rho_\sigma)\log\bar{\sigma} + \rho_\sigma log(\sigma_{X,t}) + \sigma_\sigma \eta_{X,t+1}$$
$$\log(\sigma_{Y,t+1}) = (1-\rho_\sigma)\log\bar{\sigma} + \rho_\sigma log(\sigma_{Y,t}) + \sigma_\sigma \eta_{Y,t+1} \tag{2}$$

The four shocks follow the standard normal distribution. The two goods aggregate into a consumption basket. The aggregator takes the form of constant elasticity of substitution:

$$C = [(1-\alpha)C_X^{\frac{\sigma-1}{\sigma}} + \alpha C_Y^{\frac{\sigma-1}{\sigma}}]^{\frac{\sigma}{\sigma-1}}, C^* = [(1-\alpha)C_Y^{*\frac{\sigma-1}{\sigma}} + \alpha C_X^{*\frac{\sigma-1}{\sigma}}]^{\frac{\sigma}{\sigma-1}}$$

C_X, C_Y are home households' consumption of X and Y, while variables with an asterisk refer to the foreign counterpart. Households in the home and foreign countries put different weights on X and Y with consumption home bias, i.e., $\alpha < \frac{1}{2}$. σ is the price elasticity of substitution between X and

Y. We choose the home composite good as numeraire and define real exchange rate as the price of foreign composite good Q_t. An increase in Q_t means a real appreciation of the foreign currency.

In every period, given composite consumption of C, and prices P_X, P_Y, home households choose how much X and Y to consume. Home households solve the intratemporal optimization problem:

$$\min_{C_X, C_Y} P_X C_X + P_Y C_Y$$

$$s.t.: C = [(1-\alpha) C_X^{\frac{\sigma-1}{\sigma}} + \alpha C_Y^{\frac{\sigma-1}{\sigma}}]^{\frac{\sigma}{\sigma-1}}$$

The allocation between X and Y are solved as:

$$C_X = \frac{C(\frac{P_X}{P_Y}\frac{\alpha}{1-\alpha})^{-\sigma}}{P_Y + P_X(\frac{P_X}{P_Y}\frac{\alpha}{1-\alpha})^{-\sigma}}, C_Y = \frac{C}{P_Y + P_X(\frac{P_X}{P_Y}\frac{\alpha}{1-\alpha})^{-\sigma}} \tag{3}$$

For foreign households, the price of X and Y in foreign consumption basket are $\frac{P_X}{Q}, \frac{P_Y}{Q}$, thus the solution to foreign intratemporal optimization problem is:

$$C_X^* = \frac{C^*(\frac{P_X}{P_Y}\frac{\alpha}{1-\alpha})^{-\sigma} Q}{P_Y + P_X(\frac{P_X}{P_Y}\frac{\alpha}{1-\alpha})^{-\sigma}}, C_Y^* = \frac{C^* Q}{P_Y + P_X(\frac{P_X}{P_Y}\frac{\alpha}{1-\alpha})^{-\sigma}} \tag{4}$$

All households have identical Constant Relative Risk Aversion (CRRA) preferences over their country-specific consumption basket with risk aversion γ. A fraction α_l of the endowment goes to the households as labor income, while the remaining are capitalized as a risky financial asset. These financial assets are interpreted broadly as bank loans and other fixed income securities that are generally intermediated by the financial sector. Households do not hold the risky financial assets directly. The only financial asset they have access to is a money market account offered by the local intermediaries, paying one unit of consumption basket risklessly in the subsequent period.

This assumption is consistent with the empirical evidence on households' limited participation in the stock market (Vissing-Jørgensen, 2002) and passive portfolio behaviors without rebalancing

(Chien et al., 2012). We interpret the labor income component of the endowment as cash flows received by passive investors. Moreover, this assumption is an extreme case of large efficiency loss for households to trade risky assets, while intermediaries have a comparative advantage in investment expertise, as in Brunnermeier and Sannikov (2014).

Households solve a standard intertemporal optimization problem:

$$\max_{C_t, D_t} E \sum_{t=0}^{\infty} \frac{C_t^{1-\gamma} - 1}{1-\gamma}$$

$$s.t.: C_t + D_t = \alpha_l P_{X,t} X_t + R_{f,t-1} D_{t-1} + \Pi_t$$

D_t is the deposit by households into intermediaries at time t, while $R_{f,t-1}D_{t-1}$ is the repayment from intermediaries of principal and interest. Π_t is the net lump-sum payout from the intermediaries that exit the market, which will be specified later. Euler equations hold for households in both countries:

$$E_t \beta (\frac{C_{t+1}}{C_t})^{-\gamma} R_{f,t} = 1, \quad E_t \beta (\frac{C^*_{t+1}}{C^*_t})^{-\gamma} R^*_{f,t} = 1 \tag{5}$$

3.2 Intermediaries

Each intermediary solves a portfolio choice problem on how much deposit to take, how many domestic risky asset shares, and how many international bonds to purchase. We exclude the holding of the foreign tree by intermediaries, since domestic assets dominate foreign assets in most countries, known as "home equity bias" (Lewis, 1999).

Intermediation is imperfect with a leverage constraint on intermediaries in both countries.

$$V_t \geq \theta_t (P_t s_t + d_{I,t}), \quad V_t^* \geq \theta_t^* (P_t^* s_t^* + d_{I,t}^*) \tag{6}$$

V_t, V_t^* are the market value of an intermediary. P_t, P_t^* are the prices of the Lucas trees denominated in consumption basket in respective countries. s_t, s_t^* are the holding shares, and $d_{I,t}$, $d_{I,t}^*$ are the holding of the international bond. Lower-case variables indicate individual intermediary's choice, while upper-case indicate aggregate variables. The international bond pays off riskless return $R_{b,t}$ denominated in a half unit of the home composite good and a half unit of the foreign composite good. We assume this payoff structure to preserve symmetry between the two countries, as in Heathcote and Perri (2016). When $d_{I,t} < 0$, home intermediaries are effectively borrowing from foreign intermediaries to purchase home assets. θ_t and θ_t^* measures the tightness of leverage constraint faced by intermediaries, which are linked to the volatility in each economy. We express θ_t as a function of the volatility as:

$$\theta_t = \theta_0 + \theta_1 log(\sigma_{X,t}), \theta_t^* = \theta_0 + \theta_1 log(\sigma_{Y,t})$$

These constraints model the distinct feature of intermediaries, the value-at-risk (VaR) constraint, as we discussed in Section 2. θ_0 captures leverage restrictions caused by time-invariant frictions. $\theta_1 log(\sigma_{X,t})$ and $\theta_1 log(\sigma_{Y,t})$ model how the constraint varies with volatility. When volatility in the economy is higher, the intermediaries' balance sheets become riskier and they have the incentive to reduce risk taking. The constraint can be micro-founded within an optimal contracting framework, such as Adrian and Shin (2014). At the same time, the constraint can also be due to regulation, such as the Basel III's minimum risk-weighted capital requirement ratio, non-risk-weighted leverage ratio requirement, and stress test. Furthermore, borrowing and lending between intermediaries across borders are settled before repaying the households. Therefore, the VaR constraint is imposed on the sum of local risky asset and international bond position, even if it is a short position. We can easily extend the constraint to include different risk weights for the local risky asset and the international bond position.

From here on, we solve the intermediary problem in the home country. The problem for the foreign intermediary is exactly identical. The value function of a representative home intermediary can be written recursively as:

$$V_t(s_t, d_t, d_{I,t}) = \max_{s_{t+1}, d_{t+1}, d_{I,t+1}} E_t \beta (\frac{C_{t+1}}{C_t})^{-\gamma} [(1-p) n_{t+1} + p V_{t+1}(s_{t+1}, d_{t+1}, d_{I,t+1})]$$

$$s.t.: n_{t+1} + d_{t+1} \leq P_{t+1} s_{t+1} + d_{I,t+1}$$

$$\theta_{t+1}(P_{t+1} s_{t+1} + d_{I,t+1}) \leq V_{t+1}$$

$V(s_t, d_t, d_{I,t})$ is the value of the intermediary at the end of period t. The value function is a function of the holdings of domestic risky asset s_t, international bond $d_{I,t}$, and deposit d_t. Households own the intermediaries, so their stochastic discount factor $\beta(\frac{C_{t+1}}{C_t})^{-\gamma}$ is used to evaluate the cash flows. In period $t+1$, the intermediary exits the market and pays out its net worth n_{t+1} with probability $1-p$. Otherwise, it continues to operate and choose the holding of $s_{t+1}, d_{I,t+1}, d_{t+1}$, with continuation value $V_{t+1}(s_{t+1}, d_{t+1}, d_{I,t+1})$. The first constraint is the balance sheet identity. The left-hand side is equal to the intermediary's net worth plus deposit, while the right-hand is the intermediary's holding of risky assets. The second constraint is the leverage constraint discussed before. The dynamics of net worth for a single intermediary is given by:

$$n_{t+1} = R_{S,t+1} P_t s_t + R_{I,t+1} d_{I,t} - R_{f,t} d_t$$

where $R_{S,t+1} = \frac{P_{t+1} + (1-\alpha_l) P_{X,t+1} X_{t+1}}{P_t}$ is the return on holding domestic risky assets, and $R_{I,t+1} = \frac{1+Q_{t+1}}{1+Q_t} R_{b,t}$ is the return on holding international bonds. Even though the bond has a noncontingent return of $R_{b,t}$, intermediaries face exchange rate risks.

We guess the value function is linear in all three state variables, and verify later:

$$V_t = \nu_{S,t} P_t s_t + \nu_{I,t} d_{I,t} - \nu_t d_t$$

Assigning the Lagrangian multipliers to the two constraints $\beta(\frac{C_{t+1}}{C_t})^{-\gamma} \lambda_{t+1}$ and $\beta(\frac{C_{t+1}}{C_t})^{-\gamma} \psi_{t+1}$, we can obtain the first order conditions:

$$p\nu_{S,t+1} + \lambda_{t+1} - \psi_{t+1}(\nu_{S,t+1} - \theta_{t+1}) = 0$$

$$p\nu_{I,t+1} + \lambda_{t+1} - \psi_{t+1}(\nu_{I,t+1} - \theta_{t+1}) = 0$$

$$p\nu_{t+1} + \lambda_{t+1} - \psi_{t+1}\nu_{t+1} = 0$$

From these three first order conditions, we have the key result:

$$\nu_{S,t} = \nu_{I,t} \geq \nu_t \tag{7}$$

$\nu_{S,t}$ and $\nu_{I,t}$ are the marginal value of intermediary wealth invested in the domestic risky asset and the international bond. ν_t is the marginal cost for the intermediary to take deposits. When the financial constraint does not bind, all three of them are equal. When the financial constraint binds, the marginal benefit of investing in the domestic risky asset and the international bond are identical, both being larger than the marginal cost of taking deposits. The determinant of whether the financial constraint binds or not is the net worth of the intermediary. If the intermediary has ample net worth, it will exhaust investment opportunities before hitting the constraint.

We plug back the value function into the Bellman equation, and derive expressions for coefficients:

$$\nu_{I,t} = E_t\left[\beta(\frac{C_{t+1}}{C_t})^{-\gamma}(1-p+p\theta_{t+1}\phi_{t+1}^{-1})R_{S,t+1}\right] = E_t\left[\beta(\frac{C_{t+1}}{C_t})^{-\gamma}(1-p+p\theta_t\phi_t^{-1})R_{I,t+1}\right] \tag{8}$$

$$\nu_t = E_t\left[\beta(\frac{C_{t+1}}{C_t})^{-\gamma}(1-p+p\theta_{t+1}\phi_{t+1}^{-1})R_{f,t}\right] \tag{9}$$

ϕ_t is the leverage ratio of the home intermediary [7], defined to be:

$$\phi_t \equiv \frac{n_t}{P_t s_t + d_{I,t}}$$

[7] More precisely, ϕ_t is the ratio of home intermediaries' net worth over risky position. In our simulated economy, the properties of ϕ_t barely change if we define $\phi_t = \frac{n_t}{P_t s t + d_{It} I(d_{It} \geq 0)}$, where I is an indicator function.

Foreign intermediaries face the same problem. The pricing equation of the international bond for foreign intermediaries is:

$$v^*_{I,t} = E_t\left[\beta(\frac{C^*_{t+1}}{C^*_t})^{-\gamma}(1-p+p\theta^*_t\phi^{*-1}_t)R_{I,t+1}\frac{Q_t}{Q_{t+1}}\right] \tag{10}$$

3.3 Aggregation

Now that we have specified the problem as well as the optimality conditions for a single intermediary. The linearity of the model simplifies aggregation. Due to the representative intermediary setting, each intermediary has the same optimality conditions and makes the same choices. We can directly replace individual variables $n_t, s_t, d_t, d_{I,t}$ and their foreign counterparts $n^*_t, s^*_t, d^*_t, d^*_{I,t}$ with the aggregate variables $N_t, S_t, D_t, D_{I,t}, N^*_t, S^*_t, D^*_t, D^*_{I,t}$ in the optimality conditions.

The net worth dynamics in aggregate is different from the one for a single intermediary, due to entry and exit. The aggregate dynamics is given by:

$$N_{t+1} = (p+\xi)(R_{S,t+1}P_tS_t - R_{f,t}D_t + R_{I,t+1}D_{I,t}) \tag{11}$$

$$N^*_{t+1} = (p+\xi)(R^*_{S,t+1}P^*_tS^*_t - R^*_{f,t}D^*_t + R_{I,t+1}D^*_{I,t}\frac{Q_t}{Q_{t+1}}) \tag{12}$$

3.4 Equilibrium

Lastly, we have market clearing conditions for good markets and asset markets.

$$C_{Xt} + C^*_{Xt} = X_t, \quad C_{Yt} + C^*_{Yt} = Y_t, \quad S_t = S^*_t = 1, \quad D_{I,t} + D^*_{I,t}Q_t = 0 \tag{13}$$

A competitive equilibrium consists of a sequence of allocations$\{C_{Xt}, C_{Yt}, C^*_{Xt}, C^*_{Yt}, D_t, D^*_t, N_t, N^*_t, S_t, S^*_t, D_{I,t},$ $D^*_{I,t}, \phi_t, \phi^*_t\}$, a sequence of prices $\{R_{f,t}, R^*_{f,t}, P_{Xt}, P_{Yt}, P_t, P^*_t, Q_t, R_{b,t}\}$, and a sequence of intermediary valuation $\{v_{S,t}, v_{I,t}, v_t, v^*_{S,t}, v^*_{I,t}, v^*_t\}$ such that:

(i) Households in both countries solve their optimization problems;

(ii) Intermediaries in both countries solve their constrained optimization problem;s

(iii) Good markets (X and Y) clear;

(iv) Asset markets (home and foreign deposits, home and foreign risky assets, and the international bond) clear.

4 Model Mechanisms

4.1 Impulse Response Functions

Figures 2 and 3 report the impulse response functions of different variables in both countries to the home country's one-standard-deviation positive endowment shock and volatility shock. Parameters are estimated and shown in Table 2.

When the home country has a positive endowment shock, the dividend payment of the Lucas tree increases, and home households' consumption growth increases. The interaction between intermediary net worth and asset price amplifies the response of return to the home tree. The marginal value of net worth ν_I and the marginal cost of borrowing ν both decline, as does the wedge between the two. The real risk-free rate in the home country increases slightly. The leverage ratio of intermediaries increases, because the strengthening of net worth dominates the expansion of their balance sheets. The endowment shock in the home country is transmitted to the foreign country, with all foreign variables moving in the same direction but smaller magnitude, as a result of imperfect international risk sharing. The mechanism of intermediary balance sheet synchronization is similar to Dedola et al. (2013). Since both ν_I and ν_I^* decrease, both intermediaries require a lower expected return on the international bond and R_b decreases. However, ν_I in the home country declines more than ν_I^*. Consequently, the foreign currency appreciates contemporaneously and is expected to depreciate. We can also understand the exchange rate movement from the goods market side. An increase in the supply of home good X is accompanied by a contemporaneous foreign appreciation.

The more interesting channel in our model can be seen in the impulse responses to a one standard deviation volatility shock. The volatility shock is amplified through the same interaction between intermediary net worth and asset price illustrated previously. The greater volatility will tighten home intermediaries' financial constraints. Since the home intermediaries are not able to take as much deposit from households, home households' consumption increases, and home real interest rate R_f decreases. The marginal benefit of net worth ν_S as well as the marginal cost of borrowing ν both increase, and so does their difference. The transmission of the shock to the foreign country is again as previously shown: Foreign variables move in the same direction as home variables but with a smaller magnitude. Similarly, expected exchange rate change reflects the difference between home and foreign intermediaries' valuation of the international bond. Therefore, the foreign currency is expected to appreciate.

4.2 Asset Prices

In our model, intermediaries play the central role in pricing all the assets. The augmented Euler equations for intermediaries are key determinants of exchange rates as well as prices for the home and foreign risky asset. As we show in Section 3.2, the asset pricing equations are equations (8) and (9).

The stochastic discount factor that prices the domestic tree and the international bond is different from the one that prices deposits. The difference depends on the wedge between the marginal value of net worth and the marginal cost of taking deposits, which relies on the tightness of the financial constraint.

The stochastic discount factor has three components: consumption growth $\beta(C_{t+1}/C_t)^{-\gamma}$, the subsequent value of the intermediary $1-p+p\theta_{t+1}\phi_{t+1}^{-1}$, and the marginal value of net worth $\nu_{I,t}$ or the marginal cost of taking deposits ν_t. When leverage constraint binds, the leverage constraint can be rewritten as:

$$\theta_t \phi_t^{-1} = \frac{V_t}{N_t}$$

The additional term $1-p+p\theta_{t+1}\phi_{t+1}^{-1}$ is economically intuitive: With probability $1-p$, the intermediary exits the market and pays out its net worth; with probability p, the intermediary continues to operate, and each dollar remaining in the intermediary generates market value of $\theta_{t+1}\phi_{t+1}^{-1}$.

4.3 Exchange Rate Puzzles

In this subsection, we review the exchange rate puzzles in the literature and analyze how our model helps resolve these puzzles.

4.3.1 Backus-Smith Puzzle

Backus and Smith (1993) show that from consumption based Euler equations, exchange rate change is perfectly correlated with consumption growth differential under the complete market. To see it more clearly, denote the home stochastic discount factor (SDF) to be M_{t+1}, and the foreign SDF M_{t+1}^*. Consider the return of home risk-free bond $R_{f,t}$, the following equation hold:

$$E_t\left[M_{t+1}R_{f,t}\right] = E_t\left[M_{t+1}^* R_{f,t}\frac{Q_t}{Q_{t+1}}\right] = 1$$

Q_t is the price of foreign goods in terms of home goods. If the financial market is complete, then the equation holds state by state. Therefore:

$$\Delta q_{t+1} = m_{t+1}^* - m_{t+1}$$

Lower-case letters are natural logarithms of variables. If we assume a constant relative risk aversion utility function, we obtain:

$$\Delta q_{t+1} = \gamma(\Delta c_{t+1} - \Delta c_{t+1}^*)$$

Exchange rate change is perfectly correlated with consumption growth differential. Even when the financial market is incomplete, such as in the models of Heathcote and Perri (2002) and Chari et al. (2002), the correlation between Δq_{t+1} and $\Delta c_{t+1} - \Delta c^*_{t+1}$ is still close to 1. This is inconsistent with the weak correlation between exchange rate changes and consumption growth differentials in the data.

In our model, we have augmented Euler equations for intermediaries in both countries:

$$E_t\left[\beta(\frac{C_{t+1}}{C_t})^{-\gamma}\frac{(1-p+p\theta_{t+1}\phi_{t+1}^{-1})}{v_{I,t}}\right] = E_t\left[\beta(\frac{C^*_{t+1}}{C^*_t})^{-\gamma}\frac{(1-p+p\theta^*_{t+1}\phi_{t+1}^{*-1})}{v^*_{I,t}}\frac{Q_{t+1}}{Q_t}\right]$$

Exchange rate change is linked to consumption growth differential plus two extra terms: the subsequent value of the intermediary, and the relative marginal value of net worth. Therefore, consumption growth is disconnected with exchange rate.

The responses of consumption and exchange rate to endowment and volatility shocks also help us understand the disconnect. As we show in the impulse response functions in Section 4.1, when the home country has a positive endowment shock, consumption of home households increases while the home currency depreciates. On the other hand, when the home country experiences a positive volatility shock, home consumption increases as well, but the home currency appreciates. The two forces at play offset each other and generate the weak correlation between consumption and exchange rate.

4.3.2 Forward Premium Puzzle

Uncovered Interest Rate Parity suggests that when the home country has a higher interest rate than the foreign country, the home currency is expected to depreciate in the next period so that investing in home and foreign deliver the same payoffs in expectation. However, this parity condition is rejected by data (Hansen and Hodrick, 1980; Fama, 1984). Typically, the currency with higher interest rate tends to further appreciate. This puzzle is also called the “forward premium puzzle”.

In our model, volatility shocks explain the puzzle through intermediaries' financial constraints. We log-normally approximate the household Euler equation, and obtain:

$$r_{f,t} \approx -\log\beta + \gamma E_t \Delta c_{t+1} - \frac{1}{2}\gamma^2 Var_t \Delta c_{t+1}$$

As we show in the impulse response functions in Figure 3, when the home country experiences a positive volatility shock, the home interest rate is lower for two reasons. First of all, the variance term $\frac{1}{2}\gamma^2 Var_t \Delta c_{t+1}$ is larger and interest rate falls through the precautionary saving effect. Second, the increased volatility tightens the constraint of home intermediaries. Home households consume more, thus lower the expected consumption growth $E_t \Delta c_{t+1}$. The second force also makes foreign households consume less and increases the foreign interest rate.

As for exchange rates, increased home volatility tightens home intermediaries' constraints, and widens the wedge faced by intermediaries. The financial constraint for intermediaries will in turn affect the international bond and currency market. Home intermediaries require higher expected returns on the international bonds than foreign intermediaries. Therefore, the foreign currency is expected to appreciate, even though the foreign interest rate is higher.

With a log-normal approximation, we combine home and foreign intermediaries' Euler equations for international bond and deposit, and get:

$$E_t \Delta q_{t+1} \approx (r_{f,t} - r^*_{f,t}) + (\log \nu_{I,t} - \log \nu_t) - (\log \nu^*_{I,t} - \log \nu^*_t) + \textit{second order terms} \tag{14}$$

Equation (14) links the expected exchange rate change to the intermediaries explicitly. When the home country experiences a positive volatility shock, home intermediaries are more constrained, thus $\log \nu_{I,t} - \log \nu_t > \log \nu^*_{I,t} - \log \nu^*_t$. If the wedges do not exist, uncovered interest rate parity holds. In our model, the wedge dominates the interest rate difference in driving exchange rates.

There is a vast literature about the relationship between stochastic volatility and forward premium puzzle. Backus et al. (2001) show that in a complete market setting with affine linear stochastic discount factors, stochastic volatility is necessary to generate time-varying currency premium.

Bansal and Shaliastovich (2013) attributes time variation in currency risk premium to volatility fluctuations in a structural model. Different from their channel, volatility affects exchange rates in our model through time-varying financial constraint faced by intermediaries. Therefore, we are proposing a new mechanism to link volatility to exchange rates that complements the existing mechanisms.

4.3.3 Exchange Rate Volatility Puzzle

Most international macro-finance models with incomplete financial market cannot generate volatile exchange rates as in the data. The exchange rate volatility in our model is close to data because the financial constraints of intermediaries amplify the endowment volatility. As a result, exchange rates are more volatile than in standard two-country models.

4.3.4 Deviation from Covered Interest Rate Parity

Covered Interest Rate Parity (CIP) is one of the most famous no-arbitrage conditions in finance. Borrowing in home currency and lending in foreign currency with a currency swap is risk free, and should yield zero profit. CIP condition holds quite well before the global financial crisis in 2007 (Akram et al., 2008), but is deviated persistently after the crisis (Du et al., 2018). Du et al. (2018) and Cenedese et al. (2017) illustrate that tightened banking regulation is a key driver of the CIP deviations. The requirement of the leverage ratio is a non-risk-based constraint imposed on intermediaries' balance sheet. Even if CIP arbitrage is riskless, it expands the balance sheet. To make the expansion subject to the constraint, banks need more capital that is costly. Moreover, stringent risk-weighted capital requirement and stress tests also increase the opportunity cost of CIP arbitrage.

This phenomenon is naturally interpretable in our model with intermediaries as arbitrageurs. The return on foreign risk-free lending through a currency swap is usually called the synthetic home currency rate, denoted as $R_{cip,t}$[8]. In the model, if the intermediaries can conduct CIP arbitrage without any constraint, then the synthetic home currency rate will have the same Euler equation as the home currency risk-free rate.

$$\nu_t = E_t\left[\beta(\frac{C_{t+1}}{C_t})^{-\gamma}(1-p+p\theta_{t+1}\phi_{t+1}^{-1})R_{cip,t}\right]$$

Therefore, the two rates are equal and CIP holds. After the tightening of regulation, intermediaries cannot freely trade currency swaps without any constraint. In this case, the marginal value of a synthetic home currency lending is $\nu_{I,t}$, the same as other constrained investments and higher than the marginal value of deposits ν_t.

$$\nu_{I,t} = E_t\left[\beta(\frac{C_{t+1}}{C_t})^{-\gamma}(1-p+p\theta_{t+1}\phi_{t+1}^{-1})R_{cip,t}\right]$$

The currency basis $r_{cip,t} - r_{f,t}$ becomes:

$$r_{cip,t} - r_{f,t} = \log\nu_{I,t} - \log\nu_t > 0$$

Hence, constrained intermediaries allow deviations from CIP. In our model, as in the real world, intermediaries are the major participants in the currency market. Households barely trade currency swaps, and cannot arbitrage away the currency basis.

Since our model has market segmentation and limits to arbitrage, it is natural for deviations from CIP to arise. Beyond the existence of the CIP deviations, the model is also able to explain some of its key cyclical properties. Avdjiev et al. (2016) and Sushko et al. (2017) document that CIP deviations are large when home currency is strong, and when volatility is large. In the model, CIP deviations correspond to the tightness of the constraint. When the constraint tightens, home currency appreciates contemporaneously and is expected to depreciate, as we discussed in the forward

[8] We assume both the synthetic rate and deposit rate are risk free and ignore the risk exposure of CIP arbitrage. Sushko et al. (2017) explain CIP deviation through counterparty risks of forward contracts. Andersen et al. (2017) consider funding risks and funding value adjustments as an explanation.

premium puzzle. Therefore, a stronger home currency is associated with larger CIP deviations. As for volatility, intuitively, higher volatility tightens the constraint and enlarges the CIP deviations.

5 Quantitative Results

After illustrating the mechanisms to resolve the exchange rate puzzles in the model, we bring the model to data and match the key facts about exchange rates quantitatively.

5.1 Parameter Estimation

The model is at quarterly frequency. We estimate the model with the simulated method of moments (SMM). The estimation details are in the Appendix. Benchmark parameter values are reported in Table 2.

Following the standard practice, we set the time discount factor, labor income share, and risk aversion at standard values, 0.995, 0.67, and 2 respectively. We assume the average growth rate to be 0 in order to match the low interest rate level[9].

Volatility and of endowment processes are estimated first, using the data in the G7 countries from 1973 to 2015 as in Colacito et al. (2018). Shocks are uncorrelated across countries. The stochastic volatility processes are the main driving forces of our model. The persistence of the volatility is 0.90, and the volatility of volatility is 0.075. In our model, it is the idiosyncratic volatility that moves the relative tightness of leverage constraints. Fluctuations in the common component of volatility do not affect the risk sharing between intermediaries, so they are abstracted from the model. We impose a weak cointegration relationship between the two endowment processes with the error correction parameter τ to be 0.0005 to keep the global economy stationary.

[9] The tension between consumption growth and risk-free rate is a long-standing puzzle (risk-free rate puzzle, Weil, 1989). This paper does not attempt to provide any new insight on the resolution of the risk-free rate puzzle. For example, introducing recursive utility to separate relative risk aversion and elasticity of intertemporal substitution will match the risk-free rate even with an average growth rate of two percent (Bansal and Shaliastovich, 2013).

In the SMM, we estimate six parameters, home bias α, trade elasticity σ, survival rate p, initial funds ξ, the constant and slope of the VaR constraint θ_0 and θ_1 to match six key moments about intermediaries and exchange rates: the leverage ratio ϕ[10], exchange rate volatility $sd(\Delta q)$, correlation between exchange rate and consumption growth differential $corr(\Delta q, \Delta c - \Delta c^*)$, OLS estimates of currency return on interest rate differential β_{FP} and exchange rate change on log volatility β_{vol}, and absolute deviation from CIP $r_{cip} - r_f$. Despite using a new set of exchange rate related moments in the estimation, our estimates are close to the literature.

The degree of consumption home bias α is as small as 0.043, close to Colacito and Croce (2013). The elasticity of substitution between the two goods is 0.587, consistent with estimates based on macro quantities (Stockman and Tesar, 1995; Heathcote and Perri, 2002). The survival rate p and initial funds rate ξ are 0.964 and 0.003, which implies an average horizon of bankers of a decade. θ_0 is estimated to be 0.376. In Gertler and Kiyotaki (2010), these three parameters are 0.972, 0.003, and 0.383, very close to the result of our estimation. The slope of θ_1 is 0.207, which determines the relative importance of VaR induced constraint fluctuations on exchange rates.

5.2 Quantitative Results

Table 3 presents the quantitative results of the model.

The first two columns report the moments in the data and in our benchmark model. The upper panel lists country-specific moments. Among the moments, consumption growth volatility is close to endowment growth volatility, which is estimated directly from data, and the leverage ratio ϕ is chosen as the target moment in our estimation.

Beyond these targets, our benchmark model is able to match the mean and standard deviation of risk-free rate and the volatility and persistence of the leverage. In terms of the risky asset

[10] We follow the definition by Krishnamurthy and Vissing-Jorgensen (2015) of the "financial sector" of all institutions supplying short-term debt. These institutions include US-Chartered Depository Institutions, Foreign Banking Offices in the US, Banks in US-Affiliated Areas, Credit Unions, Money Market Mutual Funds, Issuers of Asset-Backed Securities, Finance Companies, Mortgage Real Estate Investment Trusts, Security Brokers and Dealers, Holding Companies and Funding Corporations. Quarterly assets and liabilities data for each type of financial institution are from the Flow of Funds.

return, we interpret it broadly as intermediated assets, including bank loans and other fixed income securities, so bond excess returns are preferred proxies to stock excess returns. In the data, the investment-grade corporate bond holding period return (from Barclays) is 4.01 percent on average, with a volatility of 5.40 percent. Our model matches the volatility but undershoots risk premium. However, if we proxy the excess return with the long-term credit spread between Moody's BAA corporate bonds and treasury bonds as in Gertler and Kiyotaki (2010), the excess return is 1.78 percent on average, roughly the same magnitude as our model. To highlight the main mechanism, we abstract from additional features such as habit formation, long-run risks, or disaster risks, to resolve the equity premium puzzle. The model delivers additional implications on the money market: the spread between risk-free interbank lending and wholesale funding $r_{mm} - r_f$ is equal to the wedge $\log v_I - \log v$. Our model implies an average spread of 24 basis points, similar to the data counterpart of LIBOR-OIS spread.

The lower panel shows that our model can resolve the exchange rate puzzles quantitatively. Exchange rate volatility is 8.61 percent, close to the 10 percent in the data. Consumption growth differential is weakly correlated with exchange rate change, and the regression coefficient of currency return on interest rate differential is 2.04, greater than unity. Finally, our model generates an average CIP deviation of 24 basis points as in the data. We note that the magnitude of average CIP deviation is similar to LIBOR-OIS spread. It is precisely what our model implies: the wedge $\log v_{I,t} - \log v_t$ is equal to CIP deviation, as well as the spread between risk free interbank lending and wholesale funding. Moreover, the model generates the cyclicality of CIP deviations consistent with empirical evidence documented by Avdjiev et al. (2016). The change of CIP basis has a positive regression coefficient on log currency implied volatility ($\beta_{\Delta cip,\Delta vol} = -0.26$) [11] and a negative regression coefficient on the change of exchange rates ($\beta_{\Delta cip,\Delta q} = -2.08$). Our model can closely match the size of $\beta_{\Delta cip,\Delta vol}$ and the sign of $\beta_{\Delta cip,\Delta q}$[12]. The undershooting of $\beta_{\Delta cip,\Delta q}$ could be a result of the specialty of the dollar discussed in Avdjiev et al. (2016).

[11] Our definition of the basis is the negative of theirs, so the coefficient also has an opposite sign.

[12] Since we do not have currency implied volatility in the model, we use the log fundamental volatility $\sigma log(\sigma_{X,t})$. Assuming unity elasticity between the two volatilities, the model should replicate the regression in the data.

To demonstrate the importance of volatility channel through the intermediaries, we turn off the link between the financial constraint and volatility ($\theta_1 = 0$) and report the moments in Column 3. In this case, the Backus-Smith correlation is as large as 0.70. The forward premium regression coefficient β_{FP} is extremely large, as in this case the real interest rate barely moves. Exchange rates are not related to volatility, and the CIP deviation is 69 basis points, much larger than what we observe in the data. $\beta_{\Delta cip,\Delta vol}$ becomes very small, while the sign of $\beta_{\Delta cip,\Delta q}$ remains negative. We can conclude that the volatility mechanism through intermediaries goes a long way to explain the exchange rate puzzles.

Finally, we turn off stochastic volatility completely and report the results in Column 4. The results are very similar to Column 3, showing that stochastic volatility itself does not play an important role beyond its effects through the intermediaries.

6 Empirical Implications

Our model provides an exchange rate determination theory through intermediaries, with equation (14) as the main prediction: the expected exchange rate change is driven by both interest rate differential and the relative tightness of financial constraints across the two countries. Furthermore, the financial constraint tightness is driven by the volatility in each country. In this section, we show that this relation is supported by data.

We first show that a higher dollar exchange rate volatility predicts a foreign appreciation as well as a higher currency return to borrow the dollar and invest in foreign currencies. As a more direct test on the channel of intermediaries and financial constraint, we measure the tightness of financial constraint in the US using the annual growth rate of US financial commercial paper outstanding. An increase in commercial paper is associated with looser financial constraints. We show that a higher amount of US commercial paper outstanding predicts a foreign depreciation and a lower currency return.

6.1 Data

We have the spot and forward exchange rate data vis-a-vis dollar for 12 countries: Australia, Belgium, Canada, Denmark, France, Germany, Italy, Japan, New Zealand, Switzerland, Sweden, and the UK. The exchange rate data are obtained from Datastream. We also obtain daily spot exchange rate, compute the realized volatility in each year, and take the average over all these countries. This measure is the average dollar exchange rate volatility, which is faced by all investors involved in dollar trade in the FX market. For direct measures of financial constraint, we use the amount of US outstanding commercial paper for financial business, published by the Federal Reserve Board. The data spans from January 1991 to December 2015 at monthly frequency. We use the annual growth rate of commercial paper as our measure. We include several controls of average forward discounts, US price dividend ratio, US annual growth rate of industrial production, and exchange rate volatility. The control variables are from National Income and Product Accounts and CRSP.

6.2 Predictive Regressions with Dollar Exchange Rate Volatility

In this subsection, we examine the relationship between dollar exchange rate volatility, future dollar exchange rate change, and the return of borrowing dollar and investing in foreign currencies. We choose the average log dollar exchange rate volatility as a measure of financial constraint tightness in the US, as it is faced by all investors involved in dollar trade in the FX market.

The results of predictive regressions are shown in Table 4. The upper panel shows results for exchange rate changes, and the lower panel shows results for currency returns. Standard errors are robust to heteroskedasticity, serial autocorrelation, and overlapping observations (Hodrick, 1992). Univariate regression results in Row 1 to 3 show that a higher dollar exchange rate volatility predicts a foreign appreciation and a higher currency return. A one percent increase in dollar exchange rate volatility predicts a 20-basis-points average foreign currency appreciation and 25-basis-points currency excess returns per annum in horizons of 1 month, 3 months, and 12 months. The results are robust to including various controls, including average forward discount, US price dividend ratio, US industrial production growth. Average forward discount and industrial production growth are considered drivers of countercyclical currency risk premium (Lustig et al., 2014). Furthermore, we find that the predictive power of average forward discounts on both exchange rate changes and currency returns are weakened after controlling for exchange rate volatility.

The upper panel of Figure 4 reports the regression coefficients and confidence intervals of exchange rate predictability at 3 months horizon for each currency pair. All points estimates are positive and close to our results in Table 4, and most coefficients are statistically significant.

6.3 Predictive Regressions with US Commercial Paper

In this subsection, we further test the predictive power financial constraint tightness on exchange rate changes and currency returns. A tighter financial constraint manifests in the money market first and leads to a smaller amount of commercial paper. Therefore, the financial commercial paper outstanding is used as a measure of US financial constraint tightness.

Table 5 reports the predictive regression results of commercial paper growth for average dollar exchange rate and currency returns with different predictive horizons of 1 month, 3 months, and 12 months. The upper panel shows the results for exchange rate changes and the lower panel for currency returns. From univariate regression results in Row 1 to 3, a one-percent higher commercial paper growth rate in the US predicts a 30 basis point foreign depreciation in the subsequent month or quarter, and a 20 basis point foreign depreciation in the subsequent year. As for currency returns, a one percent higher commercial paper growth rate in the US predicts a 38 basis points lower excess return in the subsequent month or quarter, and a 26 basis points lower excess return in the subsequent year. In both exchange rate and currency predictive regressions, R^2 increases with predictive horizons.

The predictability of exchange rates and currency returns are also robust to controlling various variables, including average forward discount, US price dividend ratio, US industrial production growth. In this case, price dividend ratio and industrial production growth rate are considered credit demand indicators as well. After controlling for these variables, the information contained in commercial paper mostly comes from the credit supply side, or the tightness of financial constraints faced by intermediaries. We also find that the predictive power of average forward discounts is weakened after controlling for commercial paper, while dollar exchange rate volatility becomes insignificant as well.

In the lower panel of Figure 4, we show the univariate predictive regression coefficients and confidence intervals of exchange rates predictability at 3 months horizon for each currency pair. All point estimates are negative, and most coefficients are statistically significant.

7 Conclusion

Financial intermediaries are major participants in the foreign exchange market. In light of the dominance of intermediaries in the FX market and the constraints they are facing, we introduce these features into an otherwise standard international asset pricing model. An essential feature of financial intermediaries is the constraint on taking leverage. The financial constraint is tightly linked to the volatility in the economy because of the value-at-risk (VaR) rule adopted by major financial institutions.

We estimate the model using the simulated method of moments (SMM), and show that the model can resolve four exchange rate puzzles quantitatively. We resolve the Backus-Smith puzzle by replacing the standard consumption Euler equation with an intermediary Euler equation, so that consumption and exchange rates are disconnected. As for the forward premium puzzle, when volatility increases in the home country, its interest rate declines. Meanwhile, because of higher excess return required by home intermediaries, there is an expected foreign appreciation. The exchange rate volatility is closer to data, as the financial constraint amplifies the shocks in the economy. Tightened banking regulations after the global financial crises constrain the intermediaries from making arbitrage in the currency forward market and generate deviations from covered interest rate parity. Moreover, the model generates the cyclicality of CIP deviations consistent with empirical evidence. The deviations are large when home currency is strong, and when volatility is large.

Several model implications are supported by the data. As measures of intermediary financial constraints, dollar exchange rate volatility and US financial commercial paper outstanding predict exchange rate changes and currency returns. When we include the commercial and exchange rate volatility in the standard regression of currency returns on interest rate differentials, the coefficient on interest rate becomes smaller and less significant. It indicates that our mechanism is supported by data in resolving the forward premium puzzle.

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Table 1: Foreign Exchange Turnovers by Counterparties

Units are in percentage point. Data source: BIS triennial survey for specific years.

	1998	2001	2004	2007	2010	2013	2016
Reporting dealers	63	59	53	43	38.9	39	42
Nonfinancial customers	20	13	13	17	13.4	9	7
Other financial institutions	17	28	33	40	47.7	53	51

Table 2: Parameters

The parameters in the upper panel are calibrated to the common value in the literature and empirical estimates. The parameters in the lower panel are estimated using the simulated method of moments.

Variable	Notation	Value
	Calibration	
Discount factor	β	0.995
Nontradable share	α_l	0.67
Risk aversion	γ	2
Volatility	$\bar{\sigma}$	0.012
Volatility persistence	ρ_σ	0.90
Volatility of volatility	σ_σ	0.075
Error Correction	τ	0.0005
	Estimation	
Home bias	α	0.043
Trade elasticity	σ	0.587
Survival rate	p	0.964
Initial funds	ξ	0.003
VaR constant	θ_0	0.376
VaR slope	θ_1	0.207

Table 3: Quantitative results

The model moments are obtained from the average of repeated simulations of a sample of 40 years. All moments are annualized. "Benchmark" indicated the moments of the benchmark model. "No VaR" indicated the moments of the model with constraint not related to volatility ($\theta_1 = 0$). "No SV" indicated the moments of the model with no time-varying volatility ($\sigma_X = \sigma_Y = \bar{\sigma}$).

	Data	Benchmark	No VaR	No SV
	Country -specific moments			
$sd(\Delta c)$	1.75	1.73	1.65	1.63
r_f	0.83	1.67	1.74	1.74
$sd(r_f)$	1.45	0.39	0.02	0.02
$r_s - r_f$	4.01	1.59	1.58	1.57
$sd(r_s - r_f)$	5.40	5.68	4.16	4.12
$r_{mm} - r_f$	0.28	0.24	0.69	0.69
$sd(r_{mm} - r_f)$	0.29	0.11	0.17	0.17
ϕ	0.11	0.13	0.13	0.13
$sd(\phi)$	0.02	0.04	0.03	0.03
$corr(\phi_t, \phi_{t-1})$	0.96	0.87	0.87	0.88
	Exchange rates moments			
$sd(\Delta q)$	10.50	8.61	8.35	8.25
$corr(\Delta q,\ \Delta c - \Delta c^*)$	-0.13	-0.10	0.70	0.70
β_{FP}	2.20	2.04	7.82	7.91
β_{vol}	0.21	0.09	0.00	0.00
$r_{cip} - r_f$	0.24	0.24	0.69	0.69
$sd(r_{cip} - r_f)$	0.27	0.11	0.17	0.17
$\beta_{\Delta cip, \Delta vol}$	-0.26	-0.18	0.01	0.00
$\beta_{\Delta cip, \Delta q}$	-2.08	-0.07	-0.22	-0.21

Table 4: Volatility and Exchange Rates

The table reports estimates from OLS regressions of future exchange rate changes and currency excess returns on currency volatility and other controls. $\Sigma_{i=1}^{h}\Delta y_{t+i} = \beta_0 + cp_t\beta_1 + AFD_t\beta_2 + pd_t\beta_3 + \Delta ip_t\beta_4 + vol\beta_5 + u_{t+h}$. Δy_t is either exchange rate changes or currency excess returns. cp_t is the annual growth rate of commercial paper outstanding. AFD is the average forward discount. pd is price-to-dividend ratio. Δip_t is the annual growth of industrial production. the average dollar realized volatility. h shows the predictive horizon on month. The t-statistics are based on heteroscedasticity and autocorrelation consistent (HAC) standard errors (Hodrick, 1992). Data are monthly from 1980M1 to 2015M12.

h	vol	(t-stat)	AFD	(t-stat)	pd	(t-stat)	Δip	(t-stat)	R^2
				Exchange Rate					
1	0.20	(2.43)							0.02
3	0.21	(2.59)							0.05
12	0.21	(3.22)							0.16
1			1.26	(1.43)					0.01
3			1.06	(1.41)					0.01
12			1.03	(1.76)					0.04
1	0.17	(1.96)	0.68	(0.71)					0.02
3	0.19	(2.26)	0.40	(0.51)					0.05
12	0.20	(2.83)	0.35	(0.56)					0.17
1	0.22	(2.32)	0.94	(0.91)	0.04	(1.02)	0.55	(1.16)	0.02
3	0.21	(2.33)	0.72	(0.85)	0.05	(1.27)	0.36	(0.82)	0.06
12	0.19	(2.39)	0.70	(1.08)	0.06	(1.50)	0.09	(0.25)	0.21
				Currency Excess Return Regressions					
1	0.24	(2.93)							0.02
3	0.25	(3.04)							0.07
12	0.24	(3.62)							0.20
1			2.59	(2.93)					0.03
3			2.20	(2.89)					0.06
12			1.80	(3.05)					0.12
1	0.17	(1.94)	2.02	(2.15)					0.04
3	0.19	(2.24)	1.55	(1.96)					0.09
12	0.20	(2.84)	1.12	(1.80)					0.24
1	0.22	(2.31)	2.16	(2.10)	0.02	(0.51)	0.51	(1.08)	0.04
3	0.22	(2.36)	1.73	(2.01)	0.03	(0.65)	0.35	(0.79)	0.10
12	0.20	(2.52)	1.28	(1.98)	0.03	(0.66)	0.12	(0.31)	0.25

Table 5: Commercial Paper Outstanding and Exchange Rates

The table reports estimates from OLS regressions of future exchange rate changes and currency excess returns on currency volatility and other controls. $\Sigma_{i=1}^{h}\Delta y_{t+i} = \beta_0 + vol\beta_1 + AFD_t\beta_2 + pd_t\beta_3 + \Delta ip_t\beta_4 + u_{t+h}$. Δy_t is either exchange rate changes or currency excess returns. vol is the average dollar realized volatility. AFD is the average forward discount. pd is price-to-dividend ratio. Δip_t is the annual growth of industrial production. h shows the predictive horizon of months. The t-statistics are based on heteroscedasticity and autocorrelation consistent (HAC) standard errors (Hodrick, 1992). Data are monthly from 1991M1 to 2015M12.

h	cp	(t-stat)	AFD	(t-stat)	pd	(t-stat)	Δip	(t-stat)	vol	(t-stat)	R^2
					Exchange Rate						
1	-0.30	(-2.18)									0.02
3	-0.30	(-2.35)									0.05
12	-0.19	(-2.01)									0.08
1	-0.39	(-2.17)	-1.56	(-0.95)							0.02
3	-0.40	(-2.57)	-1.68	(-1.28)							0.07
12	-0.24	(-2.38)	-0.83	(-1.14)							0.09
1	-0.53	(-2.54)	-1.66	(-0.91)	0.02	(0.18)	0.66	(0.98)			0.02
3	-0.48	(-2.60)	-1.68	(-1.18)	0.02	(0.23)	0.38	(0.62)			0.07
12	-0.22	(-1.81)	-0.55	(-0.67)	0.04	(0.52)	-0.20	(-0.45)			0.10
1	-0.32	(-2.06)							-0.02	(-0.19)	0.02
3	-0.28	(-2.00)							0.02	(0.16)	0.05
12	-0.12	(-1.11)							0.09	(1.03)	0.10
					Currency Excess Return						
1	-0.38	(-2.73)									0.03
3	-0.37	(-2.87)									0.08
12	-0.26	(-2.65)									0.14
1	-0.41	(-2.32)	-0.55	(-0.37)							0.03
3	-0.41	(-2.67)	-0.71	(-0.57)							0.08
12	-0.26	(-2.52)	-0.01	(-0.02)							0.14
1	-0.53	(-2.61)	-0.74	(-0.44)	0.00	(-0.01)	0.63	(0.95)			0.03
3	-0.47	(-2.65)	-0.76	(-0.57)	0.01	(0.08)	0.33	(0.54)			0.08
12	-0.22	(-1.83)	0.28	(0.34)	0.04	(0.49)	-0.28	(-0.63)			0.15
1	-0.40	(-2.60)							-0.03	(-0.25)	0.03
3	-0.36	(-2.54)							0.01	(0.08)	0.08
12	-0.19	(-1.77)							0.08	(0.93)	0.16

Figure 1: Cross-border Banking Claims and Liabilities

The figure plots weighted average of 21 countries' cross border banking claims (liabilities) over external portfolio claims (liabilities). Cross-border banking claims (liabilities) are from BIS locational banking statistics, and external portfolio claims (liabilities) are from Lane and Milesi-Ferretti (2007), updated until 2011. We use the share of a country's external portfolio claims (liabilities) as the weight.

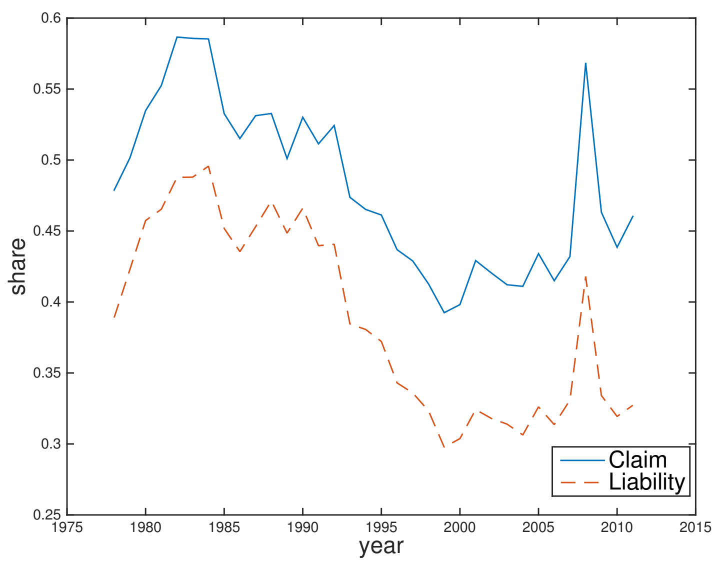


Figure 2: Impulse Response Functions to a Positive Home Endowment Shock

The figure reports the impulse responses to a positive one-standard-deviation home endowment shock. Variables include consumption growth (Δc), risky asset price (P_s), risky asset return (R_S), risk-free rate (R_f), international bond return (R_b), marginal value of investment for intermediaries (ν_s), marginal cost of taking deposit for intermediaries (ν), and leverage (ϕ). Impulse responses of both home and foreign variables are shown in the same figure. Also, the responses of exchange rate (Q) are reported.

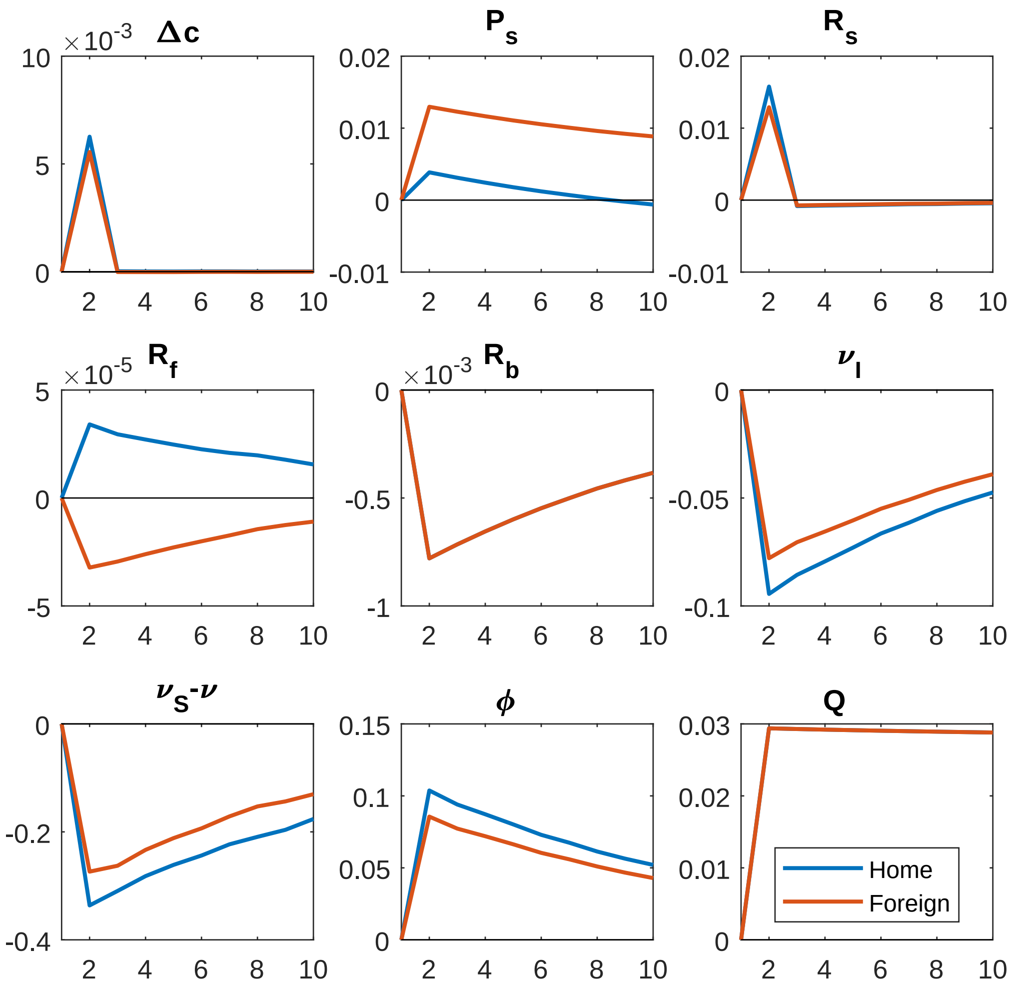


Figure 3: Impulse Response Functions to a Positive Home Volatility Shock
The figure reports the impulse responses to a positive one-standard-deviation home volatility shock. Variables include consumption growth (Δc), risky asset price (P_s), risky asset return (R_S), risk-free rate (R_f), international bond return (R_b), marginal value of investment for intermediaries (ν_s), marginal cost of taking deposit for intermediaries (ν), and leverage (ϕ). Impulse responses of both home and foreign variables are shown in the same figure. Also, the responses of exchange rate (Q) are reported.

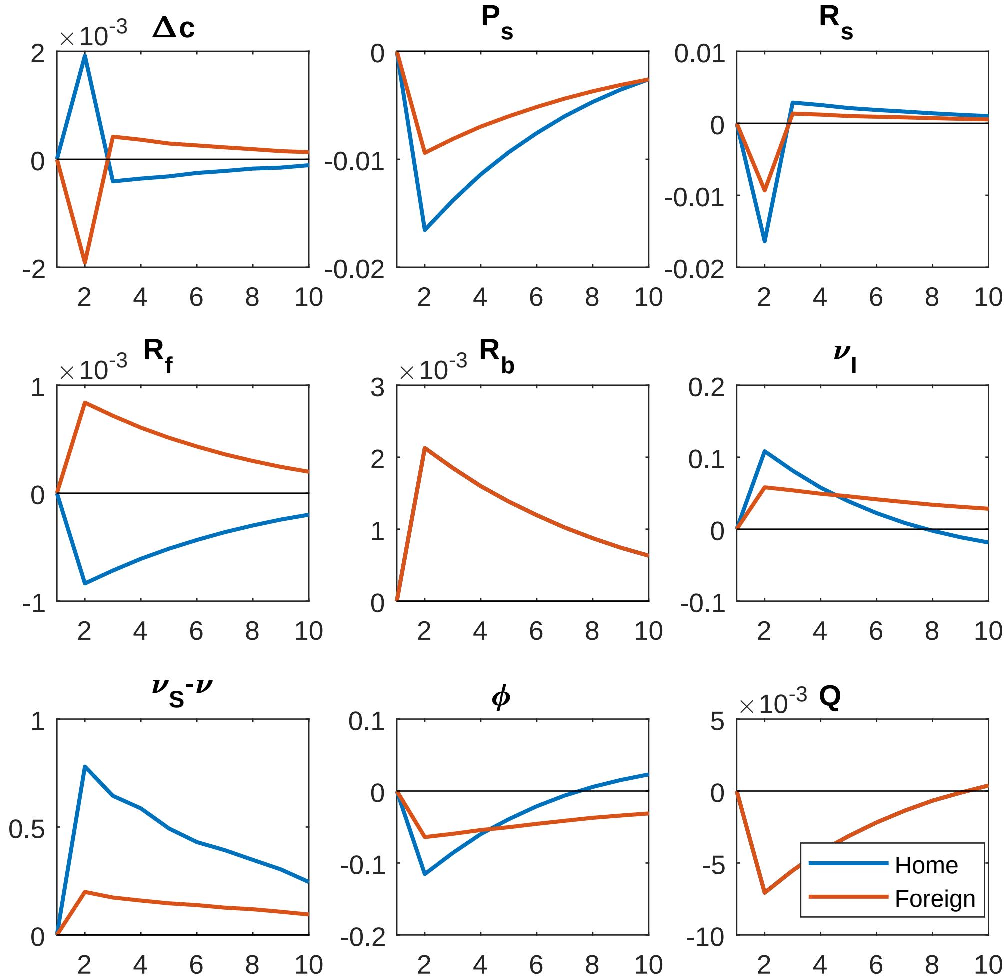
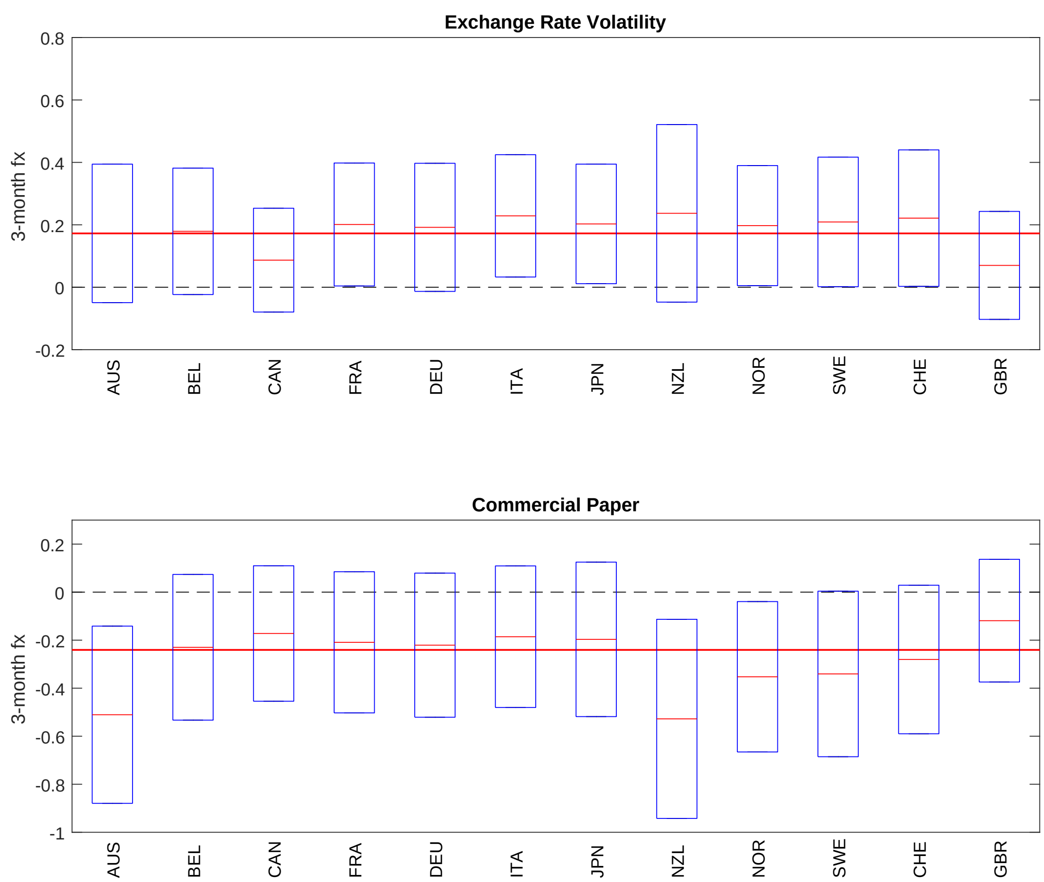


Figure 4: Exchange Rate Predictability: Individual Countries

The Figures presents the univariate regression evidence of predictability of future dollar value by volatility and growth of commercial paper outstanding. The dependent variables are the log changes in real dollar values against individual currencies. The Figure shows the OLS coefficients on exchange rate volatility (upper panel) and commercial paper outstanding (lower panel) and the associated HAC 95% confidence intervals. Data are monthly from 1980$M1$ to 2015$M12$.



Appendix: Model Estimation

The equilibrium model is estimate by simulated method of moments (SMM). Estimation methods are detailed in Fernández-Villaverde et al. (2016).

Denote the moment from data sample by $\hat{m}_T(Y)$ and mode-implied moments $E[\hat{m}_T(Y)|\theta_0,\ M_1]$ under model $M_1$and parameter θ_0. Define the discrepancy

$$G_T(\theta|Y) = \hat{m}_T(Y) - E[\hat{m}_T(Y)|\theta_0,\ M_1]$$

Our estimator $\hat{\theta}_{smm}$ minimizes the criterion function of weighted discrepancy

$$\hat{\theta}_{smm} = argmin_{\theta} G_T(\theta|Y)' W G_T(\theta|Y)$$

Suppose these is a unique θ_0 that $G_T(\theta|Y) \to 0$ almost surely, then the estimator is consistent.

Our model has six estimated parameters is exactly identified by six moments. The weight matrix adjust for the difference of the units. When computing the model-implied moments, we simulated $\lambda = 80$ short samples of 40 years data ($T = 160$).

$$E[\hat{m}_T(Y)|\theta_0,\ M_1] = \frac{1}{\lambda} \sum_{i=1}^{\lambda} \hat{m}_T(Y^i|\theta_0,\ M_1)$$