Dollar Funding Fragility and non-US Global Banks[*]

Philippe Bacchetta
University of Lausanne, Swiss Finance Institute, and CEPR

J. Scott Davis
Federal Reserve Bank of Dallas

Eric van Wincoop
University of Virginia and NBER

July 15, 2025

Abstract

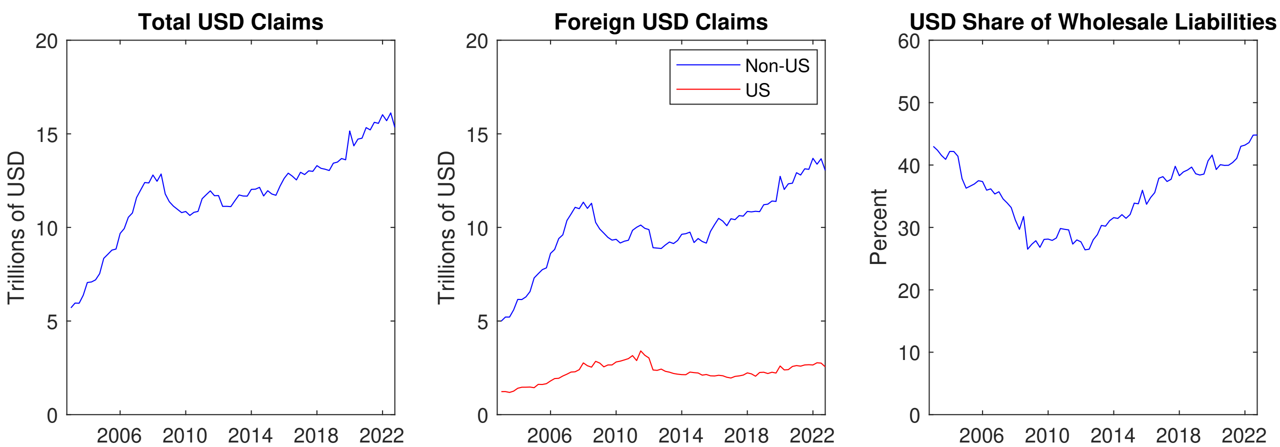
Global non-US banks have significant dollar exposure both on and off their balance sheet. We develop a model to analyze their adjustment to dollar funding shocks, whether from reduced direct lending or external dollar shortages. The model provides insight into banks' responses through borrowing, lending, and FX swap positions, as well as the impact on their net worth, their probability of default and CIP deviations. Implications of the model are confronted with data on the response of non-US global banks to major dollar funding shocks. We examine the benefits from buffering these shocks through central bank dollar swap lines or local currency lending by the central bank.

[*]We would like to thank Patrick McGuire for guidance with regards to the dollar component of G-SIB balance sheets. We like to thank Beata Javorcik (discussant) and seminar participants at Peking University, Fudan University, the ECFIN-JIE Global Macro conference, and the BSE Forum for comments. We gratefully acknowledge financial support from the Bankard Fund for Political Economy. This paper represents the views of the authors, which are not necessarily the views of the Federal Reserve Bank of Dallas or the Federal Reserve System.

1 Introduction

Non-US global banks play a critical role in global dollar markets, as illustrated in Figure 1. The first panel shows that non-US banks hold dollar denominated assets of more than \$15 trillion in 2022, a number that has been steadily increasing. The second panel shows that non-US banks far dominate US banks in cross-border dollar claims. The third panel relates specifically to non-US Global Systematically Important banks (G-SIB). It shows that in recent years more than 40 percent of their wholesale liabilities are dollar denominated. These tend to be short-term liabilities that need to be frequently rolled over. This share has continued to gradually increase since the 2008 Global Financial Crisis (GFC).

Figure 1: USD Claims of US and Non-US Banks



Notes: USD claims of non-US banks in the first two panels are calculated from the BIS International Banking Statistics using the method described in Aldasoro and Ehlers (2018). The foreign USD claims of US banks is from the BIS Locational Banking Statistics. Foreign claims include a bank's cross-border claims and the local claims of foreign affiliates. The USD share of wholesale liabilities is based on data for 40 non-US G-SIB banks that is discussed in Section 4 and the Online Appendix.

The reliance on dollar funding introduces potential vulnerabilities to the global financial system, especially in periods of dollar shortages or market stress (see IMF, 2019).[1] Such vulnerabilities can arise both due to a decline in wholesale dollar funding to non-US banks and to general dollar shortages external to banks. We investigate, both empirically and

[1]In its Global Financial Stability Report (October 2019) the IMF writes "In the run-up to the global financial crisis, lending in US dollars by global non-US banks, together with their reliance on short-term and volatile wholesale funding, became crucial transmission mechanisms for shocks that originated in the major funding markets for US dollars. Whereas regulation following the crisis has improved the resilience of banking sectors in many dimensions, these mechanisms remain a source of vulnerability for the global financial system."

theoretically, how non-US banks are affected by such dollar shortages. Closely related, we ask if there are benefits to central bank dollar swap lines in case of such dollar shortages. Such swap lines have been extensively used both during the 2008 global financial crisis and the COVID crisis.

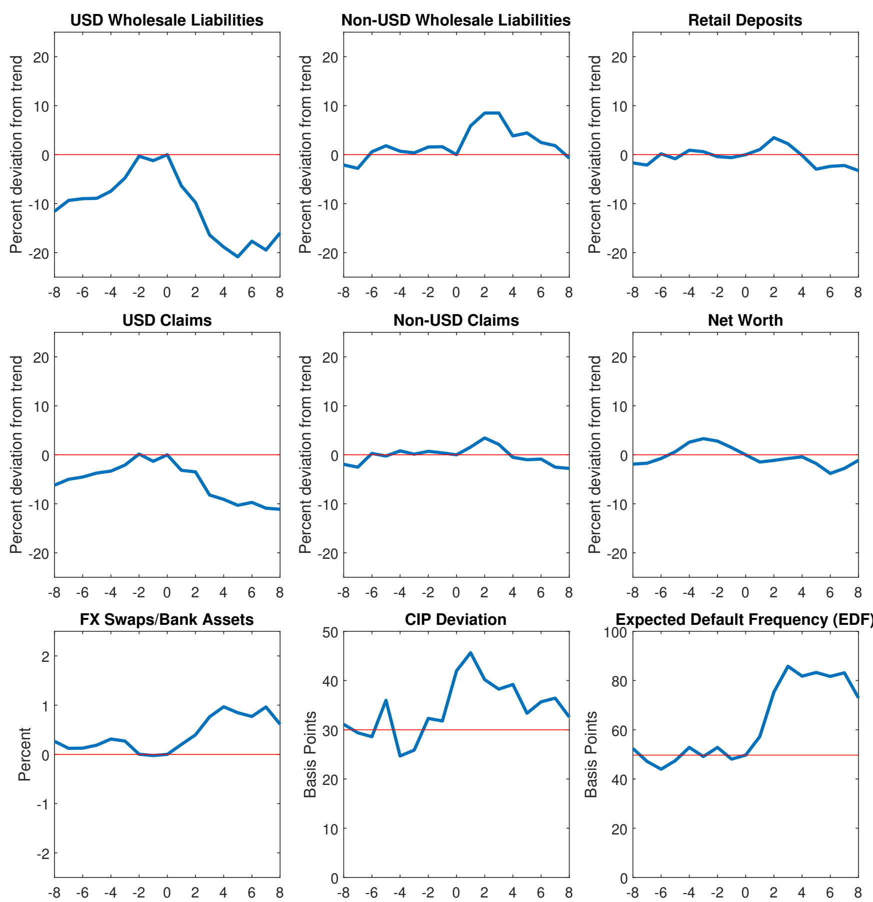
We develop a simplified analytical framework to clarify the mechanisms underlying the vulnerabilities of non-US global banks and their response to dollar funding shocks. We consider the implications for bank balance sheet and non-balance sheet positions, as well as the CIP deviation and probability of bank default. We also consider how the outcome is altered by providing banks with dollar liquidity through central bank swap lines or liquidity in the domestic currency.

We connect the model to data for the balance sheets of non-US G-SIB banks. These data are used both to calibrate the model and to illustrate the quantitative impact of dollar funding shocks faced by non-US banks. Since there is no precise data on the currency composition of the balance sheets of individual banks, we construct quarterly estimates for G-SIB banks by combining country-level bank data from the BIS with bank-level data for G-SIB banks from public financial filings. The procedure is described in detail in Section 4 and the Online Appendix.

Figure 2 plots different components of our constructed bank balance sheets in the 8 quarters before and after events where there is a sudden drop in bank dollar funding. In a panel of banks across 14 countries from 2003 to 2022, we identify 22 separate episodes where the four-quarter sum of dollar liabilities in a country's banks fell by over 10% relative to the prior four quarters. The full list of these 22 crises is in Appendix A. Of these 22 events, 7 occurred during 2007-2008 and another 7 occurred between 2010 and 2012 during the European debt crisis. For the average across these 22 episodes, Figure 2 plots dollar wholesale liabilities, non-dollar wholesale liabilities, retail deposits, dollar and non-dollar claims, bank net worth, an estimate of off-balance sheet FX swap positions, the country's OIS-CIP deviation, and the expected default frequency from Moody's Analytics (EDF) for the G-SIB banks in that country. The balance sheet variables in the top two rows are scaled by an HP trend. The FX swap position refers to dollar swaps, where banks sell foreign currencies in exchange for dollars today at the spot exchange rate and reverse the transaction at a future date at the forward rate.

Figure 2 shows that wholesale dollar funding falls by close to 20%. Bank retail deposit funding is more or less constant. Non-dollar wholesale funding rises slightly and non-dollar claims drop slightly. Dollar claims drop sharply, by about 10%, while synthetic dollar borrowing (shown as a percentage of all assets) increases substantially. Bank net worth falls slightly, while the bank probability of default and CIP deviation increase. The average non-US G-SIB bank responds to the fall in wholesale dollar funding with a combination of reduced dollar lending and increased synthetic dollar borrowing through FX swaps. The latter involves borrowing more in foreign currencies that are swapped into dollars through off-balance sheet swap market positions. The increase in demand for dollar swaps is associated with an increase in the CIP deviation.

Figure 2: Response to dollar liquidity shocks



Notes: USD claims and liabilities are based on BIS International Banking Statistics. Net worth and deposits are constructed using bank balance sheet data from S&P Capital IQ. Non-USD claims and liabilities are constructed using bank balance sheet data from S&P Capital IQ and BIS International Banking Statistics. The CIP deviation is the 3-month OIS CIP deviation and is calculated with data from Bloomberg. EDF is from Moody's Analytics. Details about the data are presented in the Online Appendix.

To address these stylized facts, we propose a three-period model for non-US banks. They hold long-term assets in dollars and domestic currency, which are costly to liquidate prior to their maturity date. Banks have a stable base of insured retail deposit funding in the domestic currency at a given interest rate. They also obtain wholesale funding, both in dollars and in domestic currency. Investors who provide wholesale funding demand a premium that depends on the probability of default of the bank. Banks are assumed to hedge their total dollar exposure, so that their net on-balance sheet dollar exposure is offset through FX swaps. However, there are regulatory costs associated with swap market positions.

The bank's probability of default is endogenous. It is affected by losses associated with liquidated assets, interest rates on wholesale funding and synthetic dollar funding, as well as the expected probability of default on both dollar and domestic currency assets.

We examine how exogenous dollar funding shocks affect bank lending, borrowing, swap market positions, the default probability and the CIP deviation. We distinguish between two different shocks to the dollar funding supply. The first shock is a dollar liquidity shock, modeled by tightening a dollar borrowing constraint faced by banks. The second shock is an external dollar shortage shock reflected in the FX swap market. This can, for example, be the result of reduced dollar lending to non-banks by US financial institutions. It affects banks as it leads to increased synthetic dollar borrowing, which increases the swap rate and CIP deviation.

When we consider a dollar liquidity shock of a magnitude similar to what is observed in Figure 2, we find a response that is quantitatively consistent with the data. In particular, it leads to adjustments such as reduced dollar lending and increased purchases of dollar swaps. It also leads to an increase in the probability of default and CIP deviation.

Overall, we find that the impact of both shocks on banks is limited. An external dollar shortage shock can significantly raise the CIP deviation, but has virtually no effect on the bank balance sheet and its probability of default. A dollar liquidity shock that reduces dollar lending to banks has a small impact on the bank probability of default and CIP deviations are small, also consistent with the data. However, we do find that a dollar liquidity shock substantially larger than what we have observed in the data can lead to a sharp increase in the probability of bank default. There is an endogenous feedback mechanism. Lower net worth due to asset liquidation leads to an increased probability of default. This raises wholesale borrowing costs, which further raises the probability of default.

Since we have not observed bankruptcies of non-US global banks in recent years,[2] we focus our analysis on the effects of exogenous dollar shortages in the absence of a bank run. Nevertheless, given the maturity mismatch that banks face in our model, there is a possibility of a bank run when the liquidation cost of assets is large enough. We also find that when a dollar liquidity shock is large enough, the unique equilibrium is a bank run.

We also investigate how central banks may affect the outcome by providing dollar liquidity (dollar swap lines) or domestic currency liquidity. We find that liquidity provision

[2] One exception is Credit Suisse, which went bankrupt in 2023 and was absorbed by another global bank, UBS. However, the fall of Credit Suisse is due to mismanagement problems rather than dollar shortages (e.g., see Lengwyler and Weder di Mauro, 2023).

by central banks is mostly useful to avoid the worst possible outcomes. These include both bank run equilibria and a sharp increase in bank default probability under very large dollar liquidity shocks. Otherwise, in the no-run equilibrium we analyze in the context of a dollar liquidity shock consistent with Figure 2, we find that the benefits in terms of bank stability (probability of bank default) are small. We also find that providing dollar liquidity to banks when there is an external dollar shortage shock is inefficient. Moreover, domestic currency liquidity has no effect with external dollar shortage shocks and can make matters worse with dollar liquidity shocks.

1.1 Related Literature

Various papers describe dollar activities of non-US banks, mainly based on BIS data. The BIS report by the Committee on the Global Financial System (CGFS) (2020), the IMF Global Financial Stability Report (GFSR) (2019) and Aldasoro and Ehlers (2018) describe vulnerabilities associated with dollar funding of non-US banks. The problem of dollar shortages faced by non-US global banks during the GFC is discussed in McGuire and von Peter (2009), McGuire and von Peter (2012) and McCauley and McGuire (2009). Similar periods of dollar shortages are described by Ivashina et al. (2015) during the European debt crisis, by Anderson et al. (2025) and Iida et al. (2018) for the 2016 US money market reform episode and by Eren et al. (2020) during the Covid crisis.

As described in the CGFS and GFSR reports, the vulnerability of non-US banks to dollar liquidity shocks has improved since the GFC as a result of new regulations. One important new regulation is the LCR (Liquidity Coverage Ratio), which gradually went into effect starting in 2015, being fully in effect by 2019. It requires that banks hold high-quality liquid assets at least equal to 100 percent of the expected net cash outflows during a 30-day stress scenario. The GFSR report shows that liquidity ratios have indeed increased in most countries between 2008 and 2018. But the LCR applies to all currencies combined. Barajas et al. (2020) show that dollar liquidity ratios are much lower than for other currencies and half of all countries have dollar liquidity ratios below 100%.

Limited data on FX swap positions of banks makes it difficult to evaluate off-balance sheet dollar positions of non-US banks. It is generally assumed, based on supervisory guidance, that banks use off-balance sheet derivatives to balance out their net on-balance sheet dollar positions (e.g., Aldasoro et al., 2020; Kloks et al., 2023). We make that assumption as well, both in the empirical analysis and in the model. Aldasoro et al. (2020) show that the implied net positions in the swap market vary across countries, with Canada and Japan on net buying dollar swaps (borrowing dollars through the swap market) and Australia selling dollar swaps (lending dollars through the swap market). They also discuss the need for central bank swap lines when short-term dollar borrowing from money market funds and through FX swaps is not rolled over.[3]

Some papers use actual data of swap and forward market positions of banks that are settled via the CLS cash settlement system. These data have good coverage of interbank swap market positions, but capture only a small fraction of swap market positions with non-bank customers. Kloks et al. (2023) obtain an estimate of net positions with non-bank customers by combining interbank CLS positions with the overall net swap market positions obtained by assuming that off-balance sheet positions fully hedge the on-balance sheet positions.

The large literature on CIP deviations stresses the role of global banks and their more limited CIP arbitrage after the GFC. However, much of the emphasis is on US global banks, which are suppliers of global dollars, starting with the seminal paper of Du et al. (2018). Interesting recent papers using US bank-level data include Anderson et al. (2025), Barbiero et al. (2024), and Moskowitz et al. (2024). More closely related to our analysis, Khetan (2024) examines the impact of reductions in direct US dollar lending by US money market funds (MMFs), a major source of wholesale dollar financing for non-US global banks. Using CLS data, he shows that these reductions lead to an increase in synthetic dollar borrowing by global banks and an increase in CIP deviations.[4]

Using data for non-US banks, several papers show that dollar shortages negatively affect dollar lending. Ivashina et al. (2015) show that European banks decreased their syndicated dollar loans during the European debt crisis, when MMFs reduced their dollar funding. Eguren-Martin et al. (2024) show that an increase in the CIP deviation reduces cross-border lending by UK banks, while Keller (2024) shows that it reduces bank credit by Peruvian banks. Barajas et al. (2020) present evidence showing that a rise in CIP deviations reduces cross-border lending by non-US banks and increases their probability of default. Iida et al. (2018) also present evidence of a link between CIP deviations and the probability of bank default for non-US banks.

While most of the literature is empirical, Ivashina et al. (2015) present a model that is related to our framework as they analyze the impact of funding shocks on the balance sheet of non-US banks. They consider a shock to the exogenous default probability of banks, which affects their dollar borrowing and lending. They also allow for synthetic dollar borrowing and show that shocks to non-US banks affect CIP deviations. Iida et al. (2018) develop a similar model and analyze a wider set of shocks. Our model differs from these analyses in several ways. We explicitly distinguish between stable retail deposits and short-term

[3] There is a vast literature describing central bank swap lines and documenting that they lower CIP deviations. See for example Bahaj and Reis (2022), Cerutti et al. (2021), Rime et al. (2022), Ferrara et al. (2022), Goldberg and Ravazzolo (2022) and Kekre and Lenel (2024).

[4] Empirical analyses using bank-level data on non-US banks include Abbassi and Bräuning (2020) and Kloks et al. (2024), who analyze the impact of non-US banks on the FX swap market at quarter ends.

wholesale funding that is not necessarily rolled over. The cost of wholesale funding and the probability of bank default are endogenous in our model. This enables an analysis of bank vulnerability, in addition to introducing richer mechanisms through endogenous default premia and borrowing costs. We make a distinction between short-term liabilities and long-term assets that can only be liquidated at a cost. Finally, a major difference from previous analyses is that we calibrate the model to get a sense of the magnitude of the effects.[5]

The rest of the paper is organized as follows. Section 2 describes the model. Section 3 discusses analytical results based on a linearized version of the model. Section 4 presents the numerical analysis based on a calibrated version of the model and Section 5 concludes.

2 Model Description

There are a continuum of non-US banks on the interval [0,1]. We will describe a representative bank. There are three periods. Our main focus will be on period 1. Period 0 is the past. We take the bank balance sheet from period 0 and interest rates from period 0 as given. There are two currencies, the domestic currency and the dollar. Although we will apply the model to non-US global banks from all over the world, for simplicity we refer to the domestic currency as the euro.

Apart from non-US banks, there are also US banks, wholesale lenders to non-US banks and agents that have an exogenously given demand for synthetic dollar funding. Since non-US banks are the focus of our analysis, most of the time we simply refer to them as "banks". The only role of US banks is to conduct CIP arbitrage, which non-US banks will do as well. Wholesale lenders provide dollar and euro funding to banks. They demand interest rates that depend on the risk of default of the bank. They may also impose borrowing constraints on the bank.

We take exchange rates and interest rates on safe dollar and euro assets as given. One can think of the interest rates as set by the central banks. Assume that the safe interest rate for both currencies is i^s. Its level will not be important in what follows. Although there is uncertainty about the period 2 exchange rate, this will not affect banks as they are assumed to balance out any on-balance sheet net dollar exposure with an off-balance sheet net dollar position through the swap market. We assume that the exchange rate (dollars per euro) is 1 in both periods 0 and 1.

[5] Bohorquez (2023) analyzes the amplifying role of dollar appreciation in self-fulfilling crises. The exchange rate plays a limited role in our analysis, as non-US global banks hedge exchange rate risk. In a model without banks, Bacchetta et al. (2025) analyze the impact of offshore dollar funding shocks on the exchange rate.

2.1 Bank Assets

Consider a representative non-US bank. The bank has long-term (illiquid) euro and dollar assets. These are two-period loans made in period 0. The interest rates on the euro and dollar loans are $i_0^{€,l}$ and $i_0^{\$,l}$. Interest is paid in period 1 and 2, while the principal is due at time 2. The value of euro and dollar loans is $L_0^{€}$ and $L_0^{\$}$.

The bank does not make any new loans in period 1, but can sell some of its loans. However, since these are illiquid assets, the loans are sold at a discount. Specifically, the prices that the bank receives for selling respectively a one euro and one dollar loan in period 1 are

$$p_1^{€} = 1 - \nu_e \left(L_0^{€} - L_1^{€} \right) \tag{1}$$

$$p_1^{\$} = 1 - \nu_d \left(L_0^{\$} - L_1^{\$} \right) \tag{2}$$

The values of euro and dollar loans not sold in period 1 are $L_1^{€}$ and $L_1^{\$}$. The bank therefore sells $L_0^{€} - L_1^{€}$ euro loans and $L_0^{\$} - L_1^{\$}$ dollar loans. Since all banks are identical in the model, in equilibrium they will all sell the same number of loans. However, the prices of these loans are determined by the aggregate sale of euro and dollar loans by all banks. Therefore the bank takes these prices as given.[6]

When banks sell very few loans, the prices are close to 1, so that the discount is very small. However, the more loans banks sell in period 1, the higher the discount at which they are sold. One can also interpret this as banks first selling their most liquid assets and then increasingly illiquid assets at higher discounts. The parameters ν_e and ν_d are important as they determine the size of the bank's losses from selling loans at a discount.[7]

We assume that there is a stochastic period 2 default rate on the principal of euro and dollar loans of $d_2^{€}$ and $d_2^{\$}$. Define d and σ^2 as the mean and variance of these default rates. They are the same for euro and dollar loans. The two default rates are assumed to have independent Gamma distributions $\Gamma(k, \theta)$, where the shape parameter is $k = (d/\sigma)^2$ and the scale parameter is $\theta = \sigma^2/d$. The payments in period 2 on euro and dollar loans are $(1 + i_0^{€} - d_2^{€})L_0^{€}$ and $(1 + i_0^{\$} - d_2^{\$})L_0^{\$}$.

[6]We will not explicitly model the agents who buy the loans. In Gertler and Kiyotaki (2015) the bank sells the assets to households, who have an inferior technology of managing them. In their model the price of the assets is also a negative linear function of the number of assets that banks sell (that households buy).

[7]We assume that the prices are linear in the number of loans sold as opposed to depending on the percentage of bank loans that are sold. What matters is the absorptive capacity of these assets by the market rather than their share of total bank loans.

2.2 Bank Liabilities

On the liability side of the bank balance sheet are retail euro deposits, as well as wholesale euro and dollar borrowing. The retail deposits are $B^{€}$. These remain the same in period 1 as in period 0, capturing the difficulty of quickly expanding this source of funding when a sudden funding need arises. These retail deposits are guaranteed by deposit insurance. Since they are safe assets, the interest rate is the safe interest rate i^s.

Wholesale funding in both currencies is short-term (one-period). Wholesale euro and dollar liabilities are $B_t^{€,w}$ and $B_t^{\$,w}$ in period $t = 0, 1$. The period 1 interest rates are[8]

$$i_1^{€} = i^s + p_D \tag{3}$$

$$i_1^{\$} = i^s + p_D \tag{4}$$

Here p_D is the probability of default of the bank in period 2. Lenders are assumed to be risk neutral and therefore demand interest rates that are equal to the safe rate plus the probability of default. The probability of default of the bank is endogenous and will be discussed below. In Section 4.6 we will discuss two extensions to this framework, one where the lenders are risk averse and one where there is a partial bailout of wholesale euro lenders in case of bank default.

The net worth of the bank is the difference between assets and liabilities. So for period 1 we have

$$W_1 = L_1^{€} + L_1^{\$} - B^{€} - B_1^{€,w} - B_1^{\$,w} \tag{5}$$

2.3 Off-Balance Sheet Activity

Apart from these on-balance sheet assets and liabilities, the bank is also active off balance sheet in the FX swap market. We describe it for period 1, though it is analogous for period 0.

One unit of a dollar swap market position is defined as follows. An agent who buys one dollar swap at time 1 receives one dollar at time 1 in exchange for 1 euro (the spot exchange rate is 1) and at time 2 receives 1 euro in exchange for F_1 dollars. Here F_1 is the period 1 forward rate (dollars per euro). Buying a dollar swap therefore implies that the agent is net short in forward dollars as it has an obligation to pay F_1 dollars at time 2. By analogy, a seller of dollar swaps is net long in forward dollars.

Let S_1 be the dollar swap market position of the representative bank. We assume that the bank's net dollar exposure through the swap market exactly offsets its net on-balance

[8] More precisely, $1 + i_1^{€} = (1 + i^s)/(1 - p_D)$ and analogously for the dollar. While we use these precise expressions when solving the model in Section 4, this makes virtually no difference except for one extreme case we will discuss in which the probability of bank default can asymptote to a very high level.

sheet dollar exposure:

$$S_1 = L_1^{\$} - B_1^{\$,w} \tag{6}$$

When $S_1 > 0$, the bank is net short dollars off balance sheet. It will then be equally net long dollars on the balance sheet through dollar lending minus dollar borrowing. From (5)-(6) we can also write

$$S_1 = B^{€} + B_1^{€,w} + W_1 - L_1^{€} \tag{7}$$

When the bank buys S_1 dollar swaps in period 1, in period 2 it receives S_1 euros and pays $F_1 S_1$ dollars. Converted to euros, the period 2 profit on these dollar swaps is then

$$\left(1 - \frac{F_1}{E_2}\right) S_1 \tag{8}$$

Here E_2 is the period 2 spot exchange rate. The analogous period 1 profit on dollar swaps bought at time 0 is $(1 - F_0)S_0$, using that $E_1 = 1$.

We assume that there is a quadratic cost to the bank of swap market positions, equal to

$$0.5\eta S_1^2 \tag{9}$$

One can think of these costs as related to regulations that limit CIP arbitrage. Specifically for G-SIB banks, capital surcharges are imposed dependent on the G-SIB score. One element of the G-SIB score is the complexity score, which is related to off-balance sheet derivatives such as FX swaps.

2.4 Bank Net Worth and Probability of Default

In period 0 the net worth W_0 of the bank is equal to the value of its assets minus liabilities:

$$W_0 = L_0^{€} + L_0^{\$} - B^{€} - B_0^{€,w} - B_0^{\$,w} \tag{10}$$

We assume that in period 1 the bank pays out a dividend equal to its regular net profits, excluding any losses from selling loans. This dividend is equal to

$$i_0^{€,l} L_0^{€} + i_0^{\$,l} L_0^{\$} - i^s B^{€} - i_0^{€} B_0^{€,w} - i_0^{\$} B_0^{\$,w} + (1 - F_0) S_0 \tag{11}$$

These profits include interest on assets and liabilities and the profit on the FX swap position.

When the bank does not sell loans in period 1, its net worth remains the same as in period 0: $W_1 = W_0$. More generally, if the bank does sell loans at a discount, its period 1 net worth is

$$W_1 = W_0 - (1 - p_1^{\$})(L_0^{\$} - L_1^{\$}) - (1 - p_1^{€})(L_0^{€} - L_1^{€}) \tag{12}$$

In the Online Appendix we derive the following expression for the net worth of the bank at time 2:

$$\begin{aligned} W_2 &= \left(i_0^{€,l} - i_1^{€} - d_2^{€}\right) L_1^{€} + \left(i_0^{\$,l} - i_1^{\$} - d_2^{\$}\right) L_1^{\$} + (1+i_1^{€})W_0 + (i_1^{€} - i^s)B^{€} \\ &+ \left(i_1^{\$} - i_1^{€} + e_1 - f_1\right) S_1 - (1-p_1^{\$})(L_0^{\$} - L_1^{\$}) - (1-p_1^{€})(L_0^{€} - L_1^{€}) \end{aligned} \tag{13}$$

The last two terms of (13) capture the losses that the bank suffers from selling assets in period 1 at a discount, which also reduces the period 2 net worth. Most other terms in (13) are excess returns. For example, the first two terms are the return from lending euros or dollars minus the interest rate on euro or dollar wholesale borrowing. The term $i_1^{\$} - i_1^{€} + e_1 - f_1$ is equal to the difference between the interest rate on wholesale dollar borrowing and synthetic dollar borrowing (euro borrowing swapped into dollars). The interest rate on synthetic dollar borrowing is $i_1^{€} + f_1 - e_1$. Here f_1 and e_1 are the log forward and spot rates (we assumed $e_1 = 0$). $f_1 - e_1$ is the forward discount or swap rate. We can think of $\left(i_1^{\$} - i_1^{€} + e_1 - f_1\right) S_1$ as a CIP arbitrage profit.

Given the Gamma distributions of $d_2^{€}$ and $d_2^{\$}$, we can then compute the probability of default, which is the probability that the net worth of the bank is negative in period 2:

$$p_D = Prob(W_2 < 0) \tag{14}$$

2.5 Bank Maximization Problem

The bank maximizes

$$ER_2^p - 0.5\gamma var(R_2^p) - 0.5\frac{1}{W_1}\eta S_1^2 \tag{15}$$

Here R_2^p is the period 2 portfolio return, defined as W_2/W_1. The first two terms are the risk-adjusted portfolio return of the bank, where γ is the rate of risk aversion. We subtract the cost of swap market positions, also scaled by W_1 to convert to a return. The bank then solves a simple mean-variance portfolio problem.

The bank operates under four constraints. We have already discussed two of them. The bank cannot increase its loan portfolio at time 1. It can only sell assets. Therefore

$$L_1^{€} \leq L_0^{€} \tag{16}$$

$$L_1^{\$} \leq L_0^{\$} \tag{17}$$

In addition we assume that the bank is subject to borrowing constraints on short-term wholesale euro and dollar borrowing in period 1:

$$B_1^{€,w} \leq \bar{B}^{€} \tag{18}$$
$$B_1^{\$,w} \leq \bar{B}^{\$} \tag{19}$$

These borrowing constraints can be motivated by a familiar contract enforcement problem. The bank can divert a portion of the funds that it has borrowed. If it does so, it faces a penalty of $\bar{B}^{€}$ for euro borrowing and $\bar{B}^{\$}$ for dollar borrowing, for example imposed by the courts.[9] The constraints (18)-(19) may also be motivated by regulations. For example, Khetan (2024) reports that US money market funds have strict regulatory concentration limits, restricting how much they can lend to any institution. Assuming that (19) is binding, we will refer to a drop in $\bar{B}^{\$}$ as a dollar liquidity shock, which reduces the ability of non-US banks to borrow wholesale dollars.

When (18)-(19) hold, the lenders are not concerned that the bank will default other than in times where its net worth is negative. So default of the bank in period 2 happens due to inability to pay (negative net worth) rather than unwillingness to pay.

Let the Lagrange multipliers associated with the constraints (16)-(17) be μ_e and μ_d. The Lagrange multipliers associated with the constraints (18)-(19) are l_e and l_d. These Lagrange multipliers are zero when the constraints do not bind and positive when they do bind. So we must impose $l_d\left(B_1^{\$,w} - \bar{B}^{\$}\right) = 0$ and $l_d \geq 0$ and similarly for the other constraints. Scaling the Lagrangian multipliers by W_1, the bank maximizes the Lagrangian

$$\begin{aligned} &ER_2^p - 0.5\gamma var(R_2^p) - 0.5\frac{1}{W_1}\eta S_1^2 \\ &-\frac{l_e}{W_1}\left(B_1^{€,w} - \bar{B}^{€}\right) - \frac{l_d}{W_1}\left(B_1^{\$,w} - \bar{B}^{\$}\right) - \frac{\mu_e}{W_1}\left(L_1^{€} - L_0^{€}\right) - \frac{\mu_d}{W_1}\left(L_1^{\$} - L_0^{\$}\right) \end{aligned} \tag{20}$$

From (6)-(7), $B_1^{\$,w} = L_1^{\$} - S_1$ and $B_1^{€,w} = L_1^{€} - B^{€} - W_1 + S_1$. Substituting these into (20), the bank maximizes with respect to $L_1^{€}$, $L_1^{\$}$ and S_1. Together with the complementary slackness conditions, this gives the optimal on-balance sheet and off-balance sheet positions.

2.6 Optimal Decisions by Bank

The first-order condition with respect to S_1 is (see Online Appendix for details)

$$S_1 = \frac{\left(i_1^{\$} + l_d\right) - \left(i_1^{€} + l_e + f_1 - e_1\right)}{\eta} \tag{21}$$

[9] Technically, payments on the left-hand side of these expressions should include the interest payments. This will make little difference for the results. For simplicity we assume that concerns about default relate to the principal, not the interest that is due.

One can think of this as the CIP arbitrage position of non-US banks. The numerator is equal to the cost of borrowing dollars from wholesale lenders minus the cost of borrowing synthetic dollars. The former is $i_1^{\$} + l_d$. It includes both the dollar wholesale funding rate and the dollar Lagrange multiplier. The latter is zero when the dollar borrowing constraint does not bind. When it binds, $l_d > 0$ and $i_1^{\$} + l_d$ is the effective cost to the bank of borrowing dollars.

The cost of borrowing synthetic dollars is $i_1^{€} + l_e + f_1 - e_1$. It is the cost of borrowing euros from wholesale lenders, swapped into dollars. The effective cost to the bank of borrowing euros is $i_1^{€} + l_e$. When the euro borrowing constraint binds, so that $l_e > 0$, this effective cost of borrowing euros is larger than the interest rate on wholesale euro borrowing.

The larger η, the larger the cost to the bank of conducting swap market transactions. This reduces CIP arbitrage. It leads to smaller swap market positions in response to a difference between the (effective) costs of wholesale dollar borrowing and synthetic dollar borrowing.

The first-order conditions with respect to $L_1^{€}$ and $L_1^{\$}$ lead to expressions for period 1 euro and dollar lending that depend on the prices $p_1^{€}$ and $p_1^{\$}$ at which the bank is able to sell euro and dollar loans. An individual bank takes these prices as given. But the prices depend on the aggregate sales of euro and dollar loans as in (1)-(2). Using that equilibrium euro and dollar lending is the same in all banks and equal to aggregate euro and dollar lending, the Online Appendix derives expressions for $L_1^{€}$ and $L_1^{\$}$ after substituting the expressions for the prices into the first-order conditions. This gives

$$L_1^{€} = \frac{i_0^{€,l} - d - i_1^{€} - l_e - \mu_e + (1 + l_e)\nu_e L_0^{€}}{\gamma\sigma^2 + (1 + l_e)\nu_e W_1} W_1 \tag{22}$$

$$L_1^{\$} = \frac{i_0^{\$,l} - d - i_1^{\$} - l_d - \mu_d + (1 + l_e)\nu_d L_0^{\$}}{\gamma\sigma^2 + (1 + l_e)\nu_d W_1} W_1 \tag{23}$$

Consider, for example, euro lending $L_1^{€}$. It can be written as a weighted average of a standard mean-variance portfolio and period 0 lending $L_0^{€}$. The mean-variance portfolio is

$$\frac{\left(i_0^{€,l} - d - \mu_e\right) - \left(i_1^{€} + l_e\right)}{\gamma\sigma^2} W_1$$

The numerator is the effective expected return on lending euros minus the effective cost of borrowing euros. The weight on this mean-variance portfolio is $\gamma\sigma^2/[\gamma\sigma^2 + (1 + l_e)\nu_e W_1]$. This weight is smaller, and the weight on period 0 lending is larger, the bigger the cost of selling euro loans as captured by ν_e.

2.7 FX Swap Market Equilibrium

Three types of agents take positions in the swap market: US banks, non-US banks and non-banks. For non-banks we simply assume an exogenous demand of u for dollar swaps. They can, for example, be non-US firms that have limited access to the US dollar funding market and instead borrow dollars by borrowing euros that they swap into dollars. Alternatively, they can be non-US institutional investors that hold US dollar assets and wish to hedge the exchange rate risk by buying dollar swaps. We will refer to an increase in u as an external dollar shortage shock. Dollar shortages external to banks lead to an increased demand for synthetic dollar funding and therefore a demand for dollar swaps. Such dollar shortages can for example arise as a result of reduced lending by US financial institutions or increased demand for hedging services when non-US investors buy US assets.

US banks have a demand for dollar swaps of

$$S_1^{US} = -\frac{f_1 - e_1}{\eta} \tag{24}$$

This corresponds exactly to the demand for dollar swaps (21) by non-US banks when their dollar and euro borrowing rates are equal (which is the case for non-US banks as well) and they do not face a borrowing constraint in the currency in which they wish to borrow for CIP arbitrage (generally the dollar).

Since we will not model US banks, we can simply think of them as CIP arbitrageurs that can borrow and lend in safe dollar and euro assets. Assume that they borrow B_1 dollars, lend B_1 euros and swap these into dollars by selling B_1 dollar swaps. Therefore $S_1^{US} = -B_1$. This delivers a profit of $(f_1 - e_1)B_1 = -(f_1 - e_1)S_1^{US}$. Assuming a quadratic cost of swap market transactions analogous to non-US banks, this delivers the optimal swap market position of (24).[10]

Swap market equilibrium is then

$$S_1 + S_1^{US} + u = 0 \tag{25}$$

This implies a swap rate of

$$f_1 - e_1 = 0.5\eta u + 0.5\left[\left(i_1^{\$} + l_d\right) - \left(i_1^{€} + l_e\right)\right] \tag{26}$$

We will refer to $f_1 - e_1$ as the CIP deviation. It is equal to the (safe) synthetic dollar interest rate $i^s + f_1 - e_1$ minus the (safe) cash dollar interest rate i^s.

[10] Even if we assumed that US banks do not have access to safe borrowing and lending rates (e.g. Libor is not completely safe), (24) remains the optimal swap market position when the risk premia are identical for the dollar and euro assets used for arbitrage.

2.8 Solution

The endogenous variables that we solve are the wholesale funding rates $i_1^{€}$ and $i_1^{\$}$ and the four Lagrange multipliers l_e, l_d, μ_e and μ_d. To solve these, we impose $i_1^{€} = i_1^{\$} = i^s + p_D$ and the four complementary slackness conditions. The probability of default and the complementary slackness conditions depend on other variables that ultimately can be written as functions of the 6 variables that we solve. These include bank loans $L_1^{€}$ and $L_1^{\$}$ (eqns (22)-(23)), the bank swap market position S_1 (eqn (21)), the swap rate $f_1 - e_1$ (eqn. (26)), the prices of bank loans $p_1^{€}$ and $p_1^{\$}$ (eqns. (1)-(2)) and wholesale euro and dollar funding. For the latter we use that $B_1^{\$,w} = L_1^{\$} - S_1$ and $B_1^{€,w} = L_1^{€} - B^{€} - W_1 + S_1$.

The model exhibits either one equilibrium or three equilibria. The possible outcomes are: i) a single no-run equilibrium; ii) three equilibria, including a self-fulfilling bank run equilibrium and two no-run equilibria; iii) a unique bank-run equilibrium. The key parameter determining the type of equilibria that exist is the cost cost $\nu = \nu_e = \nu_d$ of liquidating bank assets. A single no-run equilibrium exists when ν is below a certain cutoff ν_1. Three equilibria exist for values of ν above ν_1. The Online Appendix derives the threshold value for multiple equilibria to exist.[11] The multiple equilibria case ii) applies under the calibrated model parameters in Section 4. Case iii) can occur only when the bank is forced to sell at least some assets, for example due to a decline in wholesale funding. When the cost ν is large enough, then the only possible outcome is a self-fulfilling bank run.

When $\nu > \nu_1$ and case ii) applies, two of the equilibria are no-run equilibria. These equilibria can be checked graphically by assuming a given probability of default p_D, solving the model under that assumed probability of default and then mapping that into a realized probability of default $p_D = Prob(W_2 < 0)$ implied by the solution of the model. As illustrated in the Online Appendix, there are two fixed points of this mapping. This is familiar from the literature on sovereign default models. A high probability of default leads to high period 1 wholesale funding rates for the bank. This reduces the period 2 net worth, which increases the probability of default. A high probability of default can then be self-fulfilling. However, the equilibrium with a high probability of default and high interest rates is unstable. We therefore focus the analysis on the no-run equilibrium with the lower probability of default.

When $\nu > \nu_1$, there is also a bank run equilibrium. But there are two types of bank run equilibrium. The more familiar one occurs when ν is above an even higher threshold $\nu_2 > \nu_1$. If wholesale deposits are not rolled over, banks must liquidate assets at fire-sale prices, implying large losses. When $\nu > \nu_2$ these losses are so high that the bank is unable to repay the period 0 wholesale lenders ($W_1 < 0$). This justifies that both dollar and euro wholesale deposits are indeed not rolled over.

A different type of bank run equilibrium can occur when ν is in the range $[\nu_1, \nu_2]$. In that

[11] Other parameters, such as the extent of retail deposits, also matter.

case the cost of liquidating assets is low enough that in period 1 banks are able to pay all the period 0 wholesale lenders even when none of this funding is rolled over in period 1. But at the same time the cost of liquidating assets to pay period 0 lenders is high enough that net worth becomes negative in period 2 even in the most favorable state were $d_2^{\$} = d_2^{€} = 0$. In this case, default in period 2 is certain, $p_D = 1$, so that it is indeed optimal not to roll over any of the wholesale funding in period 1.

In most of the analysis we focus on no-run equilibria. But as we discuss further in Section 4, different types of liquidity policy, including central bank swap lines, can play an important role in avoiding self-fulfilling bank runs that may or may not be accompanied by dollar liquidity shocks.

2.9 Pre-Shock Equilibrium

Before introducing shocks to the model, we first solve a pre-shock equilibrium. In this equilibrium period 1 variables (wholesale interest rates, forward discount, swap market position, bank lending and borrowing and net worth) are identical to period 0 variables. It is therefore a type of pre-shock steady state. We set $\bar{B}^{€} = B_0^{€,w}$ and $\bar{B}^{\$} = B_0^{\$,w}$ and $u = 0$ in the pre-shock equilibrium. The period zero balance sheet variables, and therefore also S_0, are taken as given and calibrated in Section 4. As we will see, non-US banks overall have slightly higher dollar assets than liabilities. This would imply a positive swap market position of non-US banks. But we set period 0 dollar assets equal to dollar liabilities in the main analysis, so that $S_0 = 0$. We will allow for non-zero values of S_0 in one of the extensions in Section 4.7.

We discuss the pre-shock equilibrium in more detail in Appendix B. The borrowing and lending constraints do not bind, so that $l_e = l_d = 0$ and $\mu_e = \mu_d = 0$.[12] The pre-shock swap rate (CIP deviation) is zero. We set σ to target a given pre-shock default probability, which determines wholesale dollar and euro funding rates. From (22)-(23), equating period 1 to period 0 loan levels and setting $l_e = l_d = 0$ then implies

$$i_0^{€,l} = d + i^{€} + \gamma\sigma^2 L_0^{€} \frac{1}{W_0} \tag{27}$$

$$i_0^{\$,l} = d + i^{\$} + \gamma\sigma^2 L_0^{\$} \frac{1}{W_0} \tag{28}$$

where $i^{€}$ and $i^{\$}$ are the pre-shock euro and dollar wholesale funding rates that are equal in periods 0 and 1. This determines the interest rates on bank loans, which are set in period 0 for the next two periods.

[12] We consider an extension in Section 4.7 where the dollar borrowing constraint is strictly binding in the pre-shock equilibrium, so that $l_d > 0$.

3 Analytical Implications of the Model

In this section we derive a set of analytical results by taking derivatives at the point of the pre-shock equilibrium. These are therefore small shocks. We consider large shocks in Section 4. For large shocks we need to solve the model numerically as there is no closed form solution to the probability of default. As shown in the Online Appendix, for marginal shocks at the pre-shock equilibrium, the derivative of the probability of default with respect to the shocks is zero. The key to this is that the derivative of W_1 with respect to shocks is zero at the pre-shock equilibrium. This is immediate from (12), using that in the pre-shock equilibrium the asset prices are 1 and period 0 and 1 loan volumes are identical. In Section 4 we will see that with large shocks the net worth and the probability of default will change, but for now we abstract from this.

We consider four scenarios for the shocks. The first two involve a dollar liquidity shock in the form of a tightening of the wholesale dollar borrowing constraint. In the pre-shock equilibrium, period 1 wholesale dollar borrowing is equal to period 0 wholesale dollar borrowing, $B_0^{\$,w}$. The shock we consider is one where the period 1 borrowing constraint is tightened, so that banks can borrow a marginal ϵ^b less: $\bar{B}^{\$} = B_0^{\$,w} - \epsilon^b$. We consider two versions of this. One assumes no euro slackness. This means that $\bar{B}^{€} = B_0^{€,w}$. Banks cannot make up for the dollar liquidity shock by borrowing more euros than they did in period 0. The other scenario is one where euro borrowing is slack. This means that $\bar{B}^{€}$ is sufficiently large that banks are not euro-borrowing constrained and therefore $l_e = 0$.

The next two scenarios involve an external dollar shortage shock, which raises demand for synthetic dollar funds. It takes the form of an increase in u by ϵ^u. Since this shock will raise the cost of synthetic dollar borrowing for the bank (euro borrowing swapped into dollars), banks wish to reduce euro borrowing in equilibrium. The euro borrowing constraint therefore will not bind and $l_e = 0$. But the dollar borrowing constraint may be binding. A higher swap rate makes it attractive for banks to sell dollar swaps and offset the resulting long forward dollar position by borrowing more dollars wholesale. We both consider the case where $\bar{B}^{\$} = B_0^{\$,w}$, so that banks are unable to borrow more dollars than in period 0, and the case of dollar slackness, where banks are not dollar-borrowing constrained. This means that $\bar{B}^{\$}$ is sufficiently high such that $l_d = 0$.

We can also think of euro and dollar slackness (the borrowing constraints not binding) as being a result of central bank liquidity policy. When the central bank provides sufficient liquidity in the domestic currency in case of a dollar liquidity shock, the euro borrowing constraint is non-binding and $l_e = 0$. When the central bank provides sufficient liquidity in dollars (e.g., through central bank swap lines) in case of an external dollar shortage shock, the dollar borrowing constraint is non-binding and $l_d = 0$.

The analytical results discussed here are derived in the Online Appendix based on

Table 1: Model Results

	\$ liquidity shock no euro slackness	\$ liquidity shock euro slackness	u-shock no dollar slackness	u-shock dollar slackness
$\Delta L_1^{€}$	$\frac{-0.5\tilde{\nu}}{\eta W_0+\tilde{\nu}}\epsilon^b$	0	0	0
$\Delta L_1^{\$}$	$-\frac{\eta W_0+0.5\tilde{\nu}}{\eta W_0+\tilde{\nu}}\epsilon^b$	$\frac{-\eta W_0}{\eta W_0+0.5\tilde{\nu}}\epsilon^b$	$\frac{-0.5\eta W_0}{\eta W_0+0.5\tilde{\nu}}\epsilon^u$	0
$\Delta B_1^{€,w}$	0	$\frac{0.5\tilde{\nu}}{\eta W_0+0.5\tilde{\nu}}\epsilon^b$	$\frac{-0.5\eta W_0}{\eta W_0+0.5\tilde{\nu}}\epsilon^u$	$-0.5\epsilon^u$
$\Delta B_1^{\$,w}$	$-\epsilon^b$	$-\epsilon^b$	0	$0.5\epsilon^u$
ΔS_1	$\frac{0.5\tilde{\nu}}{\eta W_0+\tilde{\nu}}\epsilon^b$	$\frac{0.5\tilde{\nu}}{\eta W_0+0.5\tilde{\nu}}\epsilon^b$	$\frac{-0.5\eta W_0}{\eta W_0+0.5\tilde{\nu}}\epsilon^u$	$-0.5\epsilon^u$
$\Delta(f_1 - s_1)$	$\frac{0.5\eta\tilde{\nu}}{\eta W_0+\tilde{\nu}}\epsilon^b$	$\frac{0.5\eta\tilde{\nu}}{\eta W_0+0.5\tilde{\nu}}\epsilon^b$	$0.5\frac{\eta W_0+\tilde{\nu}}{W_0+(0.5/\eta)\tilde{\nu}}\epsilon^u$	$0.5\eta\epsilon^u$

marginal shocks ϵ^b and ϵ^u. Table 1 provides a summary of the results for the four scenarios. We set $\nu_d = \nu_e = \nu$. The parameter $\tilde{\nu} = \gamma\sigma^2 + \nu W_0$ is linearly related to ν. Since the probability of default does not change to the first order, wholesale dollar and euro funding rates do not change either. They are therefore not reported. As shown in Table 1, the results depend importantly on ν and η, which capture, respectively, the cost of selling loans and conducting swap market transactions.

3.1 Dollar Liquidity Shock

The results in the first two columns of Table 1 can be summarized as follows.

Result 1 *Assume a dollar liquidity shock reduces dollar lending to banks by ϵ^b.*

- *When there is no euro slackness, banks sell both euro loans and dollar loans, totaling ϵ^b. The resulting net long dollar position is offset by buying dollar swaps. This raises the swap rate and CIP deviation.*

- *When there is euro slackness, banks borrow more euros. The additional borrowing reduces the need to sell loans. Banks do not sell euro loans and sell fewer dollar loans than in the absence of euro slackness. They have a larger net long dollar position on the balance sheet than in the absence of euro slackness. This leads to a larger increase in demand for dollar swaps, a larger increase in the swap rate and CIP deviation.*

- *The extent of these changes is significantly affected by the cost of selling loans, ν, and the cost of conducting swap market operations, η.*

In general, banks have three ways to adjust their balance sheet to reduced dollar funding. They can reduce dollar lending, reduce euro lending and increase euro borrowing. To the extent that they either reduce euro lending or increase euro borrowing, they will be net long dollars on the balance sheet and therefore also need to buy dollar swaps.

Without euro slackness, banks have no choice but to sell loans by a total of ϵ^b due to the dollar liquidity shock. The only choice banks have is how many euro loans versus dollar loans to sell. Even though it is a dollar liquidity shock, there are two diversification reasons to sell both euro and dollar loans. The first reason is risk diversification of the loan portfolio. The second reason is that the discount on selling loans rises the more loans (in a particular currency) banks sell. They therefore wish to diversify the sales between euro and dollar loans.

On the other hand, the more euro loans banks liquidate, the more they will be net long in dollars, forcing the purchase of dollar swaps. It is costly for banks to conduct off-balance sheet swap market transactions and it also raises the swap rate. This creates a tradeoff that depends critically on the cost of selling loans versus the cost of conducting swap market transactions (ν versus η).

The higher the cost of selling loans, the more banks wish to diversify by selling more euro loans. This reduces the sale of dollar loans, creating a larger net long dollar position on the balance sheet. This leads to a larger demand for dollar swaps and a larger increase in the CIP deviation.

On the other hand, a larger cost of conducting swap market transactions reduces the swap market position that banks are willing to take. They sell fewer euro loans and more dollar loans, reducing the on-balance sheet net long dollar position. Maybe surprisingly, the swap rate and CIP deviation rise more. Even though the swap market position of non-US banks is smaller, US banks are less willing to take the other side when η rises.

The response by banks is quite different when there is euro slackness. Banks borrow more euros, so that they do not have to sell as many loans. They do not sell any euro loans and sell fewer dollar loans. But this causes banks to be more net long in dollars than without euro liquidity. Banks then buy more dollar swaps, leading to a larger increase in the swap rate and CIP deviation.

Even with euro slackness, banks still face a tradeoff that depends on the cost of selling loans versus the cost of swap market operations. The higher the cost of selling loans, the more euros banks borrow and the fewer dollar loans they need to sell. But this leads to a larger net long dollar position, forcing banks to buy more dollar swaps and causing the swap rate to rise more.

A higher cost of conducting swap market transactions makes it less attractive for banks to have a net long dollar position on the balance sheet. They borrow fewer euros and sell more dollar loans. Even though non-US banks choose a smaller swap market position, the CIP deviation still rises more as a result of US banks being less willing to take the other side.

3.2 External Dollar Shortage Shock

The results in the last two columns of Table 1 can be summarized as follows.

Result 2 *Assume that an external dollar shortage shock (rise in u) raises demand for synthetic dollar funding and therefore demand for dollar swaps.*

- *Both with and without dollar slackness the increased demand for dollar swaps raises the swap rate and CIP deviation. Banks sell dollar swaps as a result, creating a long dollar forward position.*
- *Without dollar slackness banks offset the off-balance sheet long dollar position by reducing dollar lending and reducing euro borrowing.*
- *In the presence of dollar slackness banks offset the off-balance sheet long dollar position by increasing dollar borrowing and reducing euro borrowing, without changing dollar or euro lending. The swap rate and CIP deviation rise less than without dollar slackness.*
- *The cost of selling dollar loans and the cost of conducting swap market operations affect changes in on and off balance sheet positions without dollar slackness, but not with dollar slackness.*

This shock is very different as it originates outside the banks. The rise in the CIP deviation is then essentially exogenous to banks. The higher dollar swap rate incentivizes banks to sell dollar swaps. This makes banks net long in forward dollars off the balance sheet.

Without dollar slackness, banks offset this by selling dollar loans and borrowing fewer euros. A higher cost of selling dollar loans makes this less attractive. The sale of dollar loans and reduction in euro borrowing are then smaller and banks sell fewer dollar swaps. As a result, the swap rate and CIP deviation rise more. A higher cost of conducting swap market transactions leads to a higher equilibrium CIP deviation. Even though the cost of conducting swap market transactions is higher, as a result of the higher CIP deviation banks sell more dollar swaps and dollar loans.

When there is dollar slackness, the Lagrange multipliers for both dollar and euro borrowing are zero. This implies that the demand for dollar swaps is the same for US and non-US banks, equal to $-(f_1 - s_1)/\eta$. As a result, the increase in demand for dollar swaps by ϵ^u external to the banks implies that in equilibrium both US and non-US banks sell $0.5\epsilon^u$ dollar swaps. This leads to a net dollar forward position of $0.5\epsilon^u$, which banks offset by borrowing $0.5\epsilon^u$ more dollars and equally reducing euro borrowing. Both on-balance sheet and off-balance sheet transactions are then unaffected by the cost of selling loans and conducting swap market transactions.

4 Numerical Results

The analytical solution provides useful insights for small shocks. In this section, we quantify the impact of dollar funding shocks with a numerical solution of the model. In this case, shocks are no longer small and have implications for the net worth of banks and the probability of default. The probability of default also affects bank borrowing rates. In addition, a drop in net worth has an amplifying effect on the balance sheet of banks, forcing banks to sell off more loans than the decline in its wholesale borrowing would imply. This may also lead to bank-runs.

The first step towards a numerical solution is to calibrate the model parameters. We first describe data that we use to calibrate on and off-balance sheet positions of the non-US banks. After that we discuss the calibration of some of the other parameters. We then present the quantitative impact of a dollar liquidity shock on on- and off-balance sheet positions, the CIP deviation and the probability of default. We compare the results with the data for the 22 episodes discussed in the Introduction. We also discuss the quantitative impact of an external dollar shortage shock. In Section 4.7 we also consider an extension where both shocks are combined.

4.1 Calibration

4.1.1 Bank Balance Sheet

We use bank balance sheet data both for the calibration of the model and for the event study in Figure 2. In both cases we use balance sheet data for the 40 largest non-US and non-Chinese G-SIB banks, which are headquartered in 14 countries.[13] The calibration is based on aggregate balance sheet data across all these 40 banks in Q4, 2022, while the event study is based on quarterly data from 2003 to 2022 and aggregates the banks by country. Here we provide a quick sketch of how the balance sheets of these banks are constructed, leaving full details to the Online Appendix.

The 40 banks are G-SIB banks for which the BIS has collected data as part of its annual G-SIB assessment since it started doing so in 2013. These are banks that have appeared on the BIS G-SIB main sample list every year from 2013 to 2022. For individual G-SIB

[13] The 14 countries are Germany, Spain, Finland, France, Italy, the Netherlands, Australia, Canada, Switzerland, Denmark, the UK, Japan, Singapore, and India. We exclude Chinese banks because China only started reporting to the BIS International Banking Statistics in Q4, 2015.

banks we obtain data about total assets, net worth, retail deposits and wholesale liabilities (total liabilities minus retail deposits) from S&P Global CapitalIQ. We will treat the retail deposits as being entirely in the local currency. Even though the local currency varies by country, we will continue to refer to it as the euro for simplicity.

While we can observe the total assets and liabilities of these global banks, the currency composition of those assets and liabilities is not observable. We therefore need to approximate the currency composition of the balance sheet. For this we turn to the BIS International Banking Statistics, which reports data at the country level. Total claims and liabilities, as well as the USD-denominated claims and liabilities, are calculated using a combination of the BIS Locational Banking Statistics by nationality (LBSN) and the Consolidated Banking Statistics (CBS), following the methodology described in Aldasoro and Ehlers (2018).

Since the BIS International Banking Statistics data are available at the country-level, we do not have data on the dollar assets and liabilities of individual banks. We approximate the share of a country's dollar assets and liabilities that are held by the G-SIB banks. We exploit the fact that 80-90% of a country's dollar assets and liabilities reported by the BIS are cross-jurisdictional (either cross-border assets and liabilities or locally booked by a bank's foreign affiliates).

We observe the cross-jurisdictional assets and liabilities of individual G-SIB banks from the annual G-SIB assessment by the BIS. These are totals across all currencies. We observe from the BIS International Banking Statistics the cross-jurisdictional assets and liabilities of all banks headquartered in a country. At the country level we can then compute the share of total cross-jurisdictional claims and liabilities booked by the G-SIBs headquartered in that country. This share varies from close to 100% in countries like the UK, Canada, Australia, and Spain to as low as 50% in Japan. On average across our 14 countries this share is around 73%.

For each country, we approximate the share of the USD claims and liabilities from the BIS International Banking Statistics that is held by G-SIB banks. Since the vast majority of USD denominated claims and liabilities are cross-jurisdictional, we assume that this share is equal to the share of total cross-jurisdictional claims and liabilities in that country booked by the G-SIB banks. This gives us the dollar assets and wholesale dollar liabilities of G-SIB banks in each country. Non-dollar assets and liabilities are the residual.

This gives us quarterly data from 2003 to 2022 of balance sheets of the aggregate of the G-SIB banks in each of the 14 countries, which we use for the event study in Figure 2. In addition, for Q4, 2022, we sum the data across all 40 G-SIB banks to calibrate the model. This is reported in Table 2.[14]

[14] Dollar assets in 2022 in Table 2 are \$8.8T. We can compare this to total dollar assets of all non-US banks in 2022 of \$15.4T, as shown in Figure 1. There are two differences. First, Table 2 applies to non-US banks of 14 countries. There are an additional \$3.4T dollar claims by non-US banks in other countries, including

We assume that the balance sheet in Table 2 is representative for all G-SIB banks. We use these balance sheet data (converted to trillions of dollars) to calibrate the first seven model parameters in Table 3, with one modification. For now we will assume that in period 0 (and the pre-shock equilibrium in period 1) dollar assets are equal to dollar liabilities and euro assets are equal to total assets minus dollar assets. Banks then choose a zero swap market position. In Section 4.7 we consider an extension where we vary the pre-shock net dollar position (and therefore swap market position), but for now we assume that dollar assets are simply equal to dollar liabilities.

Table 2: Balance Sheet non-US G-SIB banks, Q4 2022 ($bln.)

Assets		Liabilities	
$L^{€}$: euro assets	38651	W: net worth	2579
$L^{\$}$: dollar assets	8801	$B^{€}$: € retail deposits	25326
		$B^{€,w}$: € wholesale borrowing	11565
		$B^{\$,w}$: $ wholesale borrowing	7982
Total	47452	Total	47452

Note: For data description see Section 4.1.1.

4.1.2 Other Parameters

Table 3 also reports the values of other model parameters. We set d, the mean default rate on bank loans, equal to 0.03. This corresponds to the annual default rate of entrepreneurs in Bernanke et al. (1999).

We set σ, the standard deviation of the default rate on loans, to match a probability of bank default of 0.005. This 50 basis point bank default probability is based on Moody's daily EDF (expected default frequency) for the 40 banks. For each bank we take the average over the 2003-2022 sample, after which we average over the banks.

As discussed in Section 2.9, we set $u = 0$, which also implies a zero swap rate in the pre-shock equilibrium. We set the rate of risk aversion γ of banks at 2 and the interest rate on safe assets at 0.02.

We set $\eta = 0.0025$ and $\nu = \nu_d = \nu_e = 0.2$, such that the model is consistent with the rise in the CIP deviation and probability of bank default observed for the 22 episodes of dollar liquidity shocks discussed in the introduction. We do this for the case of a binding euro borrowing constraint as the model's performance without a euro borrowing constraint

$1.4T dollar claims by Chinese banks. Second, Table 2 refers to non-US G-SIB banks. Dollar claims by all non-US banks in these 14 countries amount to $12T in 2022, of which 73 percent are held by G-SIB banks.

Table 3: Model Parameters

$L_0^€$	39.5	period 0 euro loans
$L_0^\$$	8	period 0 dollar loans
W_0	2.6	period 0 net worth
$B^€$	25.3	euro retail deposits
$B_0^{€,w}$	11.6	period 0 wholesale euro borrowing
$B_0^{\$,w}$	8	period 0 wholesale dollar borrowing
S_0	0	period 0 demand for dollar swaps by non-US banks
d	0.03	default rate on euro and dollar loans
σ	0.0222	standard deviation default rate euro and dollar loans
u	0	exogenous demand for dollar swaps
γ	2	bank risk-aversion
i^s	0.02	interest rate on safe euro and dollar assets
$f_0 - e_0$	0	period 0 swap rate=CIP deviation
η	0.0025	sensitivity demand dollar swaps to swap rate
$\nu_d = \nu_e$	0.2	parameter that captures cost of selling loans

(euro slackness) is inconsistent with the data. A comparison of the model results to the data for these 22 episodes is discussed in Section 4.2.3. Section 4.6 discusses an extension where $\nu_d \neq \nu_e$.

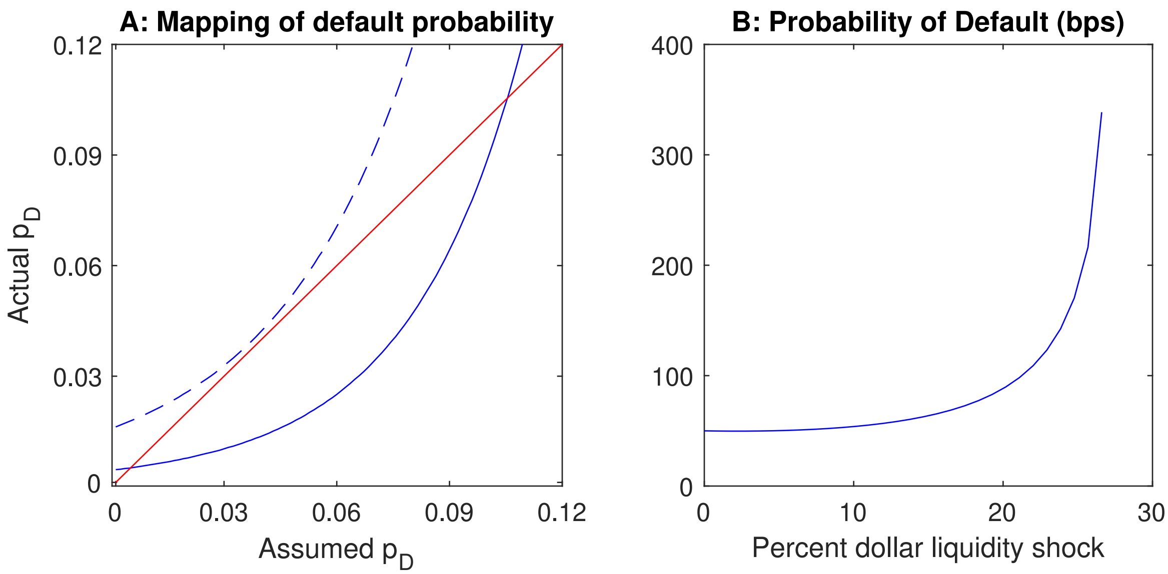
4.2 Endogenous Default Probability

In Section 3 we derived closed-form solutions for the change in the bank's balance sheet variables, its swap position, and the CIP deviation following a shock. However, to be analytically tractable, we assumed very small shocks, so that the bank probability of default remains unchanged. We now consider large shocks that lead to an endogenous change in the bank's probability of default.

Before illustrating this, we should point out that the calibrated parameters imply that we are in case ii) of Section 2.8 in which three equilibria exist, two no-run equilibria with different probabilities of default, and a self-fulfilling bank run equilibrium. As discussed in the Online Appendix, multiple equilibria exist when $\nu > 0.0126$. Since we set $\nu = 0.2$, we are well in this multiple equilibrium region.

For the no-run equilibria, the bank's probability of default can be found as the solution to a fixed point problem, where an assumed probability of default p_D determines the bank's interest rates on wholesale borrowing, which then affects the bank's balance sheet and its actual probability of default $p_D = Prob(W_2 < 0)$. For our calibrated parameters, and assuming a fixed euro borrowing constraint, the mapping from this assumed probability of default to the bank's actual probability of default is shown in panel A in Figure 3. The solid blue line is the mapping in the pre-shock state before any shock to dollar liquidity.

Figure 3: Default Probability



Notes: Chart A that shows a mapping from the assumed p_D to the actual p_D into itself for the benchmark parameterization (see Online Appendix for details). The solid blue line represents the pre-shock equilibria. In the lower equilibrium the default probability is 50 basis points. In the higher equilibrium it is 10.7 percent. The dashed line represents the mapping after a 27% dollar liquidity shock. It no longer intersects the 45 degree degree line, implying that there is no solution other than a bank run. Chart B shows the probability of bank default p_D as a function of the size of the dollar liquidity shock. The maximum size is 26.6%. After that there is no longer a solution.

Panel A in Figure 3 shows that in the pre-shock state there are two fixed points in this mapping from the assumed to the actual probability of default, corresponding to the two no-run equilibria. A high probability of default leads to high period 1 wholesale funding rates for the bank. This reduces the period 2 net worth, which increases the probability of default. However, the equilibrium with a higher probability of default is unstable. Any small perturbation in the assumed probability of default will cause the actual probability to move away from the fixed point. The only stable no-run equilibrium is the fixed point on the left with a default probability of around 50 basis points.

Dollar liquidity shocks shift the solid blue line in panel A up, leading to an increase in the bank default probability. How this default probability changes as a function of the size of the shock is shown in panel B of the Figure. For small and moderate sized dollar liquidity shocks the default probability remains small. The probability of default starts to rapidly increase when dollar liquidity shocks are above 20 percent, to well over 300 basis points.

This rapid increase in the probability of default is partly the result of a feedback loop between the wholesale funding rates and the probability of default. As the shock becomes larger, there are larger bank losses associated with the liquidation of assets. This raises the probability of default in period 2. This raises the wholesale dollar and euro funding rates, which then in turn further raises the probability of default.

This escalating feedback mechanism continues until the no-run equilibrium no longer exists. This is illustrated by the dashed-line mapping between the assumed and actual probability of default in panel A. This dashed line is drawn for a dollar liquidity shock of 27%. Here the mapping no longer intersects the 45-degree line and there is no longer a no-run equilibrium. This is further highlighted in panel B, where the probability of default as a function of the shock size asymptotes when the size of the shock approaches 26.6%. When a no-run equilibrium no longer exists we are in case iii) of Section 2.8, where the only equilibrium is a self-fulfilling bank run equilibrium.

4.3 Dollar Liquidity Shock

We now turn to dollar liquidity shocks of the size documented in Figure 2. Based on 22 episodes with a large drop in dollar funding, the average drop in wholesale dollar liabilities was 15.8%. We therefore consider a shock that tightens the wholesale dollar borrowing constraint by 15.8%. Table 4 shows the impact of the shock, both for the case where the euro borrowing constraint is binding and where it is non-binding. When it is binding we have $B_1^{€,w} \leq \bar{B}^{€} = B_0^{€,w}$. When it is non-binding we assume that $\bar{B}^{€}$ is sufficiently large that the constraint never binds.

Table 4 reports pre-shock and post-shock values of variables as well as changes from pre-shock to post-shock levels. Percentage changes are denoted with the percentage sign. The dollar swap market position is shown as a fraction of all bank assets. The CIP deviation and probability of default are in basis points.

4.3.1 Binding euro borrowing constraint

When the euro borrowing constraint is binding, banks cannot solve the dollar funding problem by borrowing more euros. Their euro borrowing is unchanged. This implies a need to reduce lending by an amount equal to the drop in wholesale dollar funding. But there is an amplifying effect as selling assets reduces their prices, which reduces the net worth of banks. Overall lending therefore drops a little more than the drop in wholesale funding. The drop in lending is almost equally divided between euro and dollar lending. But since euro lending

Table 4: Impact of Dollar Liquidity Shock

	€ borrowing constraint binding			€ borrowing constraint not binding		
	pre-shock	post-shock	change	pre-shock	post-shock	change
euro lending	39.5	38.8	-1.9%	39.5	39.5	0%
dollar lending	8	7.25	-9.3%	8	7.97	-0.4%
wholesale euro borrowing	11.6	11.6	0%	11.6	12.83	10.6%
wholesale dollar borrowing	8	6.74	-15.8%	8	6.74	-15.8%
net worth	2.6	2.38	-8.5%	2.6	2.6	0%
$ swap position (% assets)	0	1.09	1.09	0	2.6	2.6
CIP deviation (bps)	0	13	13	0	31	31
probability default (bps)	50	66	16	50	50	0
percent discount euro loans	0	14.8	14.8	0	0	0
percent discount dollar loans	0	14.9	14.9	0	0.62	0.62
interest rate € borrowing (%)	2.51	2.68	0.17	2.51	2.52	0.01
interest rate $ borrowing (%)	2.51	2.68	0.17	2.51	2.52	0.01

Notes: The results are based on the benchmark parameters shown in Table 3. The dollar liquidity shock involves a 15.8 percent tightening of the dollar borrowing constraint relative to the pre-shock equilibrium, where banks can borrow up to the level of period 0 dollar borrowing.

is considerably larger, percentage-wise dollar lending drops much more than euro lending (9.3% versus 1.9%).

The net worth of banks drops by 8.5%. This causes the probability of bank default to increase from 50 to 66 basis points. It also raises the euro and dollar wholesale funding interest rates by 17 basis points.

Since dollar borrowing drops more than dollar lending, banks are net long in dollars on the balance sheet by about $0.5T. To offset this, banks take an equal short dollar off-balance sheet position by buying dollar swaps. This raises the swap market position to just over one percent of bank assets. The demand for dollar swaps by banks raises the CIP deviation by 13 basis points.

4.3.2 Euro borrowing constraint not binding

When the euro borrowing constraint does not bind, banks offset the decline in dollar funding by borrowing more euros. Table 4 shows that the decline in dollar borrowing is almost perfectly offset by an equal increase in euro borrowing. As a result, euro loans are not liquidated at all, while dollar loans decline by only 0.4%. Banks therefore have a very large long dollars position on the balance sheet. They buy an equal amount of dollar swaps to balance out this dollar exposure. This amounts to 2.6% of bank assets. It causes a 31 bps increase in the swap rate or CIP deviation.

Since banks sell very few loans, they experience virtually no losses from loan liquidation. The period 1 net worth of banks is therefore unaffected and neither is the probability of bank default.

4.3.3 Comparison to the Data

Table 5 compares the model results just discussed to the data. The data moments are based on the 22 episodes with a decline in wholesale dollar funding of at least 10% discussed in the introduction. Figure 2 shows the average of balance sheet variables, the CIP deviation and EDF (probability of default) during the quarters prior to and after the start of these episodes. In Table 5 we convert this to a single measure of change for each of these variables.

We make a distinction between balance sheet variables and price-based variables. Balance sheet variables change slowly. We see in Figure 2 that the decline in wholesale dollar funding takes place over 4 quarters. With $T = 0$ being the start of the events, we compute the change in balance sheet variables as the percentage change from the average level over $[T-4, T-1]$ to the average level over $[T+4, T+7]$. For the swap market position we report the change in the position as a percentage of all bank assets.

The CIP deviation and EDF are different variables as they are price-based and therefore respond more quickly. For these variables, we report the change from the average level over $[T-4, T-1]$ to the average level over the subsequent 4-quarter period $[T, T+3]$.

Table 5 shows that the model fits the data well with a euro borrowing constraint. Three of these variables are targeted: the 15.8% drop in wholesale dollar borrowing as well as the changes in the CIP deviation and probability of default. But the other variables are also broadly consistent with the data. This is not the case for the model without a binding euro borrowing constraint. The 10.6% increase in euro borrowing is much larger than in the data. Dollar lending is virtually unchanged, but drops 8.4% in the data. Net worth and the probability of default are unchanged, while the increase in the swap market position and CIP deviation are much too large.

We set η and ν to target the change in the CIP deviation and probability of default with a binding euro borrowing constraint. But adjusting these parameters in the case where the euro borrowing constraint does not bind does not help improve the performance of the model. We can reduce the increase of the CIP deviation by lowering η, but changing either η or ν does not otherwise improve the performance of the model. It remains the case that net worth and the probability of default change very little, dollar lending does not fall much and euro borrowing rises far too much.

It is also possible to consider an intermediate case where there is some slack in euro

Table 5: Dollar Liquidity Shock: Data versus Model

	Data	Model	
		no euro slack	euro slack
euro lending	-1.7%	-1.9%	0%
dollar lending	-8.4%	-9.3%	-0.4%
wholesale euro borrowing	2.1%	0%	10.6%
wholesale dollar borrowing	-15.8%	-15.8%	-15.8%
net worth	-4.7%	-8.5%	0%
$ swap position (% assets)	0.75	1.09	2.6
CIP deviation (bps)	12.8	13	31
probability default (bps)	16.3	16	0

Notes: The data column refers to the average across 22 episodes where wholesale dollar liabilities between T+1 and T+4 are at least 10% lower than between T-3 and T. For all balance sheet variables the table reports the percentage change of the average over quarters [T-4,T-1] to the average over quarters [T+4,T+7]. For the CIP and probability of default (EDF), the data column reports the change of the average over quarters [T-4,T-1] to the average over quarters [T,T+3]. Model results are based on the benchmark parameters shown in Table 3 and a tightening of the wholesale dollar borrowing constraint by 15.8% relative to the pre-shock equilibrium. Euro slackness refers to the absence of a wholesale euro borrowing constraint (or one that is sufficiently slack so that it does not bind).

borrowing. Rather than removing the borrowing constraint altogether, we could relax the euro borrowing constraint by a small 2%. This may also be the result of the central bank providing euro liquidity rather than an increase in wholesale euro borrowing. The model can then by construction explain the small 2% increase in wholesale euro borrowing that we see in the data. But this is a small change in the euro borrowing constraint. As a result, the model results otherwise remain very close to the case we report where the euro borrowing constraint remains unchanged.[15]

4.4 External Dollar Shortage Shock

Table 6 reports results when there is an external dollar shortage shock that leads to an increase in demand for synthetic dollar funding and dollar swaps by $\epsilon^u = 2$. The size of the shock is not connected to any data. The results are reported both for the case of a binding and a non-binding dollar borrowing constraint. A binding dollar borrowing constraint implies that $B_1^{\$,w} \leq \bar{B}^{\$} = B_0^{\$,w}$. A sufficiently large $\bar{B}^{\$}$ implies that the dollar borrowing constraint will never bind. While a dollar liquidity shock directly affects the balance sheet of a bank,

[15]In that case we need to slightly adjust ν and η to make sure that we continue to match the observed change in the CIP deviation and probability of default.

forcing it to make adjustments, this shock is external to banks and only affects them through a rise in the swap rate or CIP deviation.

4.4.1 Binding dollar borrowing constraint

When the dollar borrowing constraint binds, the CIP deviation increases by 49 basis points. The higher swap rate incentivizes banks to sell dollar swaps, so that they are long in dollars off the balance sheet. They need to take an offsetting short dollar position on the balance sheet. But since banks cannot borrow dollars, they can only do so by selling dollar loans. However, selling loans is costly. As a result, even though the CIP deviation increases by a considerable 49 basis points, banks only sell dollar swaps equal to 0.05% of bank assets and reduce dollar lending by only 0.3%.

The impact on banks is therefore very small. Net worth and the probability of default are unchanged. The shock mainly hurts borrowers of synthetic dollars external to banks, who need to pay a substantially higher interest rate.

Table 6: Impact of External Dollar Shortage Shock

	$ borrowing constraint binding			$ borrowing constraint not binding		
	pre-shock	post-shock	change	pre-shock	post-shock	change
euro lending	39.5	39.5	0%	39.5	39.5	0%
dollar lending	8	7.98	-0.3%	8	8	0%
wholesale euro borrowing	11.6	11.58	-0.2%	11.6	10.6	-8.6%
wholesale dollar borrowing	8	8	0%	8	9	12.5%
net worth	2.6	2.6	0%	2.6	2.6	0%
$ swap position (% assets)	0	-0.05	-0.05	0	-2.1	-2.1
CIP deviation (bps)	0	49	49	0	25	25
probability default (bps)	50	50	0	50	50	0
percent discount euro loans	0	0	0	0	0	0
percent discount dollar loans	0	0.49	0.49	0	0	0
interest rate € borrowing (%)	2.51	2.51	0	2.51	2.51	0
interest rate $ borrowing (%)	2.51	2.51	0	2.51	2.51	0

Notes: The results are based on the benchmark parameters shown in Table 3. The external dollar shortage shock is $\epsilon^u = 2$.

4.4.2 Dollar borrowing constraint not binding

When the dollar borrowing constraint is not binding, banks can sell dollar swaps and offset the resulting long dollar position by borrowing dollars wholesale. Without any dollar borrowing constraint, banks increase dollar borrowing by 12.5% and sell dollar swaps equal to 2.1% of assets. There is a decrease in euro borrowing that is equal to the increase in dollar borrowing. Banks essentially replace synthetic dollar borrowing with wholesale dollar borrowing.

The impact on non-US banks is again small. There is no change in either dollar or euro lending. Bank net worth and the probability of default are again unaffected. Since non-US banks now sell a lot more dollar swaps than with a binding dollar borrowing constraint, the CIP deviation rises less, by 25 basis points.

4.4.3 Link between CIP deviations, probability of default and dollar lending

Barajas et al. (2020) find that a rise in the CIP deviation reduces cross-border lending by non-US banks and increases their probability of default. An exogenous increase in the CIP deviation that they have in mind fits well with the exogenous external dollar shortage shock considered here. Nonetheless we find that an increase in the CIP deviation is not accompanied by a rise in the probability of default of banks and also leaves dollar lending virtually unchanged. A possible explanation may be that the CIP deviation is not entirely exogenous. We have seen that a dollar liquidity shock simultaneously raises the probability of default, lowers bank dollar lending and raises the CIP deviation. So these variables are more likely to be closely connected as a result of a shock that directly affects banks.

4.5 Dollar Liquidity Shock in a Single Country

As shown in Appendix A, at any point in time only a limited number of countries are hit by a large dollar liquidity shock. By contrast, in our analysis so far we have implicitly assumed that all non-US countries are simultaneously hit by the same dollar liquidity shock. We have treated the non-US world as a single country in the theory and the empirical application. What would happen if just one or a few countries experience a dollar liquidity shock and the others do not? In terms of trillions of dollars the total size of the shock will obviously be much smaller than in the exercise above. But more relevant, in terms of percentage changes of balance sheet variables, CIP deviation and default probability, would the results be much different than we just reported?

The answer depends partially on the extent of cross-currency CIP arbitrage, which we refer to as CIP arbitrage between currencies other than the dollar. Consider a shock to Japan that raises the CIP deviation for the yen relative to the dollar. If CIP deviations relative to the dollar do not change for other currencies, there is a potential for cross-currency CIP arbitrage. It would for example be profitable to borrow euros, invest in yen and swap those yen into euros. As investors sell yen forward, the yen forward rate depreciates. This will also be the case for the dollar/yen forward rate. This cross-currency arbitrage then reduces the increase in the CIP deviation of the yen relative to the dollar. At the same time CIP deviations of other currencies relative to the dollar will rise.

Under perfect cross-currency arbitrage, CIP holds for currency pairs not involving the dollar. In that case, we can think of a single CIP deviation of all currencies relative to the dollar. That is clearly not correct as we observe significant variation across currencies in the CIP deviation relative to the dollar. But more generally, would allowing for partial cross currency CIP arbitrage affect the results when a single country is hit by a dollar liquidity shock?

We believe that it would have very little effect. In the extreme of no cross-currency CIP arbitrage, the results reported above remain exactly the same (with a scaled down balance sheet). To the extent that there is cross-currency CIP arbitrage, the CIP deviation changes less. But in the calibration we set η to match the observed change in the CIP deviation in the data. We then need to increase the value of η to match the observed increase in CIP deviations during dollar liquidity shocks. But as we discuss below, other than the CIP deviation, η has virtually no effect on the results in the model. This is related to the finding above that an increase in the CIP deviation due to an external dollar shortage shock has very little effect on the net worth of banks, their probability of default and both dollar and euro lending.

4.6 Policy Implications

We now address the role of central bank policy, both dollar liquidity (e.g., through central bank dollar swap lines) and domestic currency liquidity. The broad message is that central bank liquidity provision is mostly useful in staving off the worst possible outcomes. For more modestly sized dollar liquidity shocks that we document in Figure 2, the benefits are limited.

Really bad outcomes come in different forms. First, there may be self-fulfilling bank runs even in the absence of any dollar liquidity shock. This may happen even without dollar assets and liabilities on the balance sheet. It is well known that liquidity provision by the central bank can help avoid such bank run equilibria. In our case, both dollar and domestic currency liquidity can avoid such outcomes. Even if we rule out a run on domestic currency wholesale deposits by assuming that the central bank will ultimately bail out these lenders (as we will consider in sensitivity analysis), there could still be self-fulfilling bank runs based on dollar wholesale liabilities. The very existence of a dollar swap line can avoid such equilibria, even without ever using the swap line.

Second, there may be substantial dollar liquidity shocks beyond the size that we have observed. We have seen that for larger dollar liquidity shocks, the effect of the shock on the endogenous probability of default is highly non-linear. A feedback loop develops where the increase in the bank's probability of default, due to losses associated with assets sales, raises the cost of borrowing, which further raises the probability of default. Providing even a limited amount of dollar liquidity can avoid this feedback loop and avoid a really bad outcome. In contrast to the case of self-fulfilling bank runs discussed above, this requires the actual uptake of dollar swap lines. Related to this, even for a more modestly sized dollar liquidity shock, there may be a concern that a further decline in wholesale dollar funding will push banks into this bad feedback loop. Taking up dollar swap lines may be a precautionary measure to avoid getting there, or worse, getting to the region where only a self-fulfilling bank run exists, as illustrated in panel A of Figure 3.

Third, there could also be acute short-run dollar liquidity needs by global banks. Such high-frequency events are not captured in our model. In our theory, the bank makes balance sheet adjustments to respond to dollar liquidity shocks. In practice, such adjustments can take some time, which banks may not have when faced with an immediate dollar liquidity shortage. In that case, a quick inflow of dollars through the central bank and central bank swap lines may be critical.

All of that said, the benefits from dollar or domestic currency liquidity provision are limited when focusing on the no-run equilibria with more moderately sized dollar liquidity shocks that we have observed in the data. The same also applies to external dollar shortage shocks. We have seen that both shocks have limited effects on banks. An increase in the CIP deviation due to external dollar funding shortages has very little effect on bank balance sheets, nor on bank stability as captured by their probability of default. Dollar liquidity shocks can have a substantial effect on bank balance sheets, in particular reducing dollar lending. But again, net worth and the probability of bank default are minimally affected. From the perspective of bank stability, then, the gains from dollar swap lines appear to be limited.

While our focus has been on banks, non-banks are affected as well, both through a decline in dollar lending by non-US banks under dollar liquidity shocks and through a rise in the CIP deviation. Bank dollar borrowers are often located in other jurisdictions, which may not be the prime concern of the cental bank in question. They could also substitute towards synthetic dollar funding. A rise in the cost of synthetic dollar funding is relevant mainly for external dollar shortage shocks as we have seen that dollar liquidity shocks only increase the CIP deviation slightly. The recent literature has shown that cental bank dollar swap lines can lower the cost of synthetic dollar funding. At the same time, our model implies that providing dollar liquidity directly to non-banks is a more efficient response to external dollar shortage shocks. We see in Table 6 that providing unlimited dollar liquidity to banks only reduces the increase in the CIP deviation by half, while banks do not increase their dollar lending. This is the result of the cost that banks face in taking swap market positions.

The alternative of providing liquidity in the local currency is also inefficient. First, it is of no use when there is an external dollar shortage shock. We have seen that in that case banks wish to reduce their local currency borrowing. With dollar liquidity shocks, we see from Table 4 that providing local currency liquidity reduces the rise in the bank default probability. But the increase was never large in the first place. Moreover, providing local currency liquidity actually makes matters worse for non-banks. Table 4 shows that it more than doubles the increase in the CIP deviation, which hurts firms and financial institutions external to banks that rely on synthetic dollar funding. This occurs because domestic currency liquidity leads banks to sell fewer loans, including dollar loans. They are therefore longer in dollars. They buy more dollar swaps to offset the dollar exposure, which increases the swap rate and CIP deviation.

4.7 Sensitivity Analysis and Extensions

In the Online Appendix we show how the response to dollar liquidity shocks depends on key parameters. We also consider various extensions. Here we only briefly summarize these results.

The key parameters of the model are ν and η, which we have set at respectively 0.2 and 0.0025. In the Online Appendix we vary ν from 0 to 0.3 and η from 0 to 0.01. Unless we set ν very close to zero (below 0.01), so that euro and dollar assets are perfectly liquid, we find that ν only affects the probability of default and only when the euro borrowing constraint is binding. An increase in ν implies a higher cost of asset liquidation, which raises the probability of default. When assets become perfectly liquid (ν is very close to zero), banks only sell dollar loans and hold the swap market position at zero. The CIP deviation is also unaffected. Changing η has even less effect on the results. As expected, a higher value of η implies a larger increase in the CIP deviation in response to the shock. But other variables are virtually unaffected.

We also consider how results are affected when we allow the cost of liquidating euro and dollar loans to differ. We vary $\nu_d - \nu_e$, while keeping their average value equal to 0.2. In one extreme $\nu_d = 0$ and $\nu_e = 0.4$, so that there is no cost to liquidating dollar loans, but a high cost to liquidating euro loans. Banks then naturally sell dollar loans when faced with a dollar liquidity shock. Dollar assets and liabilities drop equally and the swap market position remains zero. The CIP deviation is unaffected by the shock. At the other extreme, where $\nu_d = 0.4$ and $\nu_e = 0$, the cost of selling dollar loans is so high that banks will not sell any dollars loans. When the euro borrowing constraint binds, they will instead sell euro loans, which they can do without any cost. But this creates a larger net long dollar position on the balance sheet. This leads to a larger demand for dollar swaps and a larger increase in the CIP deviation.[16]

Next we consider some extensions. In the first extension we allow the pre-shock synthetic dollar position to vary between -5% and +5% of bank assets. We next consider an extension that allows wholesale euro and dollar lenders to be risk-averse, with risk aversion rates varying between 0 and 2. After that we introduce an extension where a fraction $bail_e$ of obligations to euro wholesale lenders is bailed out by the government in case of bank default, with $bail_e$ varying from 0 to 1. We also consider an extension where the dollar borrowing constraint is strictly binding in the pre-shock equilibrium by raising the interest rate $i_0^{\$,l}$ on dollar loans (see also Appendix B). It turns out that the impact of a dollar liquidity shock on balance sheet variables, the synthetic dollar position, the probability of default and the CIP deviation are all virtually unaffected by these extensions.

We finally consider an extension that combines the 15.8% dollar liquidity shock with an external dollar shortage shock, with ϵ^u varying from 0 to 2. We have seen that external dollar shortage shocks mainly affect the CIP deviation. It is therefore not surprising that when the two shocks are combined, the only variable that is affected is the CIP deviation. The larger the external dollar shortage shock that we mix with a given dollar liquidity shock, the larger the rise in the CIP deviation.

5 Conclusions

Non-US global banks play a major role in lending dollars across the globe, including to the US. These dollar exposures are balanced by direct short-term dollar borrowing and synthetic dollar borrowing. This reliance on dollars represents a potential source of financial vulnerability for the global financial system in times of global dollar shortages. The model we have proposed enables us to investigate how non-US global banks react to dollar funding shocks, both dollar liquidity shocks that hit banks directly and external dollar shortage shocks. We have also investigated whether there is a role for central bank dollar swap lines or local currency liquidity to ameliorate the effects of these shocks.

For dollar liquidity shocks of the size observed in the data, as well as for external dollar shortage shocks, we found that the impact on bank stability is limited. Dollar liquidity shocks naturally generate balance sheet adjustments, but the impact on bank net worth and probability of default is zero or small for both shocks. Non-banks can be affected by an

[16] The probability of bank default rises most in the intermediate case where $\nu_e = \nu_d = 0.2$. This is because in the two extreme cases, banks avoid losses associated with selling loans. They only sell loans for which they do not incur any liquidation cost.

increase in the CIP deviation, raising their cost of synthetic dollar funding. However, the rise in the CIP deviation is small for dollar liquidity shocks.

The model can be extended in several directions. One natural extension is to more fully describe the non-bank sector. For example, reduced dollar lending to the non-bank sector could lead to an increase in demand for synthetic dollar funding, which feeds back to the swap market. Another extension, related to the discussion in Section 4.5, is to consider multiple non-US countries and currencies. This would allow us, for example, to consider how a dollar funding shock in one country or group of countries transmits to other countries. Finally, an extension could consider the implications for exchange rates that we have abstracted from.

Appendix

A Dollar Liquidity Crisis Events

In Figure 2 we plot the responses of bank balance sheet variables, the CIP deviation and the EDF around dollar liquidity crises. Specifically, we define the starting period T=0 of a dollar liquidity shock in country c to be a quarter where the average of USD liabilities from quarters T+1 to T+4 is at least 10% less than the average of USD liabilities from quarters T-3 to T. Period T=0 is the first period where this criterion is satisfied. After this period, we assume that there cannot be another dollar liquidity crisis in the same country for at least two years. Using this definition, Table A1 lists the 22 crisis events and the T=0 start date for our 14 counties between 2003 and 2022.

Table A1: Dollar Liquidity Crisis Events

Q3 2007	Switzerland	Q1 2011	Denmark
Q4 2007	Netherlands	Q1 2012	Switzerland
Q2 2008	Germany	Q2 2012	Netherlands
Q3 2008	Italy	Q3 2013	Denmark
Q3 2008	UK	Q2 2014	Japan
Q4 2008	France	Q3 2014	UK
Q4 2008	Denmark	Q2 2015	Singapore
Q1 2010	Spain	Q1 2016	India
Q1 2010	Netherlands	Q2 2019	India
Q4 2010	Italy	Q3 2020	Spain
Q1 2011	France	Q2 2021	Denmark

B Pre-Shock Equilibrium

In the pre-shock equilibrium all endogenous period 1 variables are equal to corresponding period 0 variables. Therefore $L_1^{\$} = L_0^{\$}$, $L_1^{€} = L_0^{€}$, $B_1^{\$,w} = B_0^{\$,w}$, $B_1^{€,w} = B_0^{€,w}$, $S_1 = S_0$, $W_1 = W_0$, $i_1^{\$} = i_0^{\$}$ and $i_1^{€} = i_0^{€}$.

This is accomplished as follows. First, we adjust σ to target a probability of default p_D of 0.005. This determines $i_1^{\$} = i^s + p_D$ and $i_1^{€} = i^s + (1 - bail_e)p_D$. In the main analysis we set $bail_e = 0$. We then set $i_0^{\$}$ and $i_0^{€}$ equal to these period 1 interest rates. From now on we drop the time subscript from wholesale dollar and euro funding rates as they are equal in periods 0 and 1.

It follows immediately from (12) that $W_1 = W_0$ when $L_1^{\$} = L_0^{\$}$ and $L_1^{€} = L_0^{€}$. Using $W_1 = W_0$ and setting loan levels in period 1 equal to those in period 0, it follows from (22)-(23) that

$$i_0^{€,l} = d + i^{€} + l_e + \gamma\sigma^2 L_0^{€}\frac{1}{W_0} \tag{B.1}$$

$$i_0^{\$,l} = d + i^{\$} + l_d + \gamma\sigma^2 L_0^{\$}\frac{1}{W_0} \tag{B.2}$$

Here we set $\mu_e = \mu_d = 0$. When these are the interest rates on bank loans, banks choose to keep loans unchanged, so that the constraints (16)-(17) do not bind.

Notice that $i_0^{€,l}$ and $i_0^{\$,l}$ depend on l_e and l_d. We will set $\bar{B}^{€} = B_0^{€,w}$ and $\bar{B}^{\$} = B_0^{\$,w}$. When banks without borrowing constraints ($l_e = l_d = 0$) choose to set period 1 wholesale euro and dollar funding equal to period 0 levels, the borrowing constraints are indeed not binding. We can then set $l_e = l_d = 0$ in the expressions above for $i_0^{€,l}$ and $i_0^{\$,l}$. We will show below that banks indeed choose period 1 wholesale funding levels that are equal to those in period 0.

Before we discuss the wholesale borrowing levels, first consider synthetic dollar borrowing. We assume $S_0 = \delta K$, where K is the total size of the balance sheet. We set $\delta = 0$ in most of the analysis (except for the sensitivity analysis in the Online Appendix). Since $B_0^{\$,w} + S_0 = L_0^{\$}$ and we take $B_0^{\$,w}$ as given, we set $L_0^{\$} = B_0^{\$,w} + \delta K$ and $L_0^{€} = K - L_0^{\$}$. We now need to make sure that $S_1 = S_0 = \delta K$. Using (21), together with $l_d = l_e = 0$, implies $f_1 - e_1 = i^{\$} - i^{€} - \eta\delta K$. This must be equal to the equilibrium swap rate in (26). It follows that we need to set

$$u = \frac{1}{\eta}(i^{\$} - i^{€}) - 2\delta K \tag{B.3}$$

In the main analysis $\delta = 0$ and $bail_e = 0$, so that $u = 0$.

We finally need to make sure that $B_1^{\$,w} = B_0^{\$,w}$ and $B_1^{€,w} = B_0^{€,w}$. We have from (6)- (7) that

$$B_1^{\$,w} = L_1^{\$} - S_1 \tag{B.4}$$

$$B_1^{€,w} = S_1 - W_1 + L_1^{€} - B^{€} \tag{B.5}$$

The same identities apply to period 0 as well. Setting $S_1 = S_0$, $W_1 = W_0$, $L_1^{\$} = L_0^{\$}$ and $L_1^{€} = L_0^{€}$, it indeed follows that $B_1^{\$,w} = B_0^{\$,w}$ and $B_1^{€,w} = B_0^{€,w}$.

This description of the pre-shock equilibrium also applies to the sensitivity analysis in the Online Appendix. The expression for the wholesale funding rates is slightly different when we assume risk-averse lenders, as discussed in the Online Appendix, but otherwise the pre-shock equilibrium is determined in the same way. The only case in the sensitivity analysis that is different is when we vary l_d. In the description above we assume that the dollar borrowing constraint does not strictly bind in the pre-shock equilibrium, so that $l_d = 0$. In the Online Appendix we vary the endogenous Lagrange multiplier l_d by letting $i_0^{\$,l}$ vary. It follows from (B.2) that l_d will then vary one-for-one with $i_0^{\$,l}$.

Since δ and $bail_e$ are held at zero when we vary l_d, $S_1 = S_0 = 0$ and $i^{\$} = i^{€}$. Using (21) then implies $f_1 - e_1 = l_d$. Equating this to the equilibrium swap rate in (26), it follows that we must set $u = l_d/\eta$.

References

Abbassi, Puriya and Falk Bräuning. 2020. "Demand Effects in the FX Forward Market: Micro Evidence from Banks' Dollar Hedging". *The Review of Financial Studies 34*, 4177–4215.

Aldasoro, Iñaki and Torsten Ehlers. 2018. "The Geography of Dollar Funding of non-US Banks". *BIS Quarterly Review, December*, 15–26.

Aldasoro, Iñaki, Torsten Ehlers, Patrick McGuire, and Goetz von Peter. 2020. "Global Banks' Dollar Funding Needs and Central Bank Swap Lines". *BIS Bulletin 27*.

Anderson, Alyssa, Wenxin Du, and Bernd Schlusche. 2025. "Arbitrage Capital of Global Banks". *The Journal of Finance*, forthcoming.

Bacchetta, Philippe, Scott Davis, and Eric van Wincoop. 2025. "Offshore Dollar Funding Shocks and the Dollar Exchange Rate". *Working Paper*.

Bahaj, Saleem and Ricardo Reis. 2022. "Central Bank Swap Lines: Evidence on the Effects of the Lender of Last Resort". *The Review of Economic Studies 89*(4), 1654–1693.

Barajas, Adolfo, Andrea Deghi, Claudio Raddatz, Dulani Seneviratne, Peichu Xie, and Yizhi Xu. 2020. "Global Banks' Dollar Funding: A Source of Financial Vulnerability". *IMF Working Paper 20/113*.

Barbiero, Omar, Falk Brauning, Gustavo Joaquim, and Hillary Stein. 2024. "Dealer Risk Limits and Currency Return". *Working Paper*.

Bernanke, Ben S., Mark Gertler, and Simon Gilchrist. 1999. "The Financial Accelerator in a Quantitative Business Cycle Framework". *Handbook of Macroeconomics 1*, 1341–1393.

Bohorquez, Diego. 2023. "The United States as the International Lender of Last Resort". *mimeo*.

Cerutti, Eugenio M, Maurice Obstfeld, and Haonan Zhou. 2021. "Covered Interest Parity Deviations: Macrofinancial Determinants". *Journal of International Economics 130*, 103447.

Committee on the Global Financial System (CGFS). 2020. "US Dollar Funding: An International Perspective". *CGFS Papers, No. 65*.

Du, Wenxin, Alexander Tepper, and Adrien Verdelhan. 2018. "Deviations from Covered Interest Rate Parity". *The Journal of Finance 73*(3), 915–957.

Eguren-Martin, Fernando, Matias Ossandon Busch, and Dennis Reinhardt. 2024. "Global Banks and Synthetic Funding: The Benefits of Foreign Relatives". *Journal of Money, Credit and Banking 56*, 115–152.

Eren, Egemen, Andreas Schrimpf, and Sushko Vladyslav. 2020. "US Dollar Funding Markets during the Covid-19 Crisis - The International Dimension". *BIS Bulletin 15*.

Ferrara, Gerardo, Philippe Mueller, Ganesh Viswanath-Natraj, and Junxuan Wang. 2022. "Central Bank Swap Lines: Micro-Level Evidence". *Bank of England Staff Working Paper No. 977*.

Gertler, Mark and Nobuhiro Kiyotaki. 2015. "Banking, Liquidity, and Bank Runs in an Infinite Horizon Economy". *American Economic Review 105*, 2011–43.

Global Financial Stability Report (GFSR). 2019. “Banks’ Dollar Funding: A Source of Financial Vulnerability.”. *IMF, Chapter 5*.

Goldberg, Linda S. and Fabiola Ravazzolo. 2022. “The Fed’s International Dollar Liquidity Facilities: New Evidence on Effects”. *NBER Working Paper No. 29982*.

Iida, Tomoyuki, Takeshi Kimura, and Nao Sudo. 2018. “Deviations from Covered Interest Rate Parity and the Dollar Funding of Global Banks”. *International Journal of Central Banking*, 275–325.

Ivashina, Victoria, David S. Scharfstein, and Jeremy C. Stein. 2015. “Dollar Funding and the Lending Behavior of Global Banks”. *The Quarterly Journal of Economics 130*(3), 1241–1281.

Kekre, Rohan and Moritz Lenel. 2024. “The High Frequency Effects of Dollar Swap Lines”. *AER: Insights*, forthcoming.

Keller, Lorena. 2024. “Arbitraging Covered Interest Rate Parity Deviations and Bank Lending”. *American Economic Review 114*, 2633–67.

Khetan, Umang. 2024. “Synthetic Dollar Funding”. *Working Paper*.

Kloks, Peteris, Edouard Mattille, and Angelo Ranaldo. 2024. “Hunting for Dollars”. *Swiss Finance Institute Research Paper 24-52*.

Kloks, Peteris, Patrick McGuire, Angelo Ranaldo, and Vladyslav Sushko. 2023. “Bank Positions in FX Swaps: Insights from CLS”. *BIS Quarterly Review, September*, 17–31.

Lengwyler, Yvan and Beatrice Weder di Mauro. 2023. “Global Lessons from the Demise of Credit Suisse”. *VoxEU.org, September*.

McCauley, Robert and Patrick McGuire. 2009. “Dollar Appreciation in 2008: Safe Haven, Carry Trades, Dollar Shortage and Overhedging”. *BIS Quarterly Review, December*, 85–93.

McGuire, Patrick and Goetz von Peter. 2009. “The US Dollar Shortage in Global Banking”. *BIS Quarterly Review, March*, 47–63.

McGuire, Patrick and Goetz von Peter. 2012. “The Dollar Shortage in Global Banking and the International Policy Response”. *International Finance 15*, 155–178.

Moskowitz, Tobias J., Chase P. Ross, Sharon Y. Ross, and Kaushik Vasudevan. 2024. “Quantities and Covered-Interest Parity”. *NBER Working Paper No. 32707*.

Rime, Dagfinn, Andreas Schrimpf, and Olav Syrstad. 2022. “Covered Interest Parity Arbitrage”. *The Review of Financial Studies 35*(11), 5185–5227.