The anatomy of a peg: lessons from China's parallel currencies *

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Abstract

China's current account transactions use an offshore international currency, the CNH, that co-exists as a parallel currency with the mainland domestic currency, the CNY. The CNH is freely used, but by restricting its exchange for CNY, the authorities can enforce capital controls. Sustaining these controls requires tight management of the money supply and liquidity to keep the exchange rate between the dual currencies pegged. After describing how the central bank implements this system, we find a rare instance of identified, exogenous, transitory increases in the supply of money and show that they depreciate the exchange rate. Theory and evidence show that elastically supplying money and using liquidity policies can maintain a currency peg. In turn, deviations from the CNH/CNY peg can be used as a pressure valve to manage the exchange rate between the yuan and the US dollar and avoid liquidity controls.

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1 Introduction

For more than a decade, the Chinese authorities have conducted a large-scale monetary experiment. The challenge was to reconcile an open current account with a closed capital account. An open current account, with free trade of goods over multiple destinations by the world's largest exporter and its second largest economy, comes with a large volume of payments across borders to settle imports and exports. A closed capital account, with tight restrictions on foreign investment and State control over savings abroad, requires strict control over any payments associated with financial inflows and outflows. The former provides a strong force for the yuan to be used internationally; the latter restricts the yuan to be a domestic currency.

The Chinese answer was to create an offshore currency, the Hong Kong yuan (CNH), that circulates in parallel with the onshore currency, the mainland yuan (CNY). The CNH is freely used for payments and investments by anyone outside of China. By mid-2023, there were ¥2 trillion worth in transactions per day in CNH across the world fueling 14% of global trade. The CNY, instead, is used for all domestic transactions and is required to invest in mainland China, but foreigners have limited access to it. By placing strict restrictions on the conversion of CNH to CNY and vice versa, the authorities can have tight capital controls co-existing with an internationally-used yuan.

Yet, this monetary system has the tension that is common in parallel currencies. Because Chinese firms, banks and households can exchange CNH for CNY subject to limits, if one currency were to persistently lose value relative to the other, these limits would come under severe strain and one of the currencies might stop being used (Gresham's law). The People's Bank of China (PBoC) has, since its inception, tried to keep a peg of one CNH to one CNY. It has succeeded through a deft management of the supply of CNH money, both by keeping money scarce and constraining currency exchanges, as well as by elastically expanding and contracting money to absorb shocks to demand. This has further required managing CNH liquidity through policies in response to the creation of private CNH money by financial intermediaries in Hong Kong, London, Singapore and other offshore centers that breaks the connection between the PBoC supply of CNH and its relative value (Goodhart's law). At the same time, deviations from the parity interact with another of the PBoC's policy, the management of the foreign exchange rate of the yuan with the US dollar (USD).

This paper uses this remarkable experiment to advance knowledge in five directions.

First contribution: Chinese capital controls and the CNH system. In spite of its peculiarities, the CNH monetary system is ultimately guided by using the supply of one money to peg an exchange rate. So far, it has been very successful, especially since 2017, following a wave of reforms in the preceding two years. Section 2 describes these institutions and concludes that the supply of CNH follows the standard mechanisms that are used by central banks to supply money all over the world.[1]

On the one hand, the peculiarities of CNH and CNY and their peg are unique. This includes having a single central bank (the PBoC) ultimately controlling the two monetary policies, while having a particular coordination with the policies of another central bank (the Hong Kong Monetary Authority, HKMA).[2] On the other hand, the Chinese experience of monetary policy and capital controls is interesting in its own right given the size of the Chinese economy in the international financial system.[3] Also, as the creation of the parallel currencies was a step towards internationalizing the yuan, this experience carries lessons for understanding why some currencies become used in international trade.[4] Further, other countries may in the future find this successful experiment appealing, and our paper describes how it worked.[5] Finally, ultimately the economic mechanisms connecting money and exchange rates are universal, and the Chinese experience provides a testing ground for classic questions in international economics.

Second contribution: money and exchange rates. By how much does a 1% increase in the domestic money supply depreciate the exchange rate? At one theoretical extreme,

[1] Our focus is on the CNH money supply; on CNY money supply and its relevance for mainland inflation, business cycles, and the banking sector, see Chen, Ren and Zha (2018).

[2] And yet, the US had an accidental experience in 1864 with some similarities. When the Confederacy was split in two by the civil war, the relative value of these parallel currencies diverged with changes in the relative supply of money, consistent with our results for China (Burdekin and Weidenmier, 2001). The CNH-CNY experience has several episodes with more accurate measurements and plausibly exogenous shocks to money alone with which we can more credibly test for the effect of money on exchange rates.

[3] By creating its own official parallel money market with its policy-managed arbitrage opportunities, Chinese authorities might have been able to prevent the appearance of a private offshore market, like the Eurodollar market. A comparison of CNH in the 2010s with Eurodollars in the 1970s is left for future work (see Friedman (1971)).

[4] Naef et al. (2022) provide a succinct description of some steps in this internationalization, including the role of the offshore CNH in the process, especially in relation to the CNY-USD exchange rate. Further, Bordo, Monnet and Naef (2019) establish a connection between the offshore Hong Kong market in the last decade, and the London gold market in the 1950s and 1960s during the process of internationalizaing the US dollar. We provide a more detailed description of how this system works, a model of the role of liquidity policies and controls in fostering it, and direct evidence on the interaction between the offshore-onshore exchange rate and the exchange rate between the yuan and the US dollar.

[5] There are close connections between the Chinese experience and those of European countries under Bretton Woods, which we hope to explore in future work.

the quantity theory states that the exchange rate would fall by 1%, and the experience of hyper-inflations provides some support. At the other extreme, when policy chooses the interest rate on reserves and money is a pure financial asset (say, because demand for liquidity has been satiated), then the effect would be zero, as arguably was the case when advanced economies undertook quantitative easing.

Empirically, Meese and Rogoff (1983) and many others have found no relation between measures of money and exchange rates. It is hard to pin down this link because of classic econometric problems. One is endogeneity, as the money supply usually follows money demand for a fixed policy interest rate that in turn often responds to the value of the exchange rate. Another is omitted variables, as exchange rates also depend on shocks to the other currency's money supply, the real exchange rate, or frictions to arbitrage, all of which may be correlated with money supply. And a third is measurement, across multiple types of money that are imperfect substitutes, and across time as forward-looking exchange rates respond in anticipation to fundamentals.[6]

The CNH regime overcomes some of these thorny empirical challenges since CNH deposits pay no interest, the policy rule is to keep CNH pegged to CNY, CNY monetary policy is set independently of the CNH/CNY exchange rate, and Chinese financial repression limits the emergence of alternatives. Section 3 exploits changes in the timing of CNH monetary operations by the PBoC between 2019 and 2021 that caused nine expansions in the money supply that were: exogenous, moderate in size (1.7% of deposits on average), and transitory (lasting one to two weeks). Using high-frequency data on the quantity of money controlled by the PBoC and the exchange rate during these event studies, we find that an average 1.7% increase in the supply of money causes a depreciation of the exchange rate by 0.18 percentage points. This maps to a semi-elasticity of money demand of 0.09, comparable to what is found in the literature that estimates money demand using interest rates, as opposed to exchange rates.[7]

[6]Progress has come from finding that measures of liquidity affect deviations from UIP (Engel and Wu, 2023), that foreign exchange interventions are effective (Bordo, Humpage and Schwartz, 2015), that quantitative easing announcements move the exchange rate (Dedola et al., 2021), and that the quantity of bonds in private hands affects their convenience yield (Jiang, Krishnamurthy and Lustig, 2021, Valchev, 2020, Gourinchas, Ray and Vayanos, 2022, Greenwood et al., 2023). But none of these studies estimate directly how much an increase in the stock of money changes the exchange rate.

[7]We follow in the tradition of Friedman and Schwartz (2008) narrative identification of shocks to the supply of money. The closest study is Velde (2009) that identifies three contractions in the money supply in France in 1724 and finds a quick appreciation in the exchange rate. These were large unanticipated shocks in a monetary regime quite different from the modern ones. Palma (2021) used the discoveries of precious metals in America, while Chodorow-Reich et al. (2019) exploited cross-regional variation during the Indian demonetization to identify exogenous shocks to the supply of coins and banknotes. We instead identify

Third contribution: the survival of parallel currencies. Chinese exporting firms and households can in principle make transactions with each other in either CNY or CNH. Capital controls impose restrictions on converting between CNH and CNY, so when they bind more intensely, the exchange rate will deviate from parity. But if these deviations are too large or persist for too long, Chinese capital controls would fail under the weight of arbitrage, as parallel currencies invariably do.[8]

Chinese CNH monetary policy is not independent since its overriding goal is to keep the deviations from the peg small and transitory. So far, it has been successful: since April 2017, the standard deviation of the daily exchange rate has been a mere 22 basis points with a serial correlation of 0.5. In theory, since the supply of CNH is scarce, keeping the peg and enforcing the capital controls requires having the money supply elastically absorb shocks to the demand for CNH. The PBoC does so at a weekly frequency, but at higher frequencies, this responsibility falls to the HKMA in order to preserve financial stability in Hong Kong.

Section 4 identifies shocks to the demand for CNH together with an instrument for their exogenous variation. It finds that the supply of CNH money from the HKMA increases to accommodate positive shocks to demand. The anatomy of this peg suggests that exchange rate pegs are not doomed to fail, and helps to identify which policies can succeed.

Fourth contribution: financial innovation and liquidity policies. When the public supply of money is scarce, the marginal transaction benefits of money is positive. Banks create private money through deposits, and are encouraged to financially innovate. Goodhart's law predicts that the relation between the money supply that is controlled by the central bank and the exchange rate would be lost. The peg would break, and the coexistence of the parallel currencies that allows for capital controls is in danger.[9]

Section 5 writes a model of the marginal benefit of liquidity that is consistent with the empirical effects of shocks to money demand and supply on the exchange rate.[10] The

shocks to reserves at the central bank, the conventional way in which central banks change the money supply in modern monetary systems. Monnet (2014) is closest in this regard, but we have richer and higher frequency data allowing us to more precisely pin down the monetary channels.

[8]On why and how parallel currencies fail, see Selgin (2020).

[9]Engel (2016) and Engel and Wu (2023) studied the connection between the liquidity benefits of assets, often called convenience yields, and the exchange rate in full macroeconomic models. We focus more deeply on identification of the effects, and on how both monetary and liquidity policies affect these convenience yields. That does not leave us space to lay out the implications for output or inflation, but we conjecture that these would follow the principles identified in those papers.

[10]The model is in the tradition of Poole (1968) and closer to the formulation in Bianchi and Bigio (2022).

model generates auxiliary predictions that we test in the data. First, that money demand shocks should come with higher interest rates in interbank markets.[11] Second, that they should lower the demand for CNH bonds. And third, that even as they raise the supply of money from the HKMA, they reduce the use of its discount window.

Financial innovation puts pressure on the peg and, in the limit, makes the dual currencies unsustainable.[12] Out of sample, the model suggests liquidity policies that could improve the management of the peg: reserve requirements, the interest rate in borrowing from the central bank, and helicopter drops of money or bills. Liquidity policies complement capital controls.[13]

Fifth contribution: foreign exchange rate management with a parallel currency. The PBoC uses a myriad of tools to prevent large fluctuations in the exchange rate between the yuan and the USD.[14] Section 6 inspects the role of the CNH/CNY parallel currencies in this goal. We show that deviations from the peg can work as an escape valve that attenuates movements in the CNY/USD exchange rate.

We further show that CNH liquidity policies are an extra tool to manage the exchange rate with the USD. At an extreme, a sharp tightening of liquidity controls can preserve capital controls when the yuan is sharply losing value. We discuss the Chinese experience in 2015-16, and how it validates the findings and theory in this paper. We further contrast it with the experience in May-August 2023 to show the robustness of the post-2017 liquidity framework.

Section 7 concludes.

2 The offshore market and the supply of CNH

While there is a single physical currency in China—the renminbi (RMB)—there are two separate digital currencies for bank deposits and for making electronic payments: the CNY used onshore in mainland China, and the CNH used offshore in international finan-

[11] Bianchi, Bigio and Engel (2021) also study how interbank market frictions play a role in exchange rates.

[12] We focus on financial innovation in the flow of liquidity; for the liberalization of bond and stock holdings, see Clayton et al. (2023) and He, Wang and Zhu (2023), respectively.

[13] We focus on the connection between capital controls and CNH. There is a rich literature on the impact of China's capital controls on mainland private credit, capital allocation, and financial stability, see Hachem and Song (2023), Song and Xiong (2018), He and Wei (2023).

[14] We take as given what drives the exchange rate between the yuan and the US dollar and how onshore monetary policy responds to it: see Jermann, Wei and Yue (2022) for their study, among many others.

cial centers, namely in Hong Kong.[15] A Chinese citizen or firm that deposits RMB into a bank in Shenzhen has a claim in CNY; a bank deposit a few miles away in Hong Kong is a claim in CNH. They are settled through separate real time gross settlement systems, have different interbank markets in which banks lend either CNH or CNY to each other, and distinct retail markets where firms can borrow either CNH or CNY from banks. There is a market exchange rate E stating how many CNY exchange for one CNH. An increase in $e = \log(E)$ is a depreciation of the domestic onshore yuan, the CNY, relative to the international offshore yuan, the CNH.

In what follows, we explain the institutions behind the CNH. First, we explain that the co-existence of CNH and CNY are the liquidity expression of Chinese capital controls. CNH can be used freely for foreign transactions, while CNY is used in mainland China. Chinese authorities impose strict controls in the exchange of CNY for CNH.

Second, we note that the capital controls can survive as long as the exchange rate between the two currencies does not deviate too far from one. Therefore, CNH monetary policy is subordinated to the explicit policy explicit policy target of keeping the CNH/CNY pegged at parity: $\mathbb{E}(e') = 0$, where e' is the exchange rate next period. We show that the peg has been very successful since April of 2017.

Third, we describe how the supply of CNH reserves is determined jointly by the PBoC, through conventional repurchase operations of central bank bills, and by the HKMA through a conventional lending program to large Hong Kong banks (the PLPs). The HKMA also operates a discount window. CNH monetary policy is set through the quantity of reserves, not interest rates. While its institutions and operations are peculiar, we show that they can be unpacked into standard conventional monetary mechanisms.

2.1 Parallel currencies and capital controls

Only Chinese nationals can hold CNY deposits. They can only be supplied by banks domiciled in China that have access to the onshore China National Advanced Payment System, which settles accounts via reserve balances at the PBoC. There are exceptions for foreigners authorized by the government but, broadly speaking, foreign citizens and institutions do not have unfettered access to the onshore financial market in mainland China and face strict limits in using CNY.

[15] Three quarters of offshore RMB transactions occur in Hong Kong, with London, Singapore and Taiwan being the other notable centers. We restrict ourselves to data from the Hong Kong centre, leaving for future work a comparison with the other offshore centers.

Instead, foreigners can hold deposits in CNH at will, make payments in CNH without restrictions, and convert CNH into foreign currency with no limits. The CNH deposits can be issued by foreign banks as well as by Chinese banks that have branches or subsidiaries offshore. In Hong Kong, the medium of exchange for transactions is a separate currency, the Hong Kong dollar. But, two Chinese economic agents that have accounts in both the mainland and Hong Kong and want to pay each other, can do so using their bank balances in either CNH or CNY.

Conversion of CNH for CNY, and vice versa, is subject to strict exchange controls. There are quotas on exchanging CNH and CNY for purposes of investment, whether into China using the CNY (through the Renminbi Qualified Foreign Institutional Investor program) or out of China using the CNH (through the Qualified Domestic Institutional Investor program). Additionally, households have an annual limit on how much they can transfer between CNH and CNY and vice versa, and shipping large quantities of RMB cash into and out of mainland China is forbidden, as are large cash deposits. Restrictions also apply to firms trying to export or import capital.

The major flows between CNH and CNY come from Chinese firms that sell abroad and receive payments in CNH (or in foreign currency that they can exchange freely for CNH). They can convert the CNH revenues to pay their CNY bills in mainland China only when they present the invoice behind their foreign sales. This gives large Chinese export firms the ability to build up CNH deposits and associated invoices, and earn CNH deposit rates or save in CNH bills, before converting these to CNY when there is an arbitrage opportunity.[16]

The other active arbitrageurs between CNH and CNY are the Chinese banks that have a presence offshore. They can borrow and lend in either CNY or CNH, as well as issue deposits in either, so in principle they can arbitrage differences in returns. However, again, cross-border interbank lending is controlled and limited.

In short, there are avenues for converting CNH into CNY if the exchange rate is not 1, or for arbitraging between financial investments in either currency if their returns are not the same. However, these trades of goods or assets are subject to strict controls.

Why does this monetary arrangement exist in the first place? Having a free CNH market for settlement of transactions, as well as international financial centers in Hong Kong and elsewhere that provide trade credit, was essential for Chinese firms to grow

[16]Hu and Yuan (2021) and Liu, Sheng and Wang (2022) are recent studies of how firms exploit these arbitrage opportunities.

in international trade and for the yuan to be internationalized. It contributed to making China the largest exporter in the world. At the same time, China has tight capital controls to limit inflows from foreigners, and the State controls the direction of outflows. Since all capital flows must ultimately involve an exchange of CNY for CNH, by placing most of the controls over this exchange, Chinese authorities can effectively implement them in a centralized manner.

2.2 The implementation and success of the peg to parity

Limits to arbitrage allow parallel currencies to survive even if domestic agents can convert between them. However, if the deviations from parity were large and persistent, then the profits from evading the capital controls would be large. Chinese firms, banks, and even households would make payments with the cheaper currency and hoard the more valuable one. Eventually, the controls would fail.

The PBoC has an explicit policy of pegging the CNH/CNY exchange rate at parity: $E = 1$ or $e = 0$. Figure 1 shows daily e on the left panel, and the exchange rate of either CNH or CNY with the USD on the right panel for comparison.[17]

The CNH/CNY peg is very successful, so much so that when comparing either the CNH or the CNY to the USD in the right panel, the two seem indistinguishable. The daily standard deviation of e_t is a mere 0.32%, and only in a handful of days over more than a decade has the exchange rate deviated from parity by more than 1%. At the same time, the transaction costs on the arbitrage trade of converting CNY to CNH via USD were on average about 0.04% over the sample. That deviations from parity regularly exceed this figure is evidence that the controls on converting CNH to CNY bind.

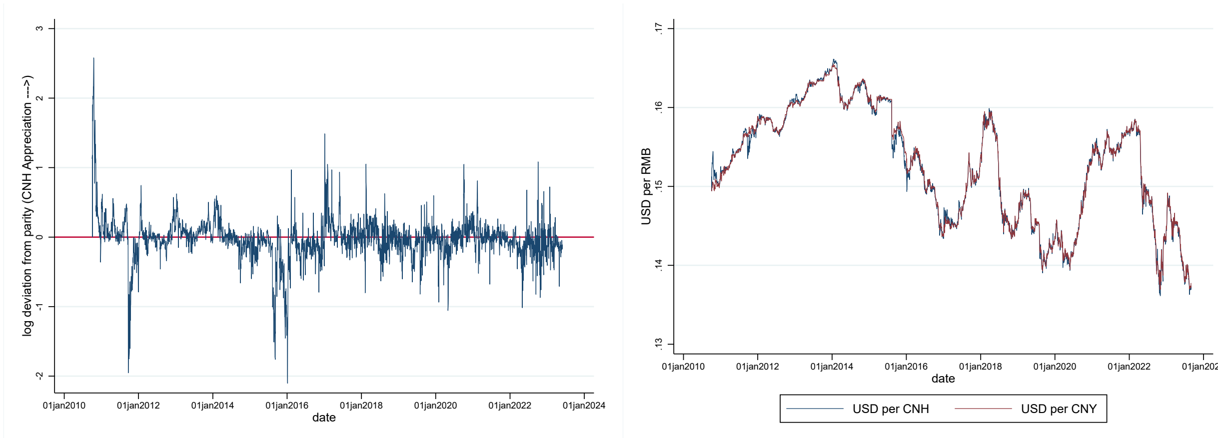
There is a noticeable decline the volatility of the exchange rate after 2017. There was a large reform in the PBoC's system for managing its exchange rate in August of 2015, followed by a period of adjustments to the framework over 2016-2017. Next, we discuss the monetary system post reform, and all the empirical tests that follow are for the sample from April 1st of 2017 until August 31st of 2023. Section 6 discusses the 2015-17 period.[18]

[17] Appendix A lists all data sources and variable definitions.

[18] For a description of pre-reform CNH/CNY exchange rate dynamics, see Funke et al. (2015), and for a description of the reform McCauley and Shu (2018).

Figure 1: The exchange rates of the CNH and the CNY

(a) CNH/CNY exchange rate **(b)** CNH/USD and CNY/USD exchange rates



Note: Sample period is all trading days between 1 October 2010 and 31 August 2023. Panel (a) shows $100 \log(CNH/CNY)$ so an increase is a CNH appreciation. In panel (b) an increase is a yuan appreciation.

2.3 How is CNH monetary policy conducted?

To fix ideas, the top panel of table 1 plots the conventional balance sheets of a hypothetical central bank and commercial banks in an advanced economy. Central banks routinely increase the money supply through three conventional operations.

The first is an open market operation: buying government bonds from banks in exchange for increasing in the balance in their reserve accounts. This can be structured as a direct sale, or as a repurchase agreement, where the two parties agree to unwind the operation in future. Either way, items (A) and (D) would increase in the central bank's balance sheet, and item (I) rises while (G) falls in the banks' balance sheet. The second operation is the issuance and redemption of central bank bills at term, item (E), in exchange for reserves, item (D). For the banks, item (H) and (I) move in the other direction. Since reserves, as a settlement asset, are more liquid than bonds or bills, both of these operations expand liquidity. The third operation works through lending facilities to banks, which raise items (B) and (D) in the central bank's balance sheet, and items (I) and (L) in the banks' balance sheet. Finally, all three channels lead to a rise in item (I), the holdings of reserves by banks, altering the money supply. In turn, this may change the willingness of banks to make loans, item (J), and the interest they pay on deposits, item (K), so that

Table 1: Monetary policy operations

Panel (a) The conventional case

Central Bank

Assets	Liabilities
(A) Government Bonds	(D) Reserves
(B) Lending Facilities	(E) Bills
(C) FX and Other Assets	(F) Equity, Others

Commercial Banking System

Assets	Liabilities
(G) Government Bonds	(K) Demand Deposits
(H) Central Bank Bills	(L) CB Facilities
(I) Reserves	(M) Equity, Others
(J) Loans, Others	

Panel (b) The CNH operations

People's Bank of China

Assets	Liabilities
(a) CNY Assets	(c) CNY Onshore Reserves
(b) FX Assets	(d) CNY Clearing Bank Reserves
	(e) CNH Bills
	(f) Equity, Others

Offshore Clearing Banks

Assets	Liabilities
(g) CNY Clearing Bank Reserves	(i) CNH Commercial Bank Sight Deposits
(h) Other Assets	(j) CNH HKMA Deposits
	(k) CNY Equity, Others

Hong Kong Monetary Authority CNH

Assets	Liabilities
(l) Deposits at Clearing Banks	(p) Equity, Others
(m) PLP Balances	
(n) Liquidity Facilities	
(o) Other Assets	

Hong Kong Commercial Banks CNH

Assets	Liabilities
(q) Deposits at Clearing Banks	(t) Demand Deposits
(r) PBoC CNH Bills	(u) PLP Balances
(s) Loans, Others	(v) HKMA Facilities
	(w) Equity, Others

measures of M1 that sum public (I) and private (K) money end up rising.[19]

The supply of CNH works essentially the same way, but with two extra arms involved, displayed in the bottom panel of table 1. The first arm is the offshore clearing banks. They are private entities, although they are all subsidiaries of one of the large state-owned banks in China, and their activities are closely regulated by the PBoC. They hold reserves onshore at the PBoC that are denominated in CNY, but they issue sight CNH deposits that are the actual settlement accounts used by offshore commercial banks.[20] Effectively,

[19] Since 2008, the Fed, the ECB, and the Bank of England, among others, have used the interest rate they pay on reserves and/or on the bills they issue as the main policy tools. They have complemented this with quantitative easing through a mix of open market operations and reverse repurchases, while liquidity facilities are reserved to infrequently provide emergency liquidity at a penalty rate.

[20] The offshore clearing banks also handle the offshore issuance of RMB banknotes, which are the same as RMB banknotes in China.

these sight deposits are the CNH reserves and each clearing bank operates its own real time gross settlement system (which is then linked to the clearing banks' accounts at the PBoC and the onshore China National Advanced Payment System). Settlement of transactions offshore happens when a correspondent bank exchanges a CNH sight deposit at a clearing bank, just as in a typical payment system. When a firm or household converts a unit of CNH to CNY in order to make a payment onshore, then lines (q) and (t) fall at their commercial bank, which triggers a fall in lines (g) and (i) at the clearing bank and a fall in line (d) and increase in line (c) at the PBoC.[21]

This separation means that CNH is only present in the PBoC's balance sheet through the small amount of bills in line (e). Therefore, movements in the CNH/CNY exchange rate have little impact on the PBoC, but create (so far small) capital gains and losses for the clearing banks. While this separation may be relevant if the peg is ever abandoned, integrating the two balance sheets makes little difference for the PBoC's influence over the money supply.

The second new arm is the HKMA, which holds its own CNH balances at the clearing banks. It uses them to lend to the commercial banks through two distinct programs. The first is a repurchase agreement that is available to nine select banks in Hong Kong. They are responsible for channelling liquidity to the CNH interbank and financial markets more broadly, and so are referred to as the primary liquidity providers (PLP). When they borrow from the HKMA at the interbank rate, they automatically increase the supply of reserves in circulation.

The other program are repo facilities that serve the role of a discount window. They are open on demand to all banks operating in Hong Kong that are willing to pay a penalty spread over the interbank rate. Unlike typical discount windows, these are used very heavily (daily, by several banks) and much more than the HKMA's discount window for Hong Kong dollars (which was used only 11 times in 2021).[22] Also, unlike in traditional corridor systems, these liquidity facilities are priced as a spread to the CNH interbank market rates in the previous three days, so the cost of emergency liquidity increases as

[21]Banks domiciled in China can access China's Cross-border Interbank Payment System (CIPS) settlement accounts to make cross-border payments for approved reasons (or to act as agents for foreign banks in doing so) but these CIPS reserves are separate from the PBoC reserves that are used for entirely onshore payments. CIPS reserves are remunerated differently and are subject to different liquidity policies, operating effectively as an offshore clearing bank that co-exists with the offshore clearing bank payment system. The value of transactions cleared using CIPS is an order of magnitude lower than the flow between CNH and CNY.

[22]Appendix B describes the programs in more detail and figure C.1 plots their usage.

existing liquidity becomes scarce.[23]

This separation again means that fiscal risk, in this case from possible default of the banks that borrow CNH, lies with the HKMA but not with the PBoC. Again, outside of a financial crisis, integrating the two authorities' balance sheets makes little difference for the joint control of the money supply.

Monetary policy in CNH does not involve setting interest rates. The interest rate on the CNH sight deposits at the clearing banks is zero. The interest rates on the PLP balances and the liquidity facilities are all endogenous, indexed to market interbank rates. Instead, the PBoC targets the money supply of CNH reserves, with the help of the HKMA.

The PBoC conducts these monetary operations through bill issuance (open market operations in CNH are not possible since there are no CNH government bonds). Namely, the PBoC has issued a stock of short-term bills, with maturities of 3, 6 and 12 months, and conducts auctions of new ones at pre-announced dates that follow a quarterly schedule. Those auctions typically coincide with previous bills maturing to keep the money supply smooth, subject to the changes in the quantity of money targeted by the PBoC. Concretely, as the bills mature and are paid, the stock of money increases, while when they are issued, it falls. By controlling the quantities in these auctions, the PBoC controls the quantity of this component of money reserves. In terms of the balance sheets, a bill that rolls off causing an increase in money supply maps into a fall in line (e) and a rise in line (d) in the PBoC balance sheet, together with a rise in lines (g) and (i) in the clearing banks, and an increase in line (q) and fall in line (r) in the commercial banks (potentially followed by rises in (s) and (t) through private money creation). While there are more intermediate links in the chain, the net operation is completely conventional.

The HKMA can also alter the money supply through its PLP lending. Again this works just as in a conventional central bank lending facility: line (l) falls and (m) rises at the HKMA, and lines (q) and (u) rise at the commercial banks. But, while the PBoC adjusts the supply of money by choosing the size of the bill auctions to at the weekly frequency, the HKMA adjusts the supply of money every day through the PLP facility with the same goal. The PBoC's actions choose the money supply potentially exogenously; the actions of the HKMA elastically supply money to absorb shocks to demand. At higher or lower

[23] Left out of the table is a swap line between the HKMA and the PBoC. If the demand by banks of the HKMA's programs exceeds the HKMA's balances at the clearing banks, it can borrow CNH as needed to prevent a liquidity crisis. As of July 2022, the HKMA's swap line limit was CNH 800bn, only slightly below the total stock of CNH demand deposits in Hong Kong (around ¥900bn). Unique among the PBoC's bilateral swap lines, the line with the HKMA is permanent and not subject to renewal.

frequencies, elastic or not, both institutions have a common goal of keeping the peg.

Finally, it is the CNH money supply, not CNY, that responds to the exchange rate e. Mainland monetary policy is set entirely by the People's Bank of China (PBoC), involving traditional channels, with a focus on mainland variables. The CNY money supply in line (c) is much larger than the CNH reserves (lines (i) and (j)), and it is used to fulfill domestic goals. There is no evidence that the PBoC has, in our sample, changed onshore monetary policy in response to the small daily fluctuations in the CNH/CNY exchange rate.

3 Exogenous money supply shocks and the exchange rate

We start with a simple model where banks can hold one of two parallel currencies as reserves, and can create deposits in either of them as well. This matches both the CNH-CNY application, as well as the broader recent literature that has emphasized the role of financial arbitrageurs and liquidity effects on exchange rates. The model shows why it is empirically difficult to nail down the causal link between money and exchange rates, and clarifies why the CNH/CNY is a useful testing ground. We then discuss how we accurately measure exogenous changes in money, and use these to estimate their impact on the exchange rate.

3.1 A simple model of money and the exchange rate

Risk-neutral atomistic banks create deposits and invest in assets offshore and onshore.

The balance sheet of a bank: An onshore bank with equity capital c^o, collects deposits d^o to either make loans x^o or hold reserves m^o. It can also go offshore to collect deposits d and hold reserves m.[24] The bank faces the resource constraint at the start of the day:

$$x^o + m^o + Em = c^o + d^o + Ed. \tag{1}$$

Returns: Next period, the bank pays positive gross interest rates R^d and $R^{d,o}$ on deposits and earns R^x on loans and R^m and $R^{m,o}$ on reserves. We normalize the cost of capital to one, which is the opportunity cost of funds in the economy.[25] All these returns are known

[24]To focus on the liquidity side of banking (reserves and deposits), we ignore the ability to make loans offshore, but this would have no impact on the monetary results.

[25]One can either think of a representative bank that raises capital from households at cost 1 or of a mass of identical banks that have a fixed endowment of capital and there is free entry.

today; the only unknown is the future exchange rate E'. The bank's expected payoff is:

$$\underbrace{R^x x^o - c^o}_{\text{Loans and capital}} + \underbrace{R^{m,o} m^o - R^{d,o} d^o - \phi^o (m^o/d^o) d^o}_{\text{Onshore liquidity}} + \underbrace{\mathbb{E}(E') \left(R^m m - R^d d - \phi(m/d) d \right)}_{\text{Offshore liquidity}} . \quad (2)$$

The cost of illiquidity: Loans are illiquid while reserves are liquid because during the day there are random withdrawals of deposits that a bank must honor. Doing so is costly, because the bank may have to borrow from other banks or the discount window. Later, we will micro-found these liquidity costs, but for now we assume they are captured by a liquidity cost function $\phi(m/d)$ per unit of deposit, so the total costs are homogeneous of degree 1 in reserves and deposits.

The function has three properties. First, it is bounded, namely $0 \leq \phi(.)d < m$ so that the costs do not exceed the payoff from reserves, and it reaches zero when the bank is narrow, $\phi(1) = 0$. Second, the function is decreasing in the reserve-deposit ratio, since expected liquidity costs are lower when the bank's assets are more liquid relative to its liabilities. This marginal benefit of liquidity is also bounded and, when the bank is narrow, it is zero: $\phi'(1) = 0$. Third, for the banking system as whole in equilibrium, the marginal benefit of improving the reserve-deposit ratio is diminishing: $\phi''(M/D) \geq 0$.

The arbitrage condition: A bank chooses x^o, m^o, m, d^o, c^o, d to maximize equation (2) subject to the constraint in equation (1). The first-order conditions with respect to the two types of reserves gives an uncovered interest parity (UIP) condition:

$$R^{m,o} - \phi^{o\prime}(m^o/d^o) = \left(\frac{\mathbb{E}(E')}{E} \right) \left(R^m - \phi'(m/d) \right) . \quad (3)$$

On the left-hand side are the expected returns from holding a marginal unit of onshore currency; on the right are those from a marginal unit of onshore currency. These include both the final return as well as the marginal reduction in liquidity costs.

Equilibrium and the money supply: The central bank chooses the supply of reserves offshore M and sets the interest on reserves R^m. Since in equilibrium, all banks are identical, $m = M$. Letting the supply of deposits be denoted by D, the UIP condition becomes an equilibrium relation for the exchange rate:

$$E = \mathbb{E}(E') \left(\frac{R^{m,o} - \phi^{o\prime}(M^o/D^o)}{R^m - \phi'(M/D)} \right) \quad (4)$$

The causal effect of money on exchange rates: All else equal, an increase in the supply of offshore money M satisfies some of the demand for transactions and liquidity. Therefore, it raises $\phi'(.)$, and so lowers E. That is, more offshore money supply depreciates the offshore currency. The demand curve for reserves, and the liquidity benefits they provide, is downward sloping.

If, instead, the demand for money is infinitely elastic, or horizontal, then the relative value of money is purely pinned down by its relative return, irrespective of the quantity of money supplied. In that case, $\phi'(.) = 0$, so that money is a pure financial asset that provides zero transaction or liquidity benefits. Equation (4) becomes the textbook condition according to which the interest rate differential determines the exchange rates. The quantity of money is only relevant insofar as it is linked to the interest rate; by itself, it has no effect on the exchange rate for a fixed interest rate.

Difficulties with testing: Testing for $\phi'(.) = 0$ is hard for several reasons. First, most central banks most of the time set policy in terms of R^m, and have the supply of money accommodate demand. Therefore, there are few if any exogenous changes in the money supply M to conduct the test.

Second, even when they choose M, central banks follow policy rules whereby the supply of money responds to the exchange rate E or to shocks that move D or shift $\phi'(.)$, creating a reverse causality.

Third, the other currency's monetary policy M^o also moves and responds to E and D^o, so there is a simultaneity problem.

Fourth, shocks to equilibrium deposits D or to other factors determining the value of liquidity include changes in relative outputs and real exchange rates, or, in the more recent literature, changes in the risk appetite of financial intermediaries and in frictions to arbitrage. All of these omitted variables are hard to control for.[26]

Fifth, there are multiple types of money that are imperfect substitutes in providing liquidity or transaction services, so that even measuring the right M that enters the $\phi'(.)$ function is difficult.

Sixth, and finally, large, persistent, and unexpected shocks to M will be correlated with changes in information and future expectations $\mathbb{E}(.)$ of future policies and macroeconomic outcomes. Therefore, there are anticipation and signaling effects that may be unrelated to the transaction services of money.

The CNH-CNY testing ground: The CNH money supply M and the CNH/CNY ex-

[26]See Itskhoki and Mukhin (2021), Maggiori (2022) for recent models of u.

change rate E provide a good setting to test for the causal impact of the money supply on the exchange rate because it overcomes the initial four empirical barriers.

First, the conduct of CNH monetary policy is to vary the quantity of CNH reserves supplied as opposed to the interest rate. In fact, $R^m = 0$ at all times in CNH reserves. There is hope to find exogenous changes in M.

Second, the monetary policy rule is known, adhered to, and successful: to keep parity, or $\mathbb{E}(e') = 0$. Because the PBoC only adjusts its component of M weekly (or less) during the auctions of CNH bills, there is no reverse causality from high-frequency E to this component of M.

Third, onshore CNY monetary variables, denoted by the superscript o, are chosen in response to onshore variables. Neither the interest rate $R^{m,o}$ nor the supply of money M^o are affected by the CNH/CNY exchange rate e, so there is no simultaneity problem.[27]

Fourth, CNH and CNY are designed to intermediate transactions in Chinese goods and services and Chinese agents have access to both. Therefore, there are few non-monetary movements in the real exchange that we must control for, especially at a high frequency.

Fifth, since the international yuan is still in its infancy, and foreigners have limited access to yuan government bonds, during our sample there were no significant repo markets for CNH, and customer money market accounts are rare. Therefore, the closest private substitutes for public money are not available making it easier to focus on the money supplied by the PBoC and the HKMA.

All combined, the model in the Chinese context has: (i) $R^m = 1$; (ii) the credible rule $\mathbb{E}(E') = 1$; (iii) and since onshore policy is set independently of offshore concerns, so we can normalize $R^{m,o} - \phi^{o\prime}(m^o/d^o) = 1$ and then interest-rate policy will be consistent with the parity peg at all dates. The equilibrium no-arbitrage condition in the reserves market for the exchange rate becomes:

$$E = 1 - \phi'(M/D). \tag{5}$$

If offshore money was ample enough to drive the liquidity costs to zero, then no-arbitrage and Gresham's law impose that $E = 1$ at all dates in any equilibrium with $M > 0$. With scarce money, more deposits raise the marginal cost of liquidity, which increases the demand for reserves, so the onshore currency appreciates and E falls.

[27] Table C.1 in appendix C confirms this: regressing the stock of monies on the exchange rate, there is a quantitatively and statistically significant correlation only with CNH money, but not CNY money.

We now explain how we can accurately measure changes in M that are exogenous and transitory, so they overcome the fifth and sixth challenges.

3.2 Shocks to the money supply from the roll-off of bills

The PBoC started issuing CNH bills in November 2018 on a schedule that would converge to a stock of ¥50bn of bills outstanding, with ¥40bn of 3-month bills and ¥10bn of 12-month bills. However, on the 20th of August of 2019, the PBoC altered the bill issuance schedule to increase the stock of bills to ¥80bn, with ¥20bn of 3 and 6-month bills, and ¥40bn of 12-month bills. On the 6th of November of 2020, the PBoC further announced it would lengthen the maturity structure by switching the composition to ¥10bn of 3 and 6-month bills and ¥60bn of 12-month bills while holding the stock fixed. Between November 2020 and August 2023, the PBoC did not made further changes to the schedule so by 2022 the stock converged to a level ¥80bn with any deviation closed within a very short window. Following the downward pressure on the RMB in Summer 2023, discussed in Section 6.5, the bill stock was expanded once again to reach ¥110bn by the end of the year.

The two changes in the schedule of auctions in 2019 and 2020 were likely an endogenous policy response to the demand for CNH (as was, more evidently, the change in 2023). However, because they shifted the maturity structure, and since the auctions for different maturities are on a different schedule, they created future dates when certain bills exogenously rolled off without being replaced for at least 5 working days. In addition, the issuance of a 6-month bill in June 2023 was a few days later than usual which created an extra period where the bill stock was diminished.[28]

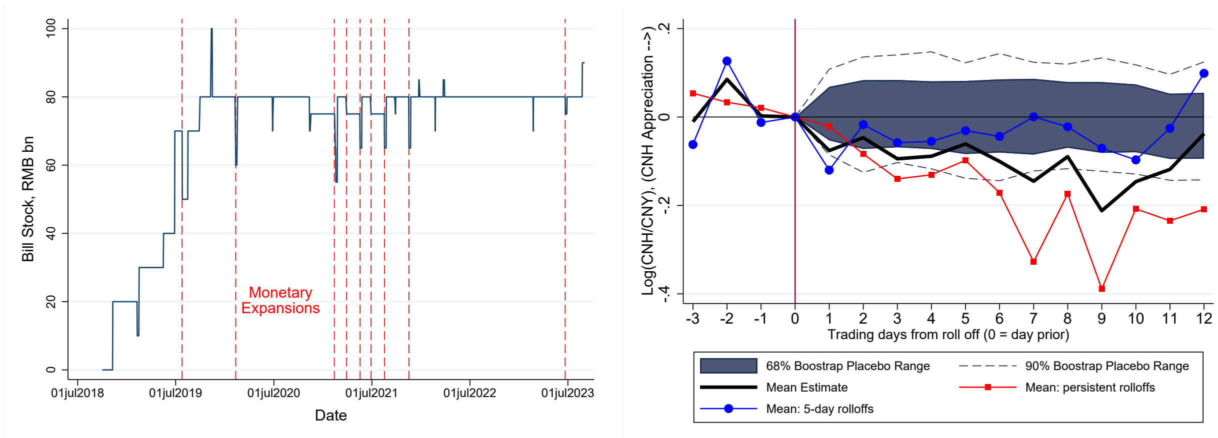
The left panel of figure 2 plots the outstanding daily stock of bills during this period. As a result of the variation in the schedule, the bills at the nine dates indicated by the vertical lines rolled off without being immediately replaced by new bill issuances.[29] These events led to sharp and large declines in the stock of bills outstanding, of on average ¥11bn. Correspondingly, the CNH money supply expanded to redeem those bills at these dates.

[28]This last event was partly due to operational constraint having to do with the days of weekends in June of 2023. Our results are not sensitive to its inclusion.

[29]The dates are 26 July 2019, 10 February 2020, 15 February 2021, 29 March 2021, 18 May 2021, 28 June 2021, 17 August 2021, 16 November 2021, and 22 June 2023. We do not consider the changes in the stock that arose immediately from the announcements on the 8 August 2019 and 6 November 2020. We exclude rolls offs that were reverted within fewer than five trading days. For comparability, we also exclude periods when the bill stock spiked due to a new bill being issued before the prior to an old bill maturing.

Figure 2: Response of the exchange rate to an increase in money supply

(a) Money supply shocks through bill roll-offs **(b)** Response of the CNH/CNY exchange rate



Note: Panel (a) shows the stock of PBoC bills outstanding and its short-lived fluctuations caused by the shift in maturity structure in August 2019 and in November 2020. Panel (b) shows 100 times the cumulative change in the log of the daily CNH/CNY exchange rate from the trading day prior to the bill roll off, averaged across the monetary expansion events. Also in the figure are bootstrapped placebo intervals from taking 10,000 random samples of an equivalent number of events dates between 1 July 2020 and 1 November 2021, excluding dates that overlap with the original event window and schedule announcements.

The monetary expansions were only temporary. Regardless of the persistence, the previous supply of bills was eventually re-established with new issuance. In five of the cases, the increase in money supply lasted 5 trading days. The remainder of roll-offs had a more persistent impact on money supply, lasting on average for 25 trading days.

At a weekly frequency, these exogenous changes in money supply would barely be detectable, as they were reverted by the next auction. Theory suggests that they would have no effect on the exchange rate beyond a few weeks. Policymakers determined to keep the peg at parity would not consider this to be a problem and, as far as we know, made no adjustments to policy as a response. But, at a daily frequency, these bill roll-offs provide an exogenous variation in the supply of money that should affect the daily exchange rate.

The changes in the money supply were predictable weeks ahead (assuming there would be no further change in the schedule). That they should have an effect on the exchange rate lies at the heart of the monetary theory of exchange rates. Price changes are random walks for pure financial assets, but not for transaction assets like money. This is because the quantity of money affects its liquidity benefit and so the demand for it.

The price of money must change, whether the change in quantity was anticipated or not. The exchange rate would be expected to appreciate when bills roll off, because by the no-arbitrage condition in equation (4), the rise in liquidity benefits from scarcer reserves increase the market clearing price of the CNH.

3.3 The impact of the money supply on the exchange rate

The right panel of figure 2 shows the average response of the exchange rate to these monetary expansions (the black line).[30] To assess statistical significance, the figure shows also a bootstrapped placebo distribution constructed by drawing eight non-overlapping events from other days in the sample.[31] Finally, the blue and red lines split the events to present, respectively, the average for the roll-offs that were reverted in 5 trading days, and the average for those that persisted for longer (the size of the roll-offs are similar in either case).

Increases in M led to a fall in E. The mean estimate shows this effect dies out after around 12 trading days, which corresponds to the average time taken across events for the bill stock to revert to the normal level. The average exchange rate depreciation of the CNH was 0.11%, over a 10 day horizon. Splitting by duration of the monetary expansions, the short-lived ones cause an immediate exchange rate movement of 0.12%. But this is temporary and rapidly reverses. The longer-lived monetary expansions have a less detectable immediate impact but lead to a larger CNH depreciation that persists beyond 12 trading days.

Quantitatively, the average roll off was ¥11bn and the average stock of CNH deposits in Hong Kong banks (M1 without currency) over 2020-2022 was ¥771bn. Therefore, a roughly 1.7% increase in the money supply lowered the exchange rate by significantly more than 0, but well below 1. If the money multiplier is near one, which is plausible for such a transitory shock at such high frequency, then the implied semi-elasticity of money demand with respect to the exchange rate is $(1/0.11) \times (11/771) = 0.13$. This is far below the textbook assumption of infinity, but also significantly above zero.

As far as we know, there is no well-identified counterpart to this elasticity in the literature. However, there is a close object has attracted much research effort, because it is

[30] Figure C.3 in appendix C shows the response after each event.

[31] Looking at the five days before each event, there were no obvious pre-trends in the exchange rate that could be biasing the estimates because of some reversion from other shocks that happen to coincide or because of anticipation effects of the rolloffs.

a key input into the welfare costs of inflation: the semi-elasticity of money demand with respect to the opportunity cost of money. This is typically estimated from regressions of the stock of M1 on the nominal interest rate on short-term bonds. At one end, Ball (2001) finds a low value of 0.05 for the United States, while at the other end Benati et al. (2021) have estimates between 0.07 and 0.16 for several countries, including 0.08 for the US and 0.15 for the Hong Kong dollar. While our estimates use a very different source of variation over other variable than this literature, the results are consistent.

4 The anatomy of the CNH/CNY peg

How can a country peg the exchange rate of its currency to another currency? The textbook answer is that if the currency depreciates, the central bank should raise its interest rate. A monetary complement is that the central bank should reduce the supply of money. Yet, the correlation between either interest rates or measures of money supply for countries that peg their currency is close to zero in the data.[32]

In the case of the CNH/CNY, the PBoC could let the forces of arbitrage re-establish the peg following a shock. If the CNH appreciates, Chinese agents prefer to make payments in CNH, which transfers onshore CNY to offshore CNH, increasing the supply of CNH until parity is back. However, with binding capital controls, this arbitrage force puts pressure that the central bank needs to get ahead of by adjusting the money supply.

Institutionally, because the PBoC adjusts the supply of money through the regular auctions of CNH bills, then between auctions it cannot control the money supply. This job is left to the HKMA, which controls the money supply daily through the PLP facility.[33] We now study the HKMA's-controlled money supply and its role in keeping the peg. We start by putting the model of arbitrage by banks into an equilibrium model with money demand shocks, then describe how to measure these shocks in the data, and finally use those measures to anatomize the actions of the HKMA to sustain the peg.

[32] Figure C.4 in appendix C plots linear regressions between either interest rates or the stock of money, and the exchange rates, for an unbalanced panel of 26 countries that pegged their exchange rate between February 1979 and December 2015. The R^2 of these two regressions are 0.001 and 0.003, respectively.

[33] Figure C.1 in appendix C shows that the PLP volume of outstanding CNH averages about ¥10bn during the sample period, which is approximately 1/8th of the volume of CNH bills outstanding, and that there is much variation day to day.

4.1 An equilibrium model of the exchange rate

Starting from the behavior of banks that led to the reserves market equilibrium condition in equation (5), we now consider the creation of endogenous money (deposits) and the demand shocks that drive them.

The demand for deposits by banks: The first-order condition from the bank's optimization with respect to offshore deposits gives the supply of deposits:

$$\left(\frac{\mathbb{E}(E')}{E}\right)\left[R^d + \phi(m/d) - \left(\frac{m}{d}\right)\phi'(m/d)\right] = 1. \tag{6}$$

The bank equates the expected return on deposits to the opportunity cost of capital, which is one.

The supply of deposits from households: A representative household (or firm) that is located onshore derives liquidity services from holding offshore deposits with which it can make payments for imports. Assuming that these services have a constant elasticity in the utility function, the supply of deposits D is given by:

$$\left(\frac{\mathbb{E}(E')}{E}\right) R^d = 1 - vD^{-\alpha}, \tag{7}$$

where v is a shock to money demand.[34]

Entry and equilibrium in deposits: Banks are perfectly competitive, so they take returns and aggregate variables as given. Free entry into banking drives their profits to zero. Markets for reserves and deposits clear, so $M = m$ and $D = d$. Combining supply and demand for deposits with market clearing and the credible peg delivers the equilibrium condition for the deposit market:

$$EvD^{-\alpha} = \phi\left(\frac{M}{D}\right) - \left(\frac{M}{D}\right)\phi'\left(\frac{M}{D}\right). \tag{8}$$

With scarce reserves, this condition gives a positive relation between E and D.[35] On

[34] Appendix D.1 writes down the problem of the household. Note that we abstract from the market power of banks, since they take R^d as given, or from the financial repression that Chinese authorities to keep deposit below market-clearing levels. It is not apparent how these features would change any of the monetarist and liquidity conclusions that we focus on in this paper.

[35] With abundant reserves, as the right-hand side of the equation goes to zero, then deposits tend to infinity and the ratio D/M is not defined, a standard property that models with a satiated reserves market

the bank side, again more deposits raise liquidity costs and raise the demand for reserves appreciating the offshore currency. However, on the household side, an appreciated offshore currency means an expected depreciation, which lowers the returns on holding deposits so the demand for deposits falls. This second effect implies that more deposits must now come in equilibrium with a more valuable offshore currency, so this second equilibrium condition is steeper than the first one.

Equilibrium and shocks to money supply: An equilibrium is a solution for the exchange rate E and for deposits D (and so for the money multiplier D/M), as a function of the demand for money v and public money supply (reserves) M. Appendix D.2 formally proves the existence of an equilibrium with $E > 0$ and $M/D < 1$.[36]

After an exogenous increase in the supply of offshore money M, the onshore currency appreciates, E falls. This is just as we found in the data in section 3. Intuitively, with more offshore reserves, the liquidity premium on reserves is lower and they can earn a lower return. By UIP, this requires the offshore exchange rate to be expected to appreciate, which for a credible peg implies that the current exchange rate must depreciate.

Shocks to money demand and the elastic supply of money: After an increase in the demand for offshore deposits v, the offshore exchange rate appreciates. This must be met by a rise in the supply of money. Intuitively, higher demand for offshore deposits raises the relative value of offshore reserves to insure against the withdrawal shocks. The bank's portfolio shift from onshore to offshore reserves moves the exchange rate away from the peg unless the supply of reserves rises.

4.2 Deviations from the peg as shocks to money demand

At a daily frequency, it is challenging for a central bank to perfectly fine tune the money supply whenever the demand for money (deposits) happens to change. As a result, the exchange rate deviates from the peg. The central bank can adjust the money supply over the next day(s) so that the deviations of the exchange rate are short lived and the peg holds at a lower frequency.

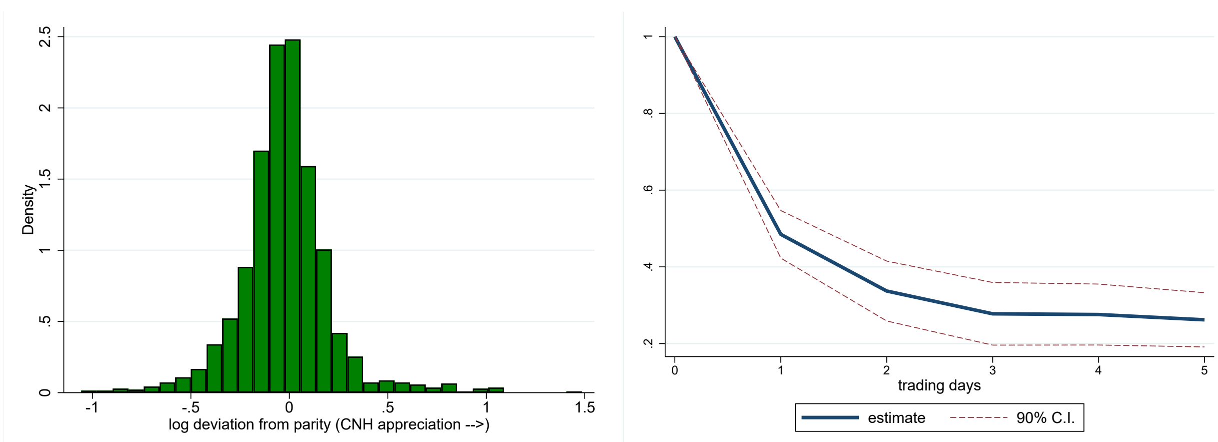
should satisfy.

[36]In the model, the amount of deposits depends on both supply and demand shocks, and the interest rate gap between onshore and offshore deposits drives the amount of deposits as much as the quantity of reserves does so. Therefore, the multiplier that we refer to is simply the measured ratio of deposits to money, not a stable exogenous relation, and CNH broad money is as much determined by supply of reserves as it is for demand from depositors.

This implies that an appreciation of the exchange rate in one day reflects mostly a positive shock to the relative demand for CNH money. Mostly, because policymakers avoid shocks to money supply; and positive, because the appreciation reflects their inability to accommodate the shock to money demand fast enough. Panel (a) of figure 3 shows a histogram of the deviations from parity. They are centered around zero and have a bell shape. It is a classic result in optimal control theory that in tracking a noisy signal with a (approximately) quadratic loss function, deviations from the objective should be (approximately) normally distributed. The HKMA CNH liquidity system adjusts money supply to track imperfectly-observed shocks to money demand, and the exchange rate measures deviations from this goal. This figure matches what one would expect to see from the policy rule in action.

Figure 3: Movements in daily CNH/CNY exchange rate as shocks to money demand

(a) Histogram of the log exchange rate **(b)** Dynamic conditional autocorrelation



Note: Panel (a) shows the histogram of the e_t. Panel (b) plots β_h from the regression $e_{t+h} = \alpha_h + \beta_h e_t + \gamma_h e_{t-1} + \text{error}_{t+h}$, for $h = 0, \ldots, 5$, where e_t is the log of the daily CNH/CNY exchange rate on all trading days between April 2017 and May 2023.

Panel (b) plots the dynamic conditional autocorrelation of the exchange rate at daily frequency. It is declining, precisely as we would expect from the HKMA gradually updating its noisy estimate of shocks to demand by adjusting supply to absorb them. Approximately half of the deviation from parity is corrected within one day, with 0.3 left after one working week.[37]

[37]Figure C.5 in appendix C shows the autocorrelation function within one trading day, calculated ev-

4.3 An instrument for shocks to money demand

Since changes in the daily exchange rate are proxies for shocks to money demand, then estimating whether the HKMA raises the supply of money in the next few days provides a monetary anatomy of how the peg is kept. However, insofar as the HKMA is able to adjust the PLP money supply already within the day, or the PBoC adjusts bill roll offs a few days later, then these estimates would understate the strength of the response of the money supply to the exchange rate. Figure C.6 in appendix C confirms this is the case by showing significant estimates of the response of PLP volumes during the day to a change in the exchange rate at the start of the day.

We use an instrumental variable approach to correct for this downward bias. The PBoC also actively manages the CNY/USD exchange rate, call it $\hat{e}$. It does so by setting a "central parity rate" at the start of the day, $\bar{e}$, and then intervening during the day so that deviations of $\hat{e}$ from it do not exceed 2% in absolute value. Most of the time, the parity rate is adjusted to match the previous market rate and this trading band does not bind. Sometimes though, the PBoC does not adjust the central parity rate to market conditions fast enough, for example if the CNY is depreciating fast and the PBoC wants to slow this down. At these times, the CNY/USD exchange rate binds at the bottom of the band, and there is unfulfilled pressure for the CNY to depreciate further.

In anticipation of this, market participants would want to sell CNH today as no trading band exists in the offshore market. Hence, the CNH will trade below parity with CNY. A good proxy for the band binding is simply whether the central parity rate tracked the previous close. Therefore, $\bar{e}' - \hat{e}$, the deviation of the CNY/USD exchange rate from the band today is an instrument for Δe, the change in the CNH/CNY exchange tomorrow. Because $\bar{e}$ is determined in the morning, the instrument is not contaminated by the within-day PLP adjustment.[38] Figure C.7 in appendix C plots the two variables and verifies they are strongly related: the F-statistic for this instrument is 20.

ery thirty minutes. It only declines moderately and this is reversed at close. Therefore, going to higher frequencies than daily seems unnecessary to isolate shocks to money demand.

[38] Technically, the central parity rate is announced at 11am, although the trading band is implemented before that. Looking at PLP facility drawings only between 11am and end of day yields very similar results. See figure C.8 in appendix C.

4.4 Testing the monetary recipe for keeping a peg

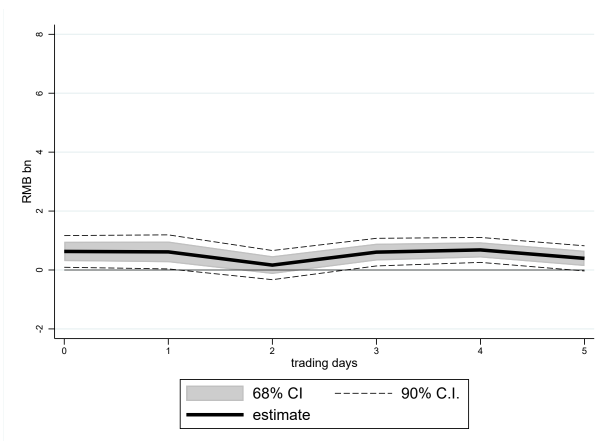
We test the hypothesis that the exchange rate is managed through the HKMA altering CNH money supply by estimating:

$$z_{t+h} = \alpha_h + \beta_h \Delta e_t + \gamma_h e_{t-1} + \delta_h z_{t-1} + \text{controls}_{t-1} + \text{error}_t^h, \tag{9}$$

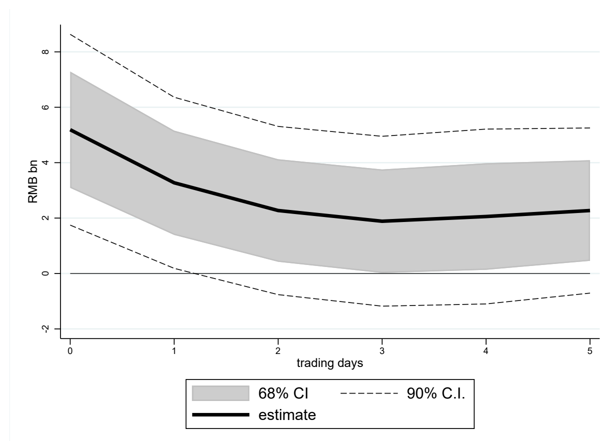
where z_{t+h} are drawings from the PLP liquidity facility h days after the money demand shock proxied by the movement in e_t and $controls_{t-1}$ includes drawings from the HKMA's discount window facility, and 3 month CNY and CNH interbank rates. Monetary theory predicts that $\beta_h > 0$ as the HKMA adjusts the money supply to respond to the money demand shocks. We estimate these local projections either by least squares or by instrumenting the exchange rate with the deviation of the USD exchange rate relative to the trading band lower limit, $\bar{e}_t - \hat{e}_{t-1}$.

Figure 4: Response of the HKMA's PLP money supply to a money demand shock

(a) Local Projection - Least Squares



(b) Local Projection - Instrumental Variables



Note: Estimates of equation (9). The sample period is all trading days between April 2017 and August 2023. Confidence intervals use White heteroskedasticity robust standard errors, following Montiel Olea and Plagborg-Moller (2021). Panel (a) estimates the equation using least squares, whereas panel (b) does so using as an instrument the deviation of the CNY/USD exchange rate from the trading band limit.

Figure 4 shows the estimates. Both least squares and instrumental variables estimates are positive and statistically significant. Moreover, as we expected, the IV results are significantly larger. After a money demand shock that increases the CNH exchange rate by 1%, the HKMA's supply of money through the PLP rises by approximately ¥5bn to re-establish the peg. The response declines with the horizon as expected, given the declining autocorrelation of the exchange rate in figure 3.

5 Liquidity management and financial innovation

The liquidity services provided by money so captured in the reduced-form function $\phi(.)$. This section derives this liquidity function as the result of reserve management by banks and equilibrium in the interbank market. These micro-foundations bring two benefits.

First, they provide a broader set of shocks that put strain over the peg. The model predicts that the money multiplier will be unstable, changing with shocks. Goodhart's law holds in response to financial innovation, which there is an incentive to undertake.

Second, the micro-foundations produce predictions for other variables in response to the money demand changes identified in the previous section. Namely, the demand for substitutes to PLP money should change with the shocks.

5.1 Withdrawals during the day and the liquidity cost function

During the day, each bank faces a change in its offshore deposits, to which it responds by adjusting its liquid reserves.

Withdrawal shocks: Each bank is indexed by ω, an idiosyncratic shock standing for the fraction of start-of-day offshore deposits that have leave with withdrawals by the end of the day. If $\omega = -1$ all of its deposits leave, whereas if $\omega = 0$ none do. Since one bank's outflow are another bank's inflows, some banks have $\omega > 0$ and receive net inflows. From the perspective of the start of the day, ω is a random variable with support $[-1, \infty)$ and distribution $\Omega(\omega)$ that satisfies:

$$\mathbb{E}(\omega) = \int_{-1}^{\infty} \omega d\Omega(\omega) = 0. \tag{10}$$

Reserve requirements and commitments: By the end of the day, banks must honor all withdrawal requests by settling them one-for-one with reserves in order to stay in business. Moreover, they must satisfy at all times a reserve requirement that reserves are at least as large as a share ρ of the deposits.

Liquidity position after the shocks: At the start of the day, the bank's liquidity was the excess of reserves over the requirement: $m - \rho d$. After withdrawals, liquidity increases by the inflow of deposits in excess of the reserve requirement: $\omega d(1-\rho)$. Its net surplus of liquidity after a shock is:

$$s(\omega) = m - \rho d + \omega d\,(1-\rho)\,. \tag{11}$$

This defines a liquidity threshold, $\bar{\omega}$ such that:

$$s(\bar{\omega}) = 0 \quad \Leftrightarrow \quad \bar{\omega} = \frac{\rho - \frac{m}{d}}{1-\rho}. \tag{12}$$

Banks with $\omega < \bar{\omega}$ will have a liquidity deficit. Those above it, have a liquidity surplus during the day. Naturally, the higher the reserve-deposit ratio m/d, the less likely it finds itself in a deficit as the threshold $\bar{\omega}$ is lower.

Interbank market tightness: Banks with liquidity surpluses and deficits try to meet each other in an over-the-counter interbank market to lend and borrow offshore reserves. They must search for each other and tightness in this market θ is the ratio of the aggregate demand for liquidity to its aggregate supply:

$$\theta = \frac{-\int_{-1}^{\bar{\omega}} s(\omega) d\Omega(\omega)}{\int_{\bar{\omega}}^{\infty} s(\omega) d\Omega(\omega)}, \tag{13}$$

which clearly falls with $\bar{\omega}$. Banks take this aggregate market tightness as given when making their decisions.

Search and bargaining in the interbank market: A bank with a liquidity deficit finds a bank with a surplus with probability $\Psi_{-}(\theta)$, that we assume falls in θ; a lender bank matches with a borrower with probability $\Psi_{+}(\theta)$ that rises with θ. If a borrower fails to find a lender (or does not agree on terms) it can borrow at the central bank's liquidity facility at a given rate R^z.[39]

In the interbank market, a lender and borrower that meet will bargain over the interbank interest rate $R^f(\theta)$. Since the outside opportunity of the lender is to earn the interest on reserves R^m, while that of the borrower is to go to the discount window at rate R^z, the function $R^f(\theta)$ has domain $[R^m, R^z]$, and we assume only that it is increasing in θ.

[39] This rate may depend on the total amount borrowed on aggregate, to capture quantity limits on the discount window. For instance, at the HKMA, the rate paid on its liquidity facility is equal to a lower rate as long as volume of borrowing is below a threshold, and a higher rate beyond that. In the first segment, the HKMA is lending from its CNH reserves at the clearing banks, while in the second segment it is using the swap line with the PBoC.

The liquidity cost function: Combining all the ingredients, if the bank finds itself in a surplus, because $\omega > \bar{\omega}$, it will find someone to lend to with probability $\Psi_+(\theta)$ and earn a profit of $R^f(\theta) - R^m$ per unit of reserves lent. Instead, if $\omega < \bar{\omega}$, it will have to cover its deficit by borrowing in the interbank market at cost per reserve of $R^f(\theta) - R^m$. With probability $1 - \Psi_-(\theta)$ it does not find a lender and must borrow from the discount window at the higher cost $R^z - R^m$. Expected liquidity costs at the start of the day are:[40]

$$\phi(m/d)d = -\underbrace{\Psi_+(\theta)}_{\text{prob. find borrower}} \times \underbrace{(R^f(\theta) - R^m)}_{\text{lending profit}} \times \underbrace{\int_{\bar{\omega}}^{\infty} s(\omega) d\Omega(\omega)}_{\text{liquidity surpluses}}$$
$$- \left[\underbrace{\Psi_-(\theta)(R^f(\theta) - R^m)}_{\text{interbank borrowing}} + \underbrace{(1 - \Psi_-(\theta))(R^z - R^m)}_{\text{CB borrowing}} \right] \underbrace{\int_{-1}^{\bar{\omega}} s(\omega) d\Omega(\omega)}_{\text{liquidity deficits}}. \quad (14)$$

In section 3.1 we assumed properties of the $\phi(m/d)$ function that we can now verify against its micro-foundation: it depends on the ratio m/d; it is bounded below by 0 and above by $R^z - R^m$ and in turn by m; and it has an upper limit $\phi(1) = 0$.

5.2 Financial innovation and liquidity policies

A key model object is $-\phi'(M/D)$, the marginal benefit of an extra reserve evaluated at the equilibrium reserve-deposit ratio. A structural change that lowers $-\phi'(M/D)$ lowers E and appreciates the onshore currency.

Taking derivatives of equation (14) with respect to m, and evaluating at the market equilibrium, gives the marginal benefit of a reserve:

$$-\phi'(M/D) = (1 - \Psi_-(\theta))(R^z - R^m)\Omega(\bar{\omega}) - \underbrace{(\Psi_+(\theta) + \Psi_-(\theta))(R^f(\theta) - R^m)\Omega(\bar{\omega})}_{=0}. \quad (15)$$

It is the sum of two potential benefits: less frequent need to use the discount window at its high cost, and having more reserves to lend at a profit in the interbank market. However, this second benefit is zero: since the banks are all ex ante identical, at the margin the

[40] Since reserves yield R^m but deposits pay R^d settling reserves for deposits one-for-one incurs a cost due to the interest differential. However, this nets out in expectation when $\mathbb{E}[\omega] = 0$.

expected benefit of participating in the interbank market is zero.[41] It is again easy to verify the assumption we made earlier about $-\phi'(M/D)$. It is non-negative, bounded from above, for a narrow bank $\phi'(1) = 0$ since when $m = d$ we have that $\bar{\omega} = -1$ so this is true in aggregate as well, and finally it falls with M/D.

One way to think of financial innovation is that the efficiency of matching in the interbank market rises. A borrower with a liquidity deficit can now find a lender more easily, so the function $\Psi_-(\theta)$ is now higher for all θ. Alternatively, innovation may manifest in a shift in the withdrawal distribution $\Omega(.)$, as banks are better able to retain depositors, or simply to predict withdrawals better. This implies that for the same liquidity threshold the tightness in interbank markets is lower (see equation (13)) and that for the same $\bar{\omega}$, the $\Omega(\bar{\omega})$ is lower.

All three shocks—fall in $\Omega(\bar{\omega})$, lower θ, higher $\Psi_-(\theta)$—imply from equation (15) that the marginal benefit of reserves $-\phi'(M/D)$ is lower. In the limit, if these shocks were to drive $-\phi'(M/D)$ to zero, then the exchange rate must be one, and the capital controls would no longer bind. The PBoC would no longer control capital flows, no matter how it adjusts the stock of reserves M.

Away from this limit, changes in the marginal benefit of reserves puts pressure to break the peg. The model predicts that they would show up as large fluctuations in the money multiplier D/M, a breakdown in the stability of monetary targets that is known as Goodhart's law. A regression of bank deposits in CNH relative to deposits in CNY on the lagged exchange rate using monthly data between April 2017 and April 2023 gives a coefficient with a p-value of just 1.7, and an R^2 of 0.04.[42] Even if there was a strong association between narrow measures of central-bank money and their relative value, because there is a private money multiplier that changes with financial innovation, the link to private money is weaker and unstable confirming Goodhart's law.

[41] Formally, the interbank market clearing condition is:

$$\Psi_-(\theta) \int_{-1}^{\bar{\omega}} s(\omega) d\Omega(\omega) + \Psi_+(\theta) \int_{\bar{\omega}}^{\infty} s(\omega) d\Omega(\omega) = 0. \tag{16}$$

Taking the partial derivative with respect to m and evaluating at M/D reveals that the second term in equation (15) is nil.

[42] Table C.1 in appendix C describes this regression in more detail.

5.3 Validation of the money demand shock

While the HKMA money supply gradually adjusts, the money market must clear through other margins. This section finds evidence that it is so from three other monetary variables suggested by the micro-foundations of the model.

Recall that an increase in money demand v leads to an increase in E and deposits D from section 4. The higher D raises the liquidity threshold $\bar{\omega}$, and so raises market tightness θ. Empirically, this would show up in a decline in the bid rate for CNH bills by banks.

Intuitively, an imperfect substitute for the missing supply of HKMA money is PBoC money. As we discussed before, the PBoC adjusts the supply of money by auctioning bills. Between announcing an auction and taking bids, on average 6 trading days go by, so at high frequency, the quantity of bills does not respond to the demand for money. An appreciation of offshore currency, reflecting a rise in demand for CNH money, will lower demand for bills and this should show up as lower subscription rates at the next bill auction.

Table 2 tests this effect by regressing the subscription rate on the average deviation from the peg during the five days prior to the auction to capture the interval after an auction is announced and before it takes place. The regression coefficients are negative as predicted.[43]

A second substitute for HKMA money is the interbank market for money. In the model, in response to that rise in money demand, the central bank raises the supply of reserves M to bring the exchange rate back to parity. This lowers market tightness θ and lowers interbank rates $R^f(\theta)$.

Intuitively, banks needing liquidity will turn to other banks that may have a liquidity surplus and borrow from them. When the overall money demand rises, as reflected in an appreciation of the offshore currency, demand in the interbank market will be higher and supply will be lower, so the interbank interest rate will rise to clear the market. Afterwards, the HKMA intervention to maintain the peg should increase the supply of liquidity and the interbank rate should revert back down.

Figure 5 estimates the same local projection as in equation (9), but with the 3-month CNH interbank rate on the left hand side (and adding lagged PLP drawings to the control

[43] Table C.2 in appendix C uses instead the exchange rate on the day of the auction. The effect is less precisely estimated and slightly weaker, but the conclusion is the same. Note that auction results are not announced until after the market closes and the bills are not settled until two days later. Therefore, the exchange rate on the day of the auction is not contaminated by the auction outcome.

Table 2: Regression of bill auction subscription rate on the exchange rate

Bill maturities	All	12M	6M	3M
	(1)	(2)	(3)	(4)
$\frac{1}{5}\sum_0^4 e_{t-h}$	-2.76***	-3.38***	-2.78***	-3.38***
	(0.93)	(1.10)	(0.93)	(1.12)
Number of Auctions	35	19	16	19
R^2	0.142	0.335	0.131	0.324

Heteroskedasticity robust standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, ***$p < 0.01$

Note: The sample has 56 issuance of bills in 35 different auctions between November 2018 and May 2023. In 19 of these auctions, the PBoC issues 3M and 12M maturities, while in the other 16 auctions it issued the 6M maturity. The subscription rate is defined as bids divided by bills auctioned. Column (1) considers the subscription rate across all maturities at the auctions date, and columns (2)-(4) each maturity separately. Columns (2) and (4) are estimated in a seemingly unrelated regressions to account for the fact the 3M and 12M subscriptions occur simultaneously.

set). This measures the change in the private-market price for liquidity in the CNH offshore market. The least squares estimates confirm the two theory predictions: the differential first rises, and then falls. The IV estimates do not have the initial rise the interbank rate, but show the gradual decline over the next few days.

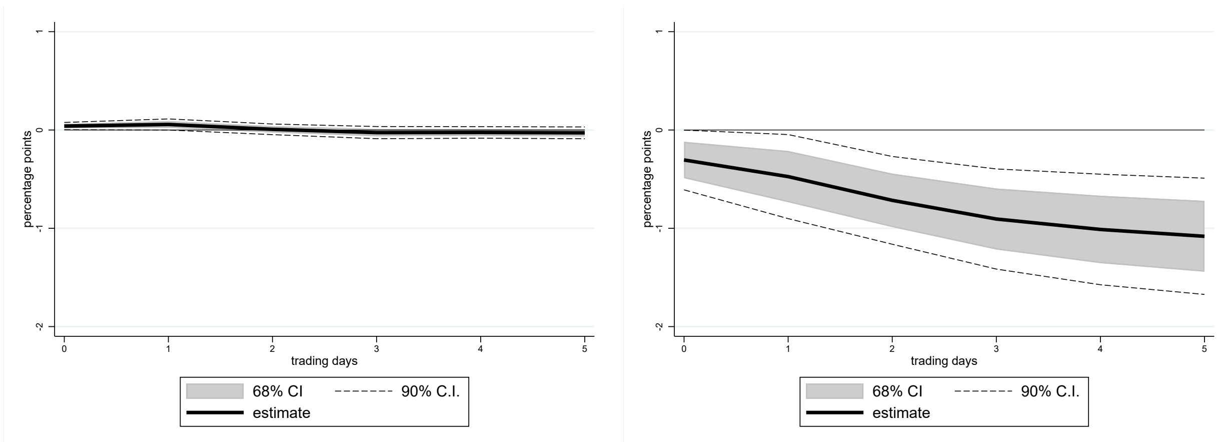
Third and finally, when banks have insufficient liquidity to honor withdrawals or payments by their customers, they have to turn to the discount window even though this is expensive. In the model, the money demand shock comes with a lower deficit threshold $\bar{\omega}$ and a lower probability that deficit banks will not find a lender $1 - \Psi_{-}(\theta)$ and go the discount window.

In the case of CNH-CNY, by keeping the money supply scarce, the PBoC ensures that on aggregate the system finds itself routinely in the position where some banks need to take this route. If the HKMA increases the supply of money through the PLP, then an immediate consequence would be that banks in Hong Kong would find themselves needing to borrow less and less often from the HKMA's discount window. Therefore, running the same regression as in equation (9), but now with drawings from the liquidity facilities as the measures of z_{t+h}, we should expect the estimates of β_h to be mirror images of the ones we found in figure 4.[44]

[44]The HKMA runs two liquidity facilities as repurchase operations that supply CNH liquidity immedi-

Figure 5: Interbank rate differential response to a money demand shock

(a) Local Projection - Least Squares **(b)** Local Projection - Instrumental Variables



Note: Estimates of equation (9) substituting PLP drawings with the 3-month CNH interbank interest rate relative to the CNY rate. The sample period is all trading days between April 2017 and August 2023. Confidence intervals use White heteroskedasticity robust standard errors, following Montiel Olea and Plagborg-Moller (2021). Panel (a) estimates the equation using least squares, whereas panel (b) does so using as an instrument the deviation of the CNY/USD exchange rate from the trading band limit.

Figure 6 shows that indeed it is so. With the expansion of the money supply, use of the discount window falls, by an amount that is similar. Taking the ratio of the two impulse responses, the substitution coefficient between use of the discount window and money supply is around 1 on impact, and rises to around 4 after four trading days.

Figure C.6 in appendix C splits the impact between different times of the day. The use of the discount window falls as soon as the market opens and persists during the day, consistent with banks anticipating that the HKMA will respond by raising the PLP balances. The system to keep the peg at parity is credible.

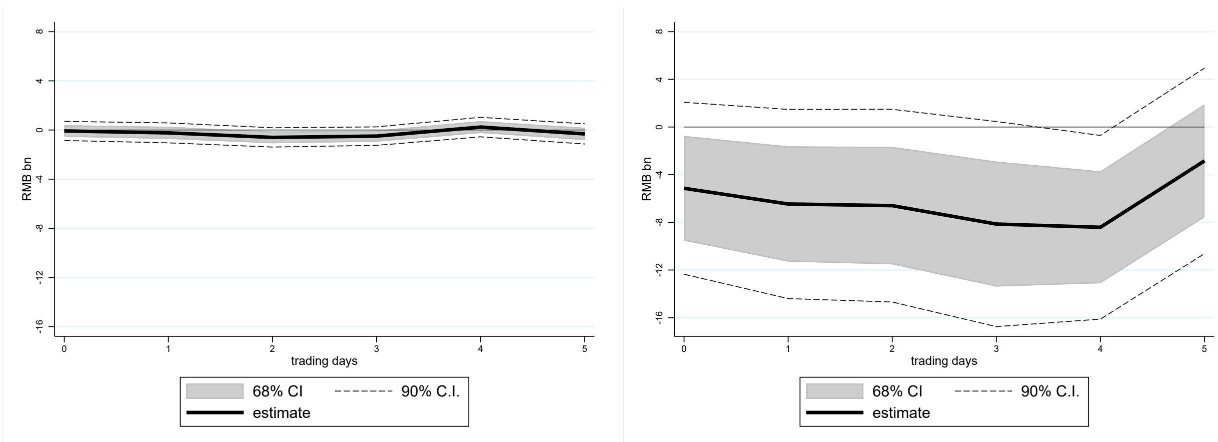
6 Liquidity policies and the foreign exchange rate

So far we have considered monetarist policies, that vary the amount of money supplied through changes in issuance (by the PBoC in its auctions), through elastic accommodation

ately, one intraday and one overnight. Because intraday funds can frictionlessly convert to an overnight loan, Hong Kong banks prefer to use the intraday facility as it retains the option to repay the loan early. As a result, while the intraday facility is heavily used every day, the overnight one has balances close to zero most days (see figure C.1 in appendix C). The regression results in figure 6 use only the intraday facility, but using the sum across the two facilities leads to almost identical results.

Figure 6: Response of HKMA discount window borrowing to a money demand shock

(a) Local Projection - Least Squares **(b)** Local Projection - Instrumental Variables



Note: Estimates of equation (9) substituting PLP drawings with liquidity facility drawings. The sample period is all trading days between April 2017 and August 2023. Confidence intervals use White heteroskedasticity robust standard errors, following Montiel Olea and Plagborg-Moller (2021). Panel (a) estimates the equation using least squares, whereas panel (b) does so using as an instrument the deviation of the CNY/USD exchange rate from the trading band limit.

of demand (by the HKMA in the PLP), and through the discount window for banks under stress. To keep a peg, the central bank can instead use policies that affect the benefit of liquidity. This section uses the model to discuss these policies. At an extreme level, liquidity controls on the flow of deposits and reserves affect the exchange rate.

One use of a parallel currency is to manage the exchange rate with a foreign currency. Movements in that exchange rate will spill over to movements in the liquidity variables that we studied so far. We extend the model to consider the rest of the world and clarify the connection between the exchange rate between the parallel currencies, the exchange rate with the foreign currency, and the liquidity policies. Two large episodes where the yuan devalued relative to the US dollar that provide some evidence for these predictions.

6.1 Liquidity policies

Any shocks that lowers the marginal benefit of reserves $-\phi'(M/D)$ will put pressure to lower E. Policies other than varying the quantity of money M can shift it.

The interest rate on central bank lending: First, the central bank could actively use the interest rate on the discount window. A higher R^z increases the cost of having a liquidity deficit, and raises the marginal benefit of holding on to reserves away from zero. Intuitively, if money markets operate more efficiently, the central bank can make its backstop liquidity more expensive.[45]

Reserve requirements: Second, if ρ increases, then the liquidity threshold in equation (12) will rise. This raises tightness θ as well the likelihood of being in a deficit $\Omega(\omega)$. Therefore, it raises the marginal benefit of holding on to reserves $-\phi'(M/D)$ offsetting the effect of financial innovation. Intuitively, raising reserve requirements makes it more likely that banks will find themselves scrambling for reserves. This new scramble offsets the financial innovation that made reserve management more efficient. Historically, central banks have done so, changing reserve requirements in response to fluctuations in the money multiplier D/M.

Helicopter drops: In the model so far, increases in reserves M are helicopter drops of money. In reality, central banks increase M by purchasing government bonds or central bank bills, just as the PBoC does.

It is straightforward to introduce a stock of central bank bills in the model G. Each bank can now hold them, showing up as an extra term g in the left-hand side of equation (1), and as an extra payoff in equation (2) with gross return R^g. This has no impact on the two equilibrium equations for the reserves and deposits markets. It changes the liquidity cost function because bills are liquid and can be sold during the day to meet withdrawals. If the holdings of bills before and after these trades are g and $g'(\omega)$, respectively, the bank's net surplus of liquidity is now:

$$s(\omega) = m - \rho d + \omega d\,(1-\rho) + g - g'(\omega). \tag{17}$$

Note that $g'(\omega)$ is zero for banks with a liquidity deficit as they will sell all their bills before turning to the interbank market and discount window. Therefore, the new liquidity threshold in equilibrium is:

$$\bar{\omega} = \frac{\rho - \frac{M+G}{D}}{1-\rho}. \tag{18}$$

Because both bills and reserves can meet withdrawals, what matters for whether banks have a deficit or surplus is the total stock of liquid assets $M+G$, not its composition.

However, the interbank market is for reserves, not bills. Therefore, the tightness in

[45]In the case of the CNH, the HKMA could do this by raising the rate it charges on its liquidity facilities, by raising its own CNH reserves to raise the threshold at which it would have to resort to the swap line with the PBoC, or by raising the rate on that line. See footnote 39.

that market is now given by:

$$\theta = \frac{-\int_{-1}^{\bar{\omega}} s(\omega) d\Omega(\omega)}{\int_{\bar{\omega}}^{\infty} s(\omega) d\Omega(\omega) - G}. \tag{19}$$

This clearly increases with G, for a fixed $M + G$, because issuing more bills means fewer reserves, and so a tighter interbank market for reserves. The rest of the model is unchanged, and so is the expression for the marginal benefits of liquidity in equation (15).

In this modified model, a helicopter drop of money M that leaves G unchanged, works just the same as in the previous model, lowering the marginal benefit of reserves. However, if instead the increase in reserves is used to pay for bills, now $M + G$ is unchanged so there is no longer an effect on $\bar{\omega}$. Instead the effect now comes from equation (19), as the interbank market is looser. This is what lowers the marginal benefit of reserves now.

In practice, the PBoC could do a helicopter drop of money M, for instance by buying CNY government bonds and paying for them with newly-issued CNH reserves. Conversely, it could do a helicopter drop of bills G, for instance by lending out offshore bills in repos against onshore bills. These provide further liquidity tools to offset financial innovation, sustain the peg, and keep capital controls.

We do not have direct empirical evidence to test the effects of these liquidity policies. We know that the PBoC has varied the terms of its swap line with the HKMA as well as imposed foreign risk reserve ratios and a countercyclical factor, effectively influencing the expected cost of liquidity shortfalls and having to borrow from the discount window. We also know that the banks that create CNH are subject to financial regulations and suasion by the Chinese authorities and their effects will be akin to those of reserve requirements. And we know, from media reports, that Chinese State banks will buy and sell CNH at the encouragement of the authorities, effectively doing FX interventions similar to helicopter drops. But for all of these three policies studied in this section, we either do not have accurate measurements, or we cannot identify exogenous movements. An exception were extreme liquidity controls adopted in 2015-165. We turn to studying them in theory and in practice next.

6.2 Liquidity controls

Another way to offset financial innovation and maintain the capital controls is to introduce separate liquidity controls on either the flow of deposits or reserves.

Deposit flows: We modify the model in two ways. First, we replace equation (10) with:

$$d \int_{-1}^{\infty} \omega d\Omega(\omega) = W^d. \tag{20}$$

The new term, W^d captures the flow of deposits from onshore to offshore during the day. These are decided by private households, but subject to the tight regulations from the PBoC. We therefore treat them as an exogenous policy tool that banks take as given.[46] An increase in W^d works just like a shift in the distribution $\Omega(\omega)$ that makes it less likely that banks will have a liquidity deficit. In that way, tightening liquidity controls that lower W^d can exactly offset financial innovation.

Reserve flows: Second, we allow banks to move onshore reserves to offshore reserves to meet liquidity needs. We denote this inflow of liquidity by W^m, and again assume that it is exogenous because the PBoC has a tight control over the clearing banks through which these transfers happen.[47] This changes market tightness in much the same way as bills did. Equation (13) is replaced by (see appendix D.3):

$$\theta = \frac{-\int_{-1}^{\bar{\omega}} s(\omega) d\Omega(\omega)}{\int_{\bar{\omega}}^{\infty} s(\omega) d\Omega(\omega) - G + W^m}. \tag{21}$$

Again, liquidity controls that lower W^m can exactly offset financial innovation's impact on tightness. They work just as more bills: they tighten the interbank market by reducing the flow of onshore to offshore reserves.

Predictions: Putting the two elements together, tighter liquidity controls that reduce the flow of either deposits or reserves will increase the marginal benefit of offshore reserves. They offset financial innovation and preserve the central bank's ability to have capital controls and for the exchange rate to temporarily deviate from parity.

At the other extreme, if these flows were liberalized, and W^d or W^m became very large, tightness in the interbank market would go to zero and so would the marginal benefit of reserves. Extreme financial liberalization in liquidity would imply that capital controls no longer bind, UIP would hold, and the quantity of CNH money would be irrelevant.

[46] The model already has an endogenous choice between the two types of deposits, by both banks and households. So, we are effectively assuming that the constraints imposed by the PBoC on the total volume of these flows are always binding.

[47] Here as well, including an onshore side—with bills, interbank markets, and discount windows—does not change the ex ante allocation of reserves between onshore and offshore in the model's dynamics once we assume that the constraint on moving onshore to offshore reserves always binds.

6.3 The foreign exchange rate

Consider a bank in the rest of the world (RoW) that can freely invest in offshore reserves or in foreign reserves, with return $R^{m,\text{RoW}}$ in the other currency. The exchange rate between RoW and the offshore money is $\hat{E}$. The optimality condition for this bank in choosing between which money to hold is:

$$R^m - \phi'(M^{\text{RoW}}/D^{\text{RoW}}) = \left(\frac{\mathbb{E}(\hat{E}')}{\hat{E}}\right)\left(R^{m,\text{RoW}} + w\right). \tag{22}$$

On the left-hand side is the return from investing in offshore yuan, including the marginal benefit of having offshore reserves for payments. Arguably, for a foreign investor, these may be negligible, but we include them for completeness. On the right-hand side is the return in foreign currency of investing abroad. We add to it a UIP wedge, w, following the literature that emphasizes financial frictions and limits to arbitrage that make foreign investors refrain from investing domestically. This is partly determined by foreign forces, like the risk capacity of foreign arbitrageurs, but also partly affected by foreign exchange interventions that change the stock of offshore money held by those arbitrageurs.

Combining equation (22) with equation (3) that had the optimality condition for offshore banks gives:

$$\hat{E} = \mathbb{E}(\hat{E}')\left(\frac{R^{m,\text{RoW}} + w}{E + \phi'(M/D) - \phi'(M^{\text{RoW}}/D^{\text{RoW}})}\right). \tag{23}$$

This is the key modified UIP condition determining the exchange rate between the offshore and the foreign currency.[48] As usual, higher returns abroad relative to returns domestically or a higher wedge that favors investing abroad, leads to an expected appreciation and so depreciates the domestic currency today.

A parallel currency adds two novel determinants of the exchange rate. The first is the offshore-onshore exchange rate E. When the domestic money is depreciating relative to the foreign currency, letting the offshore money depreciate from parity attenuates that movement. In the case of the yuan, the PBoC has an explicit desire to smooth fluctuations in $\hat{E}$ and having E as an escape valve gives it a tool to do so, subject to the limit that E cannot fall too far for too long without putting pressure on the capital controls. But, as a

[48] Recall that we assumed $R^{m,o} - \phi^{o\prime}(M^o/D^o) = 1$ to focus on offshore liquidity. Onshore interest rates and money would affect UIP in the standard way.

policy tool to absorb transitory fluctuations or smooth permanent adjustments, this can be valuable. This smoothing policy comes with an empirical prediction: that $\hat{E}$ and E will move in opposite directions. We found in section 4 this association was strong.

The second ingredient is the role of liquidity affecting the marginal benefit of offshore reserves $\phi'(.)$ held by either offshore banks banks M or by foreign banks M^{RoW}. As we studied in this section, liquidity policies and controls can keep the offshore parity through this term. Equation (23) shows that liquidity tools and controls can also offset changes in the UIP wedge w being redeployed to manage the foreign exchange rate. Foreign exchange interventions, capital controls, and liquidity policies and controls interact with each other and have to be jointly considered, using a model like the one we put forward.

6.4 The 2015-17 yuan depreciation and the regime reform

The CNH was first introduced to businesses in Hong Kong in 2004, but it was only slowly adopted until its official launch in July of 2010. The launch was part of a package of financial reforms to create an offshore market that would allow for an open current account and a closed capital account but also to jumpstart the international use of the RMB by lowering trade credit costs.[49]

In 2015-16, macro-financial forces led to a trend depreciation of the RMB relative to the USD, visible in panel (a) of figure 7. Before 2015, the trading band through which the PBoC managed the exchange rate with the dollar had a parity rate that was held fixed. Therefore, the CNY/USD exchange rate persistently traded at the lower bound of that range. In August of 2015, the PBoC switched to fixing the parity rate near the previous day's close. This prompted a 3% depreciation in the CNY between August 11th and 13th, marked with the first vertical dashed blue line in figure 7. As predicted by our model, the CNH depreciated an additional percentage point against USD, and a large deviation on the CNH/CNY parity emerged. The CNH traded at an average 0.6% discount compared to CNY throughout the remainder of 2015.

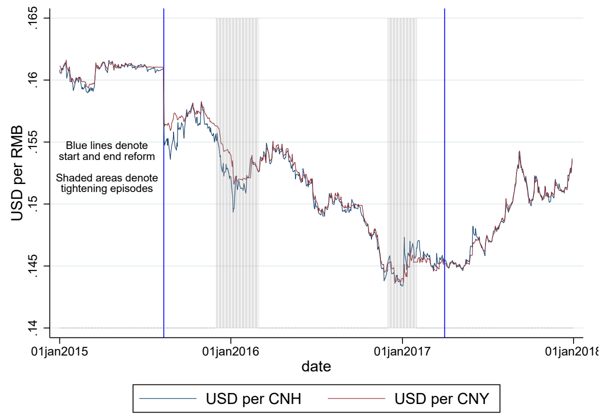
The PBoC's response in December 2015 was to tighten the liquidity controls on the flow of deposits and reserves (W^d and W^m in our model). Panel (b) shows the flows from the onshore to the offshore market in the Chinese current account.[50] They fell sharply, by more than one fifth right away, and a further two fifths over the next few months.

[49]On the jumpstart, see Bahaj and Reis (2020), and on recent evolutions in the international use of the yuan, see Chupilkin et al. (2023).

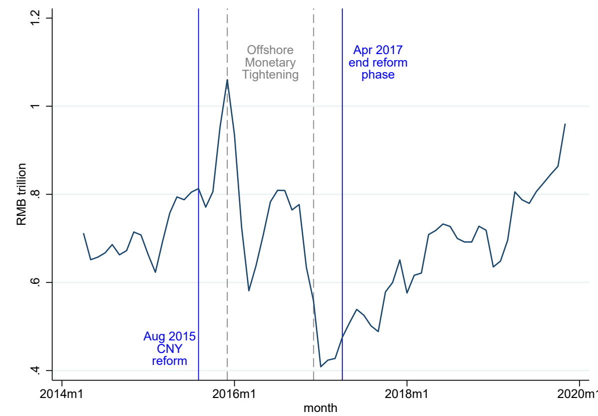
[50]The flows in the other direction are reported in appendix, figure C.9.

Figure 7: The monetary tightenings of 2015 and 2016

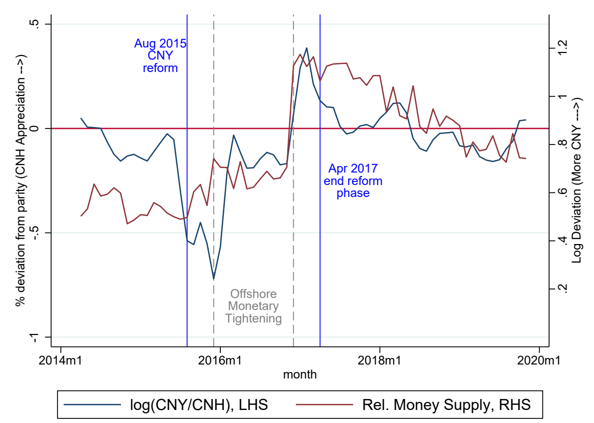
(a) CNH/USD and CNY/USD exchange rates



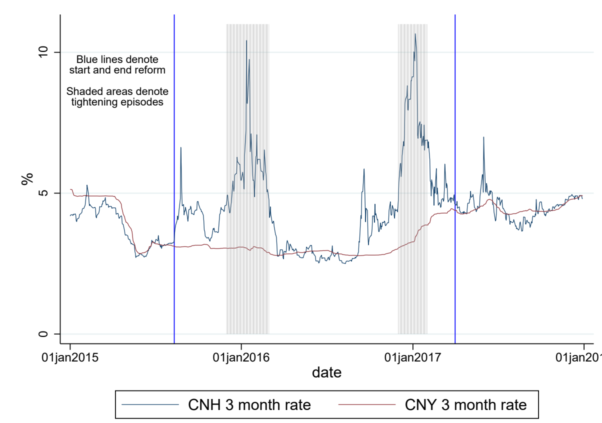
(b) RMB flows from onshore to offshore



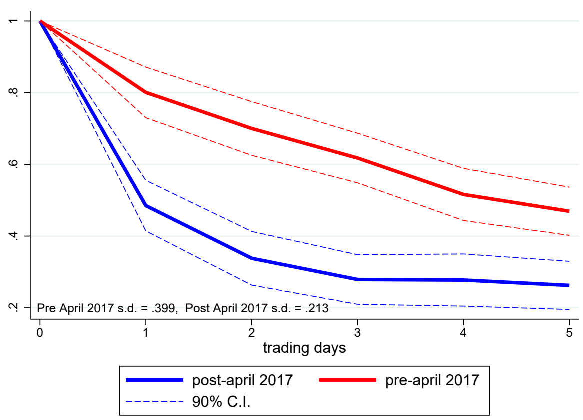
(c) Relative stock of CNH/CNY deposits and e



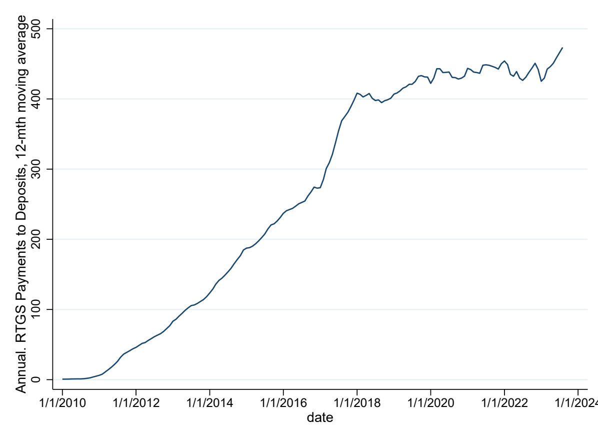
(d) 3-month interbank rates for CNH and CNY



(e) Persistence of e pre and post April 2017



(f) CNH velocity



Note: Panel (a) shows CNY/USD and CNH/USD exchange rates. Panel (b) shows the conversion of CNH into CNY from the current account, at a monthly frequency. Panel (c) shows $\log(D_t^{\text{CNY}}) - \log(D_t^{\text{CNH}})$ against monthly average e_t. Panel (d) shows CNY and CNH interbank rates relative to USD interbank rates. Panel (e) compares the daily autocorrelograms in e_t between October 2010 and March 2017 in red, and between April 2017 and May 2023 in blue. Panel (f) shows the ratio of annual transfers from the real time gross settlement system to the stock of CNH deposits.

Panels (c) and (d) show the consequences for liquidity, which line up with our model and the identified empirical mechanisms. Panel (c) shows the stock of CNH and CNY deposits at a monthly frequency. The stock of CNH deposits (D in our model) fell by 20 log points relative to CNY deposits during the December 2015 tightening. This intervention brought CNH/CNY closer to parity, as in our model of E and D. Panel (d) shows interbank rates offshore and onshore. The PBoC's actions caused the 3-month CNH interbank rates ($R^f(\theta)$) to spike above 10%, while equivalent CNY rates were stable at around 3%, again as predicted by our model as a result of increased tightness in the interbank market (θ).

Over the course of 2016, the CNY remained on a depreciating trend, and the CNH successively traded below parity (panel (a)). When depreciation intensified at the end of the year, the PBoC repeated its intervention in December 2016. Again, liquidity controls were tightened (panel (b)), CNH deposits fell by 40 log points on a relative basis (panel (c)), and interbank rates leapt (panel (d)), bringing about a sharp appreciation of CNH/CNY that pushed it above parity (panels (a) and (c)).

The start of 2017 allowed for normalization, helped by the stabilization of the exchange rate with the USD. In the spring of 2017, the PBoC introduced a countercyclical factor in its fixing that allowed for more discretion over the pace of adjustments in exchange rate policy. In the offshore market, the PBoC introduced the regular auctions of bills giving it greater control over the offshore money supply. Also, during 2016 and 2017, the HKMA reformed the automatic liquidity facilities, expanding the number of primary liquidity providers from 7 to 9, lowering the penalty rates on the discount windows, and expanding the set eligible collateral. The data since April 2017 has seen the CNH/CNY exchange rate much closer to parity, in spite of large fluctuations in the exchange rate with the USD (recall figure 1).

Our model predicts that with these reforms, the PBoC would be better able to keep the peg at parity. Panel (e) of figure 7 confirms it has been so: the standard deviation fell by almost half, and dynamic conditional autocorrelation function of the exchange rate after the 2017 reform (from figure 3) shows that deviations from parity die faster after April 2017 than they did beforehand.

Finally, panel (f) plots the velocity of CNH money, by dividing all CNH RTGS transactions in Hong Kong in one year by the average stock of CNH deposits. The 2015-2017 reforms have significantly increased this velocity, which averaged 431 between 2018 and 2022. By comparison, the average velocity for the United States, equivalently defined as the annual ratio between Fedwire transactions and M1 less currency, between 2012 and 2019 was 450. This is consistent with an efficient management of liquidity, as our model in section 5 predicted.

6.5 The August 2023 depreciation

In August of 2023, high inflation in most advanced economies led to a rise in foreign interest rates. At the same time, a slow recovery of the Chinese economy from lockdown led the PBoC to keep yuan interest rates unchanged and expand the onshore money supply. Combined, the increase in $R^{m,\text{RoW}}$ and the fall in $R^{m,o}$ led $\hat{E}$ to rise, so the yuan depreciated just as expected from equation (23).

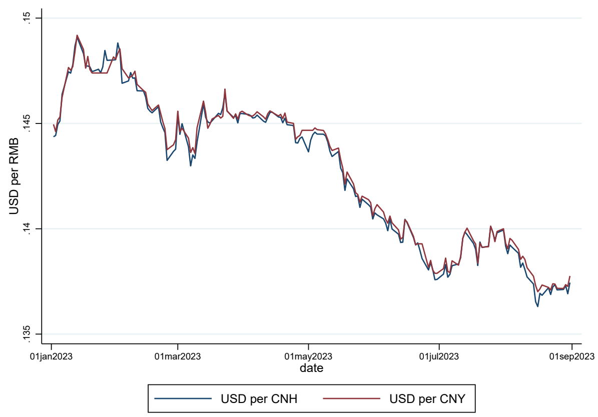
Figure 8 shows that financial variables during this month behaved exactly as our model and empirical findings would suggest. Panel (a) shows the steady depreciation of the yuan, and panel (b) shows that again CNH started trading below parity relative to CNY. Panels (c) and (d) show the automatic responses to this negative money demand shock: the interbank rate in CNH spiked relative to CNY, and borrowing from the liquidity facility at the HKMA increased. Also, the amount bid for CNH bills increased by 50% in the August auction relative to the May auction. Using the language of the model, as $\hat{E}$ rose, some of it was absorbed by a fall in E, while θ increased as shown by higher $R^f(\theta)$ and lower $\Psi_-(\theta)$.

The PBoC responded by increasing the issuance of CNH 3M bills from ¥10bn to ¥20bn in the August auction, reducing the money supply. State banks sold USD reserves in a way similar to a sterilized foreign exchange market intervention. In the language of the model captured in equation (23), the PBoC cut M to raise $\phi'(M/D)$ and lowered w, respectively. These complemented the movement in E shown in the figure, in order to prevent $\hat{E}$ moving as much as it otherwise would have.

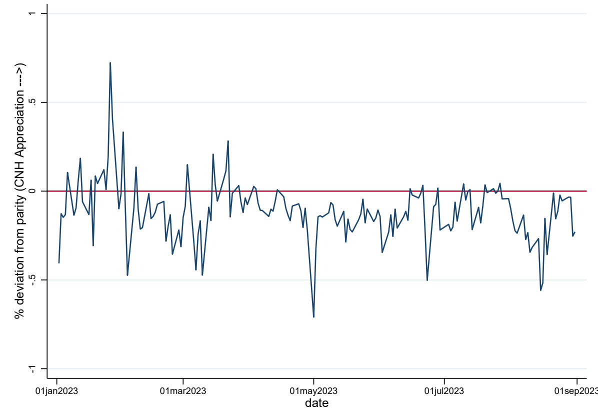
The contrast with 2015-16 is noticeable. With the post-2017 framework that we analyzed in this paper, the stress in the peg was smaller. Interbank rates rose less, and the deviations from the peg were smaller and less persistent. The exogenous control of the supply of money by the PBoC, the elastic supply of money by the KHKMA, and the use of liquidity policies played their role. The PBoC did not have to resort to liquidity controls, with the negative consequences that this would have for the development of the yuan as an international currency.

Figure 8: The August 2023 episode

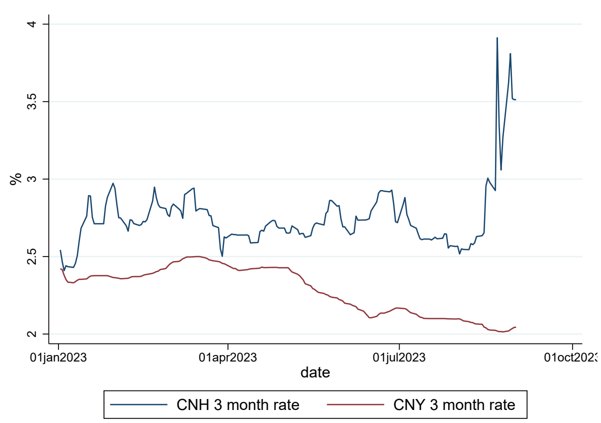
(a) CNH/USD and CNY/USD exchange rates



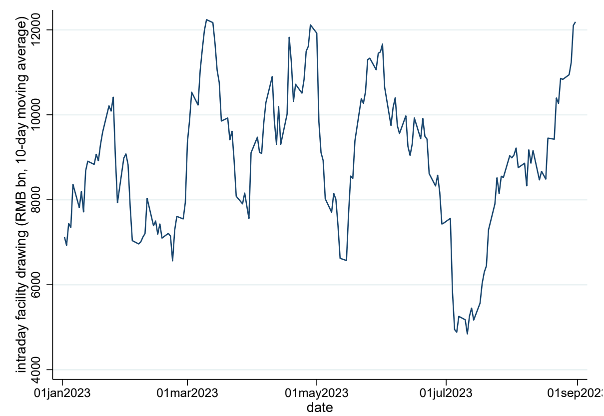
(b) CNH/CNY exchange rate



(c) 3-month interbank rates for CNH and CNY



(d) HKMA discount window borrowing



Note: The sample is all trading days between 1 January 2023 and 31 August 2023. Panel (a) shows CNY/USD and CNH/USD exchange rates. Panel (b) shows $100 \log(CNH/CNY)$ so an increases is a CNH appreciation. Panel (c) shows CNY and CNH interbank rates relative to USD interbank rates. Panel (d) shows the 10-day moving average of maximum daily drawings from the HKMA's intraday RMB liquidity facility.

7 Conclusion

More than a decade ago, Chinese monetary authorities created an offshore currency in order to be able to enforce capital controls, while at the same time allowing for an open current account and for the yuan to be used as an international currency. This created a regime of parallel currencies, the offshore and the onshore yuan, with separate money supplies, and a particular liquidity framework to control the private creation of money while keeping a peg of the two currencies close to parity.

This monetary experiment provides new insights into what drives exchange rates. We found that exogenous transitory increases in the money supply depreciate the exchange rate. This confirms that money is not a pure financial asset and liquidity matters. We also found evidence that monetary policy has responded to increases in the demand for money by raising the money supply and this has kept deviations from the peg small and short-lived. This prevented the usual demise of parallel currencies from Gresham's law and allowed capital controls to survive. The implied semi-elasticity of money demand is 0.09, consistent with estimates from money demand estimation, but significantly different from cashless-limit theories of exchange rates or the simple quantity theory. Complementing these two main findings, we also found that the use of liquidity facilities, rates in interbank markets, and the demand for bills in auctions are all consistent with money demand and supply.

Theoretically, we proposed a model of how banks create deposits and manage the liquidity to support them. The model provided a micro-foundation for the empirical results in the previous paragraph as well as for Goodhart's law. It showed how liquidity tools—like the interest rate charged in the discount window, reserve requirements, and helicopter drops of money or of bills—together with liquidity controls on the flow of deposits and reserves can keep the central bank's control over money, the exchange rate, and capital controls. With respect to foreign currency, the model suggested that by using liquidity policies and controls and allowing for deviations from parity, the central bank can partially and temporarily manage the foreign exchange rate. The behavior of liquidity variables and exchange rates in China in 2015-16 and August of 2023 are consistent with this usage by the PBoC.

Our analysis provides future guidance for the PBoC on where the seams of its liquidity framework may burst and how to reinforce them. More intriguingly, it suggests that the yuan's international use could still significantly increase and that other countries could try frameworks inspired by this experience.

References

Bahaj, Saleem, and Ricardo Reis. 2020. "Jumpstarting an International Currency." *CEPR discussion paper 14793*.

Ball, Laurence. 2001. "Another Look at Long-Run Money Demand." *Journal of Monetary Economics*, 47(1): 31–44.

Benati, Luca, Robert E. Lucas, Juan Pablo Nicolini, and Warren Weber. 2021. "International Evidence on Long-Run Money Demand." *Journal of Monetary Economics*, 117: 43–63.

Bianchi, Javier, and Saki Bigio. 2022. "Banks, Liquidity Management, and Monetary Policy." *Econometrica*, 90(1): 391–454.

Bianchi, Javier, Saki Bigio, and Charles Engel. 2021. "Scrambling for Dollars: International Liquidity, Banks and Exchange Rates." National Bureau of Economic Research Working Paper 29457.

Bordo, Michael D., Owen F. Humpage, and Anna J. Schwartz. 2015. *Strained Relations: US Foreign-Exchange Operations and Monetary Policy in the Twentieth Century.* University of Chicago Press.

Bordo, Michael, Eric Monnet, and Alain Naef. 2019. "The Gold Pool (1961–1968) and the Fall of the Bretton Woods System: Lessons for Central Bank Cooperation." *Journal of Economic History*, 79(4): 1027–1059.

Burdekin, Richard C.K., and Marc D. Weidenmier. 2001. "Inflation Is Always and Everywhere a Monetary Phenomenon: Richmond vs. Houston in 1864." *American Economic Review*, 91(5): 1621–1630.

Chen, Kaiji, Jue Ren, and Tao Zha. 2018. "The Nexus of Monetary Policy and Shadow Banking in China." *American Economic Review*, 108(12): 3891–3936.

Chodorow-Reich, Gabriel, Gita Gopinath, Prachi Mishra, and Abhinav Narayanan. 2019. "Cash and the Economy: Evidence from India's Demonetization." *Quarterly Journal of Economics*, 135(1): 57–103.

Chupilkin, Maxim, Beata Javorcik, Aleksandra Peeva, and Alexander Plekhanov. 2023. "Exorbitant privilege and economic sanctions." *EBRD working paper 281*.

Clayton, Christopher, Amanda Dos Santos, Matteo Maggiori, and Jesse Schreger. 2023. "Internationalizing Like China." *CEPR discussion paper 17781*.

Dedola, Luca, Georgios Georgiadis, Johannes Gräb, and Arnaud Mehl. 2021. "Does a Big Bazooka Matter? Quantitative Easing Policies and Exchange Rates." *Journal of Monetary Economics*, 117: 489–506.

Engel, Charles. 2016. "Exchange Rates, Interest Rates, and the Risk Premium." *American Economic Review*, 106: 436–474.

Engel, Charles, and Steve P. Y. Wu. 2023. "Liquidity and Exchange Rates: An Empirical Investigation." *Review of Economic Studies*, 90(5): 2395–2438.

Friedman, Milton. 1971. "The Euro-dollar Market: Some First Principles." *Federal Reserve Bank of St. Louis Review*, 53: 16–24.

Friedman, Milton, and Anna Jacobson Schwartz. 2008. *A Monetary History of the United States, 1867-1960.* Princeton University Press.

Funke, Michael, Chang Shu, Xiaoqiang Cheng, and Sercan Eraslan. 2015. "Assessing the CNH-CNY Pricing Differential: Role of Fundamentals, Contagion, and Policy." *Journal of International Money and Finance*, 59: 245–262.

Gourinchas, Pierre-Olivier, Walker D Ray, and Dimitri Vayanos. 2022. "A Preferred-Habitat Model of Term Premia, Exchange Rates, and Monetary Policy Spillovers." National Bureau of Economic Research Working Paper 29875.

Greenwood, Robin, Samuel Hanson, Jeremy C Stein, and Adi Sunderam. 2023. "A Quantity-Driven Theory of Term Premia and Exchange Rates." *The Quarterly Journal of Economics*, 138(4): 2327–2389.

Hachem, Kinda, and Zheng Song. 2023. "Liquidity Rules and Credit Booms." *Journal of Political Economy*, 129(10): 2721–2765.

He, Zhiguo, and Wei Wei. 2023. "China's Financial System and Economy: A Review." *Annual Review of Economics*, 15(1): 451–483.

He, Zhiguo, Yuehan Wang, and Xiaoquan Zhu. 2023. "The Stock Connect to China." *AEA Papers and Proceedings*, 113: 125–30.

Hu, Jiafei, and Haishan Yuan. 2021. "Interest Arbitrage Under Capital Controls: Evidence from Reported Entrepot Trades." *Journal of Banking and Finance*, 127: 106–129.

Ilzetzki, Ethan, Carmen Reinhart, and Kenneth Rogoff. 2019. "Exchange Arrangements Entering the Twenty-First Century: Which Anchor will Hold?" *Quarterly Journal of Economics*, 134(2): 599–646.

Itskhoki, Oleg, and Dmitry Mukhin. 2021. "Exchange Rate Disconnect in General Equilibrium." *Journal of Political Economy*, 129(8): 2183–2232.

Jermann, Urban J, Bin Wei, and Vivian Z Yue. 2022. "The Two-Pillar Policy for the RMB." *Journal of Finance*, 77(6): 3093–3140.

Jiang, Zhengyang, Arvind Krishnamurthy, and Hanno Lustig. 2021. "Foreign Safe Asset Demand and the Dollar Exchange Rate." *The Journal of Finance*, 76(3): 1049–1089.

Liu, Renliang, Liugang Sheng, and Jian Wang. 2022. "Faking Trade for Capital Control Evasion: Evidence from Dual Exchange Rate Arbitrage in China." manuscript.

Maggiori, Matteo. 2022. "International Macroeconomics with Imperfect Financial Markets." In *Handbook of International Economics*. Vol. 6, , ed. Gita Gopinath, Elhanan Helpman and Kenneth Rogoff, Chapter 5, 199–236. Elsevier.

McCauley, Robert N, and Chang Shu. 2018. "Recent RMB Policy and Currency Co-movements." *BIS working paper 727*.

Meese, Richard A., and Kenneth Rogoff. 1983. "Empirical Exchange Rate Models of the Seventies: Do They Fit Out of Sample?" *Journal of International Economics*, 14: 3–24.

Monnet, Eric. 2014. "Monetary Policy without Interest Rates: Evidence from France's Golden Age (1948 to 1973) Using a Narrative Approach." *American Economic Journal: Macroeconomics*, 6(4): 137–69.

Montiel Olea, José Luis, and Mikkel Plagborg-Moller. 2021. "Local Projection Inference Is Simpler and More Robust Than You Think." *Econometrica*, 89(4): 1789–1823.

Naef, Alain, Eric Monnet, Camille Macaire, Arnaud Mehl, and Barry Eichengreen. 2022. "The Renminbi's Unconventional Route to Reserve Currency Status." *VoxEU column*.

Palma, Nuno. 2021. "The Real Effects of Monetary Expansions: Evidence from a Large-scale Historical Experiment." *Review of Economic Studies*, 89(3): 1593–1627.

Poole, William. 1968. "Commercial Bank Reserve Management in a Stochastic Model: Implications for Monetary Policy." *Journal of Finance*, 23(5): 769–791.

Selgin, George. 2020. "Gresham's Law." *Handbook of the History of Money and Currency*, , ed. Stefano Battilossi, Youssef Cassis and Kazuhiko Yago, 199–219. Springer Singapore.

Song, Zheng (Michael), and Wei Xiong. 2018. "Risks in China's Financial System." *Annual Review of Financial Economics*, 10(1): 261–286.

Valchev, Rosen. 2020. "Bond Convenience Yields and Exchange Rate Dynamics." *American Economic Journal: Macroeconomics*, 12(2): 124–66.

Velde, François R. 2009. "Chronicle of a Deflation Unforetold." *Journal of Political Economy*, 117(4): 591–634.

Appendix

A Data appendix

All data were last accessed on September 4th of 2023 unless stated otherwise.

FX data. Daily FX data are sourced from Refinitiv datastream at a daily frequency. The CNYUSD MID daily price is ticker TDCNYSP, the CNHUSD MID daily price is ticker TDCNHSP. The CNHCNY exchange rate is the ratio of the two.

Interbank rates. 3 month interbank rates were sourced from Refinitiv datastream, onshore ticker: CHIB3MO and offshore ticker: HIBOR3M.

PBoC CNH Bills. The tender announcements and auction results from the PBoC's issuance of CNH bills were hand collected from press releases from the HKMA and PBoC.

HKMA RMB Facilities. Usage of the HKMA's RMB facilities were downloaded directly from the HKMA's website, via API. The data is available at 9am, 11am, 2pm and 4pm Hong Kong time. We take the maximum of the intraday figures when computing a daily series.

Deposits, M1. Total customer deposits in CNH in Hong Kong banks are sourced from the HKMA via datastream (ticker: HKCUSTOTA). The onshore money supply is customer deposits at mainland Chinese banks sourced from the PBoC via datastream (ticker CHCNBXLLM).

B The HKMA facilities

The HKMA runs five CNH facilities, all using repurchase agreements. Three of them settle on the day so that banks have immediate access to CNH liquidity. They are: a dedicated liquidity facility for primary liquidity providers, an intraday repo facility, and an overnight repo facility. Two others are at term with a T+1 settlement cycle and a maturity of one day and one week, respectively.

The primary liquidity providers' facility allows each of the nine provider banks access to ¥2bn available either intraday or overnight. The rates and collateral requirements on the facility are institution-specific and are not disclosed, but they are on preferential terms.

The intraday repo facility' allows authorized institutions to borrow up to ¥20bn (prior to 22nd July 2022 it was ¥10bn) against a range of debt securities at a penalty rate equal to the average of the three most recent overnight CNH HIBOR fixings plus 25bp (prior to 22nd July 2022, it was plus 50bp). Interest is charged at a per minute basis and the repo converts automatically to the overnight facility if it is not repaid by 5am on the next calendar day.

The overnight repo facility allows authorized institutions to borrow up to ¥20bn (prior to 22nd July 2022, it was ¥10bn) on the same terms as the intraday facility. The two facilities have separate limits so in principle the HKMA could lend RMB 20bn intraday and RMB 20bn overnight to the same bank, and then convert the intraday borrowing into overnight for a total of RMB 40bn. Overnight borrowing needs to be repaid by 2pm the following trading day.

Figure C.1 shows the total daily usage of these three facilities. The overnight repo is rarely used, likely because intraday borrowing converts into overnight borrowing automatically.

The term facilities operate on a T+1 settlement cycle, and are funded using the HKMA's swap line with the PBoC's as opposed to from the HKMA's deposits at the clearing bank. Interest rates on these are not disclosed apart from a reference to prevailing market rates, nor is their usage. This suggests these facilities are designed to be used as a backstop if the other facilities are exhausted and the HKMA needs to channel emergency liquidity from the PBoC.

C Complementary empirical results

Figure C.2 plots the relative growth rate of the money stock in CNY and CNH against the lagged change in the exchange rate at a monthly frequency. Money is measured using customer deposits in RMB at banks operating on the mainland and in Hong Kong: a measure of M1 without physical currency. Of course, both m and e are endogenous with respect to other variables. At the monthly frequency the PBoC varies the CNH reserves that back these sight deposits in response to shocks, and the private clearing banks respond to shocks to the demand for CNH liquidity.

Table C.1 shows that the associated regression coefficient is large. However, with only 71 monthly observations, precision is weak, and the estimate is only statistically significant at the 10% level. Figure C.2 plots the data behind this regression to confirm the weak relation. Columns (2) and (3) in the table also confirm that the entire correlation is driven by the supply of CNH, as expected. Monetary policy onshore for mainland China is driven by other factors.

Figure C.3 splits the response of the exchange rate to the exogenous shocks to money supply by each episode of a bill roll-over.

Figure C.4 plots exchange rates against either relative interest rates, or relative money supplies for a sample of peggers. The data comes from all reporting countries in the IMF International Financial Statistics (IFS) dataset that have a USD market exchange rate in Bloomberg and that have a rating of 3 or 4 in the Ilzetzki, Reinhart and Rogoff (2019) scale of pegs gives an unbalanced panel of 26 countries from February 1979 to December 2015.

Figure C.5 shows the persistence of the exchange rate deviations within one day.

Figure C.1 already showed the total daily usage of the facilities that are settled within the day. The HKMA also publishes data on drawings from the PLP and the intraday facilities at different points in time during the day. Figure C.6 shows the projections of the drawings from both the PLP and the liquidity intraday facility during the day on the exchange rate at the close of the previous day. The pattern shows that most of drawings have occurred by 11am and then are stable throughout the day.

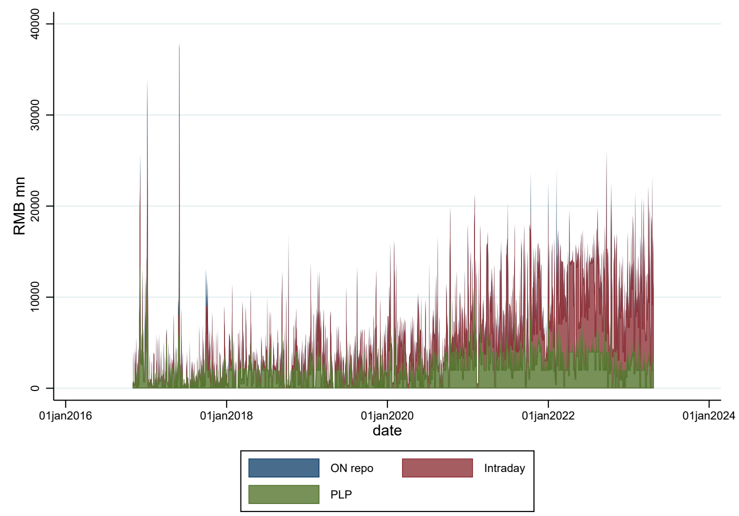
Figure C.7 plots both the CNH/CNY exchange rate as well as the instrument that we used for it in section 4: the log deviation of the CNY/USD central parity rate with the exchange rate on the previous day.

Figure C.8 is the equivalent of figure 4 panel (b), but using only drawings between 11am and 4pm to reflect that the central parity rate is announced at 11am.

Table C.2 presents the subscription rate results using the exchange rate on the day of the auction.

Figure C.9 shows the flows of RMB from offshore to onshore during 2015-16. They also show a contraction, in line with figure 7.

Figure C.1: Usage of the HKMA on-demand lending programs



Note: Maximum daily usage of the HKMA's RMB liquidity facilities by trading day, November 2016 to May 2023.

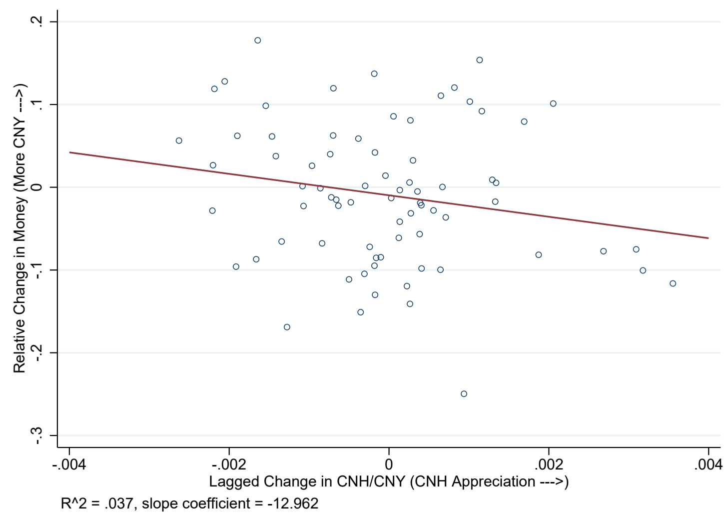
Table C.1: The correlation between the exchange rate and the relative stock of money

	$\Delta\left(m_t^{\text{CNH}} - m_t^{\text{CNY}}\right)$	Δm_t^{CNH}	Δm_t^{CNY}
$\Delta \bar{e}_{t-1}$	-12.63*	12.99*	0.35
	(7.3)	(6.9)	(2.7)
N	71	71	71
R^2	0.036	0.044	0.000

Heteroskedasticity robust standard errors in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

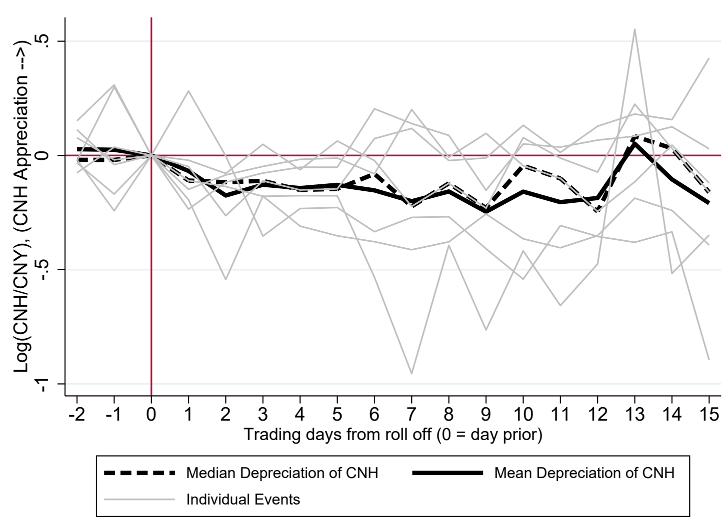
Note: OLS regressions of the lagged monthly change in the CNH/CNY exchange rate on money growth offshore and onshore. See notes to figure C.2 for a description of the data.

Figure C.2: The CNH/CNY exchange rate and the relative stock of money



Note: Scatter plot of the lagged monthly change in the CNH/CNY exchange rate (horizontal axis) against relative money growth offshore and onshore (vertical axis). The horizontal axis show the average of the logarithm of the exchange rate across all trading days in the month, so an increase is a CNH appreciation. Onshore money, m_t^{CNY}, is the logarithm of onshore bank customer deposits'. Offshore money, m_t^{CNH}, is the logarithm of deposits in Hong Kong banks. The vertical axis is $m_t^{\text{CNY}} - m_t^{\text{CNH}}$. Sample is monthly, April 2017 - April 2023.

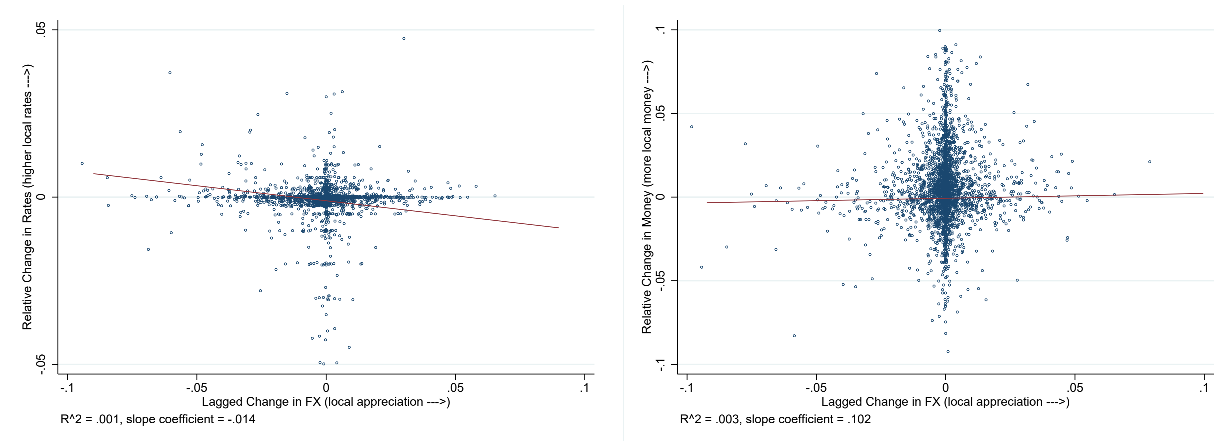
Figure C.3: Response of the exchange rate at each separate money supply event



Note: This figure breaks the response of the exchange rate in figure 2 into the specific events.

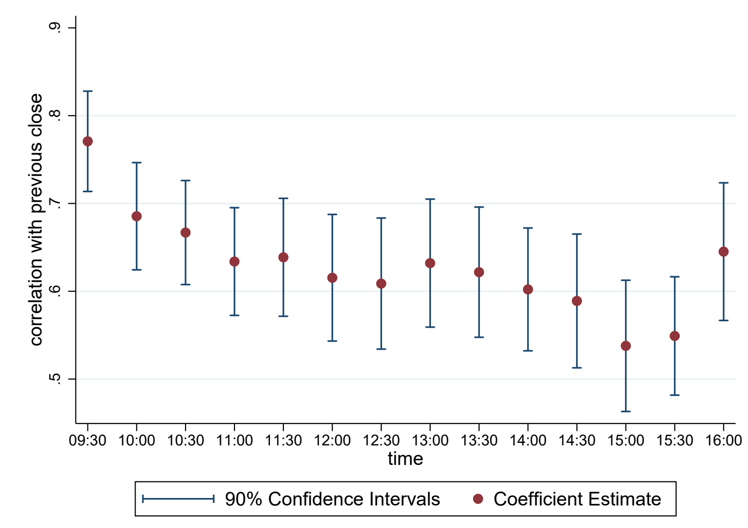
Figure C.4: The missing link between exchange rates, interest rates and money growth for currencies under a peg

(a) Exchange rates and interest rates **(b)** Exchange rates and money stocks



Note: The sample covers all reporting countries in the IMF International Financial Statistics (IFS) dataset that have a USD market exchange rate in Bloomberg and that have a rating of 3 or 4 in the Ilzetzki, Reinhart and Rogoff (2019) scale of pegs. The final sample is an unbalanced panel of 26 countries from February 1979 to December 2015. Panel (a) shows the local policy rate in the IFS data, or the discount rate or repo rate as a substitute. Panel (b) has the log first difference of local broad money growth in panel (b). Relatives are with respect to the US effective funds rate, and the US measure of M2.

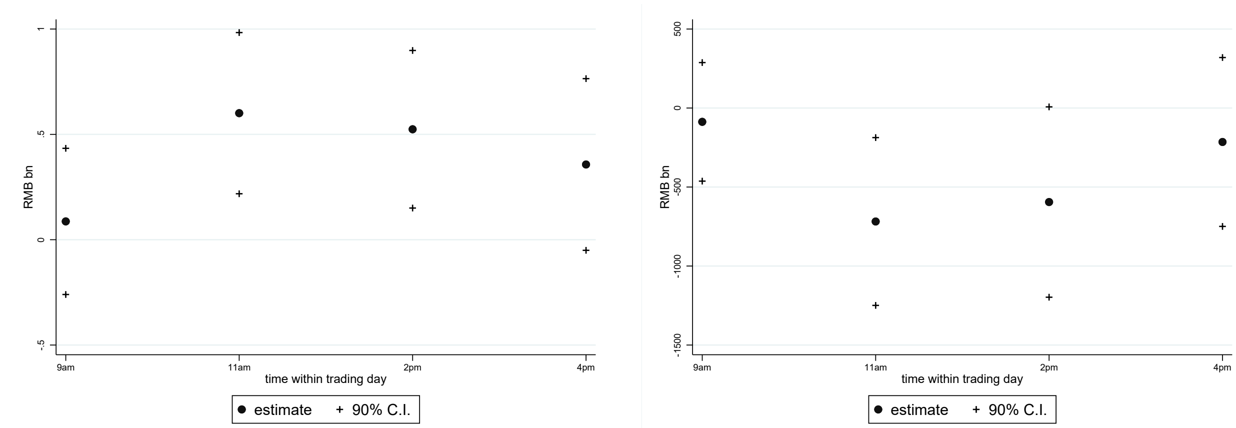
Figure C.5: Intraday CNH/CNY exchange rate persistence



Note: Correlation coefficients between the CNH/CNY exchange rate at close and observations on the following trading day at 30-minute intervals.

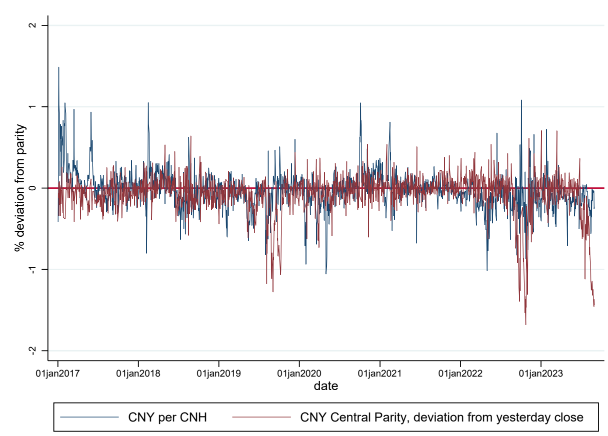
Figure C.6: Usage of the HKMA lending programs during the day

(a) PLP lending **(b)** Intraday liquidity facility



Note: Regressions of drawings from (a) the PLP liquidity facility and (b) the intraday facility at 9am, 11am, 2pm and 4pm on the CNY/CNH exchange rate at the previous day's close. Confidence intervals constructed using White heteroskedasticity robust standard errors.

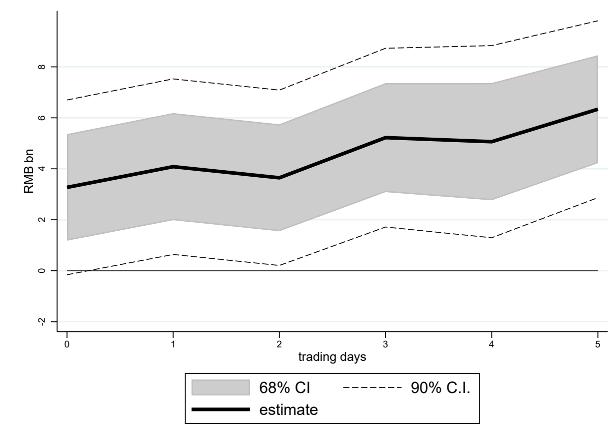
Figure C.7: CNH/CNY exchange rate and the CNY/USD band deviation instrument



Note: Plot of the natural log deviation between the CNY/USD central parity band today from the CNY/USD exchange rate yesterday against the natural logarithm of the CNH/CNY exchange rate today.

Figure C.8: Response of HKMA PLP facility to a money demand shock between: 11am and 4pm inclusive

(a) Local Projection - Instrumental Variables



Note: Same as figure 4.

Table C.2: Bill Auction Subscription Rates

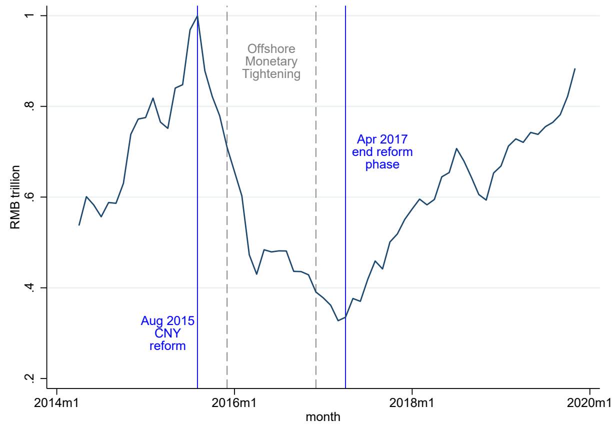
Bill maturities	All	1Y	6M	3M
	(2)	(4)	(6)	(8)
e_t	-1.28	-1.68*	-2.68**	-1.45
	(0.85)	(0.92)	(1.12)	(0.95)
Number of Auctions	35	19	16	19
R^2	0.142	0.335	0.131	0.324

Heteroskedasticity robust standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

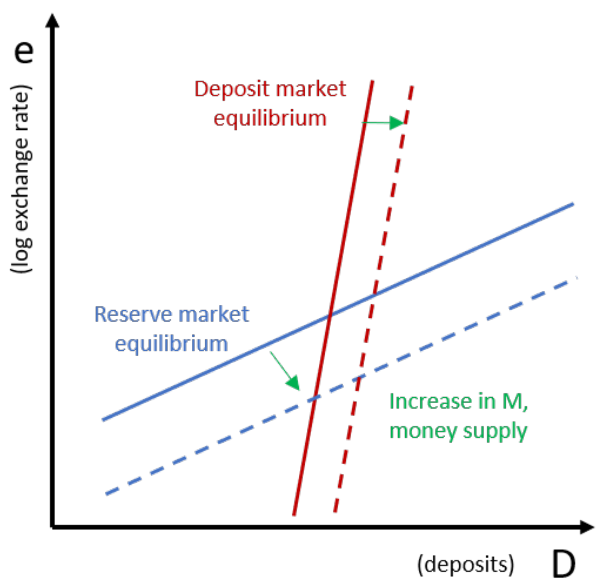
Note: Same as table 2 but using the exchange rate on the day of the auction.

Figure C.9: RMB flows from offshore to onshore



Note: Plots the quantity of RMB flows from offshore to onshore through the Chinese current account over Jan 2014 to Dec 2019.

Figure C.10: Simple model of exchange rates and deposits



D Additional theoretical results

D.1 Household problem

The problem of the representative onshore household that holds deposits gives rise to the deposit supply curve in equation (7). Also, it clarifies the opportunity cost of capital.

The household is risk neutral and only values terminal consumption. Starting from an initial endowment Y it can invest in bank equity C^o with return R^c, bank deposits onshore D^o, or bank deposits offshore D, with the remainder going into a storage technology with return 1. We assume that Y is sufficiently large such that there is always some investment in storage. While bank capital and storage are pure financial investments, deposits are a transactions assets: the household enjoys a liquidity service form their stock.

The household's problem is:

$$\max_{C,D^o,D} \left\{ R^c C^o + R^{d,o} D^o + \mathbb{E}(E') R^d D + \frac{vED^{1-\alpha}}{1-\alpha} + \frac{D^{o1-\alpha}}{1-\alpha} + (Y - C^o - D^o - ED) \right\}$$

The first optimality condition is $R^c = 1$. The second is $\mathbb{E}(E')R^d + EvD^{-\alpha} = E$. This is equation (7). There is a third optimality condition with the supply of onshore deposits, which plays no role in the model.

D.2 Existence, uniqueness, and comparative statics

The two equilibrium conditions in equations (5) and (8) are re-written below:

$$\begin{aligned} E^{\text{reserves}} &= 1 - \phi'(M/D) \\ E^{\text{deposits}} &= \frac{\phi(M/D) - \left(\frac{M}{D}\right) \phi'(M/D)}{vD^{-\alpha}}. \end{aligned}$$

The two endogenous variables are $(D, E) \in [M, \infty) \times (0, \infty]$, and the conditions are shown in figure C.10. This appendix shows that: (i) an equilibrium exists, (ii) there is a sufficient condition for its uniqueness, and (iii) an increase in M causes a decline in the equilibrium values of both E and D, while a rise in v causes a fall in E and a rise in D.

For all the proofs, recall that we assumed (and later micro-founded) that the function $\phi(M/D)$ is bounded $0 \leq \phi(.) \leq R^z - R^m$, and at the top of its domain $\phi(1) = 0$. In turn, the negative of its derivative, which is the marginal benefit of reserves is also bounded $0 \leq -\phi'(.) \leq R^z - R^m < \infty$ and at the top of its domain $\phi'(1) = 0$. In equilibrium the marginal cost of reserves increases with the aggregate deposit-to-reserve: $\phi_2 \equiv \partial\phi'(M/D)/\partial(M/D) \geq 0$. Also, for the banks to choose to be in business in equilibrium, $\phi(.)D < M$ so liquidity costs were not so large to lead to negative profits.

The function has three properties. First, it is bounded, namely $0 \leq \phi(.)d < m$ so that the costs do not exceed the payoff from reserves, and it reaches zero when the bank is narrow, $\phi(1) = 0$. Second, the function is decreasing in the reserve-deposit ratio, since expected liquidity costs are lower when the bank's assets are more liquid relative to its liabilities. This marginal benefit of liquidity is also bounded and, when the bank is narrow, it is zero: $\phi'(1) = 0$. Third, for the banking system as whole in equilibrium, the marginal benefit of improving the reserve-deposit ratio is diminishing: $\phi''(M/D) \geq 0$.

Existence: Since $\phi(1) = \phi'(1) = 0$, then $\lim_{D\to M} E^{\text{reserves}} = 1 > 0 = \lim_{D\to M} E^{\text{deposits}}$. Intuitively, this says that if deposits were backed one-to-one with reserves then banks would want to buy the stock of outstanding reserves at a positive exchange rate. At the other extreme of the domain, since $\phi(.)$ and $\phi'(.)$ are bounded, then $\lim_{D\to\infty} E^{\text{reserves}} < \lim_{D\to\infty} E^{\text{deposits}}$. Therefore, since both functions in the equilibrium conditions are continuous, they will intersect at least once, and an equilibrium exists.

Uniqueness: Since $\phi_2 \geq 0$, then from the first equilibrium condition, it is immediate that $dE^{\text{reserves}}/dD > 0$. Taking derivatives of the other equilibrium conditions:

$$\frac{dE^{\text{deposits}}}{dD} = \frac{1}{vD^{1-\alpha}}\left[\alpha v D^{-\alpha} E + \left(\frac{M}{D}\right)^2 \phi_2\right] > 0.$$

Therefore, in figure C.10, both conditions slope upwards.

Uniqueness then requires that any point in which they intersect, so $E^{\text{reserves}} = E^{\text{deposits}}$, it must be that $dE^{\text{reserves}}/dD < dE^{\text{deposits}}/dD$ (or vice versa) or:

$$\frac{M}{D^2}\phi_2(.) < \frac{1}{vD^{1-\alpha}}\left[\alpha\left(\phi(.) - \frac{M}{D}\phi'(.)\right) + \left(\frac{M}{D}\right)^2 \phi_2\right].$$

At an equilibrium $E^{\text{reserves}} = E^{\text{deposits}}$, so $v^{-1}D^{\alpha}\left(\phi(.) - \frac{M}{D}\phi'(.)\right) = 1 - \phi'(.)$. Replacing and rearranging:

$$\left(\frac{M}{D}\right)\phi_2(.) < \alpha(1 - \phi'(.)) + \left(\frac{1}{vD^{-\alpha}}\right)\left(\frac{M}{D}\right)^2 \phi_2(.).$$

Since $-\phi'(.) \geq 0$ this will be true if:

$$\left(\frac{1}{vD^{-\alpha}}\right)\left(\frac{M}{D}\right) > 1.$$

But again using the equilibrium condition in the deposit market that $vD^{-\alpha} = (1/E)(\phi(.) - (M/D)\phi'(.))$, the inequality becomes.

$$\frac{\phi(.) - (M/D)\phi'(.)}{M/D} < E = 1 - \phi'(.)$$

where the equality comes from the equilibrium condition in the reserves market. Rearranging, the sufficient condition for uniqueness is:

$$\phi(.) < M/D,$$

which holds by assumption.

Comparative statics. From figure C.10, since an increase in v shifts the deposit equilibrium curve to the right, immediately it follows that both D and E will rise.

An increase in M is trickier because it shifts both curves to the right. For sure, D will rise, but we must show that $dE/dM < 0$. Again from the figure, a sufficient condition for this is that the reserves market condition shifts right by more than the deposits market condition. Taking partial derivatives with respect to M, the condition is:

$$-\frac{\phi_2}{D} > -\left(\frac{M}{D}\right)\frac{\phi_2}{vD^{-\alpha}}.$$

Since $\phi_2 > 0$, this simplifies to the same condition that we verified for uniqueness.

D.3 Market tightness with bills and capital flows

The inclusion of bills modifies the bank surplus function to become:

$$s(\omega) = m - \rho d + \omega d\,(1-\rho) + g - g'(\omega).$$

Let S_- be the aggregate deficit of liquidity. It is now given by the expression:

$$S_- \equiv -\int \min\{s_\omega, 0\}\, d\Omega(\omega) = -\int_{-1}^{\bar{\omega}} [m - \rho d + \omega d\,(1-\rho) + g]\, d\Omega(\omega)$$

where the equality takes into account that these banks already choose $g' = 0$.

On the other side are the banks with a surplus, so aggregate supply of liquidity S_+ is:

$$\begin{aligned}\int \max\{s_\omega, 0\}\, d\Omega(\omega) &= \int_{\bar{\omega}}^{\infty} \left[m - \rho d + \omega d\,(1-\rho) + g - g'(\omega)\right] d\Omega(\omega) \\ &= \int_{\bar{\omega}}^{\infty} \left[m - \rho d + \omega d\,(1-\rho) + g\right] d\Omega(\omega) - g \\ &\equiv S_+ - G.\end{aligned}$$

The second equality comes from the market clearing condition that the bills sold by deficit banks are bought by the surplus banks: $\Omega(\bar{\omega})g = \int_{\bar{\omega}}^{\infty} g'(\omega) d\Omega(\omega)$. The last line comes from defining S^+ analogously to S^- and using the market clearing condition $g = G$.

Realizing that the flow of reserves from onshore provides new funds to lend in the interbank market, market tightness is therefore defined as

$$\theta \equiv \frac{S_-}{S_+ - G + W^m}$$

as written in the text.