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

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Abstract

Two currencies circulate in parallel in China, the mainland CNY and the offshore CNH. This implements capital controls as long as their exchange rate is pegged. This paper characterises this peculiar system by isolating the conventional channels through which monetary and liquidity policies sustain it. Using a rare instance of exogenous transitory increases in the supply of money, we find causal evidence that they depreciate the exchange rate and we pin down the interest elasticity of the demand for reserves. Using an instrument for changes in the demand for money, we quantitatively decompose the success of the peg into the joint contribution of monetary and liquidity policies. Using a model of offshore exchange rates and money creation by banks, we show that a menu of policies can be used, and has been used, to smooth fluctuations of the exchange rate of the yuan with the US dollar.

JEL codes: F31, F33, E51, G15.

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1 Introduction

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

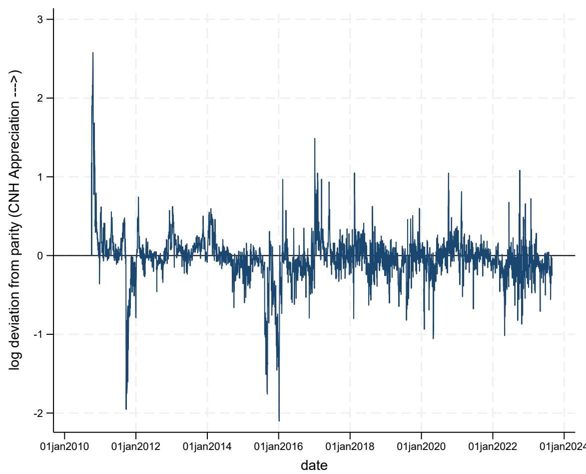
The Chinese answer was to create an offshore currency, the Hong Kong yuan (CNH), that circulates in parallel with the onshore currency, the mainland yuan (CNY). The CNH is freely used for payments and investments by anyone offshore, with no limits in converting it for foreign currency, while restricting the conversion into CNY to happen only against trade invoices. By the end of 2023, there were ¥2 trillion worth in transactions per day in CNH across the world fuelling 14% of global trade. The CNY, instead, is used onshore for all domestic transactions and it is required to directly invest in the mainland. Chinese nationals and firms wanting to invest abroad also face limits in converting it to CNH. By monitoring the conversions between CNH and CNY, the Chinese authorities can track financial flows, limit gross flows, and ensure that the assets held by Chinese abroad and by foreigners mainland are limited to specific categories.

This monetary system has the tension that is common in parallel currencies. If one of the currencies were to persistently lose value relative to the other, Chinese firms, banks and households would want to convert it into the more valuable one. The capital controls that stop them from doing so would come under severe strain, and one of the currencies would sooner or later stop being used. This is Gresham's law. Yet, as figure 1 shows, even though the value of the yuan has fluctuated widely against the US dollar (USD), the exchange rate between its two variants has been very close to one.

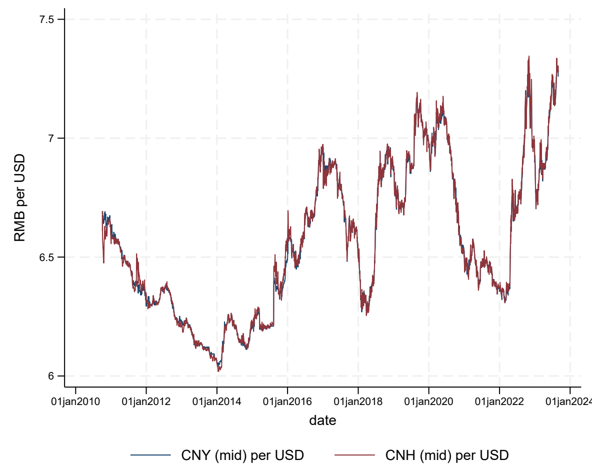
This paper studies this system and its peg in four parts. First, we characterise how the People's Bank of China (PBoC) and the Hong Kong Monetary Authority (HKMA) have jointly managed monetary and liquidity policies to sustain the peg. We show that complicated arrangements and institutions reduce to conventional monetary models and principles. Second, we use this experience to test the link between money and exchange rates. Its peculiarities provide a rare opportunity to credibly identify classical channels and to validate them with data on money, interest rates, and exchange rates. Third, we

Figure 1: The relative value of the yuan

(a) Exchange rate of CNY with CNH



(b) Exchange rate of CNY or CNH with USD



Note: Sample period is all trading days between 1 October 2010 and 31 August 2023. In both panels, an increase is a yuan depreciation, either CNY relative to CNH or USD, or CNH relative to USD.

provide a monetary anatomy of the peg by estimating the money supply policy rule that has reverted movements in the exchange rate. This reversal is incomplete. By failing to restore the peg right away, the authorities attenuate fluctuations in the exchange rate between the yuan and the USD. Fourth, we show that liquidity policies complement monetary policies in sustaining the peg. We do so by proposing a model of the benefits of liquidity when the supply of money is scarce, and using the data to provide a liquidity anatomy of the peg. Finally, we conclude that this policy mix has preserved the parallel currencies in spite of Goodhart's law and conjecture what this implies for the rise of the yuan as an international currency.

Outline, contributions, and links to the literature.

Section 2 describes the policies conducted by the PBoC and the HKMA that: constrain CNY-CNH exchanges, keep the CNH money supply scarce on average, elastically adjust it to absorb shocks, and co-exist with policies on the exchange rate with the USD.[1] We show that, in spite of its peculiarities, the CNH monetary system is ultimately about using policies that affect the supply of money and the demand for liquidity to peg an exchange rate. The mechanisms that at first sight are opaque and complicated, after inspection

[1]The two central banks independently conduct monetary policy for two other currencies, the CNY and the Hong Kong dollar (HKD), which are not our focus. On CNY monetary policy, see Chen, Ren and Zha (2018), and on the HKD, see Genberg and Hui (2011).

reduce to standard channels used by central banks around the world.[2]

This section contributes to our understanding of monetary regimes, international currencies, and capital controls. The Chinese experience is interesting in its own right given the relevance of its economy in the international financial system.[3] Also, as the creation of the parallel currencies was a step towards internationalising the yuan, this experience carries lessons for understanding why some currencies are used in international trade.[4] Other countries may find this successful experiment with capital controls appealing in the future, and this paper explains how it has worked.

The Chinese experiment with a peg is a laboratory to isolate the channels linking monetary policy and exchange rates. Section 3 provides a model for it with banks that create inside money, and there are onshore, offshore, and foreign regions.[5] Combining the model with the peculiarities of the CNY-CNH-USD regime shows how to test a classic question for which credible evidence is still scarce: by how much does a 1% increase in the domestic money supply depreciate the exchange rate?

At one theoretical extreme, the quantity theory states that the exchange rate would depreciate by 1%, and the experience of hyper-inflations provides some support. At the other extreme, when policy chooses the interest rate on reserves and the demand for liquidity has been satiated, then the effect would be zero, as arguably has been the case in advanced economies after quantitative easing with ample reserves. Empirically, showing a causal link is challenging because money is endogenous, exchange rates move in anticipation of fundamentals, and there are many omitted variables that affect both.[6]

We exploit changes in the timing of CNH monetary operations between 2019 and 2021

[2] By creating an official parallel money market with policy-managed arbitrage trades, authorities may have prevented the rise of a private offshore market, like the Eurodollar (He and McCauley, 2012).

[3] In 1864, the US accidentally had a similar experience, as the civil war created parallel currencies with an exchange rate driven by the relative supply of money (Burdekin and Weidenmier, 2001).

[4] Naef et al. (2022) describe the components of this internationalisation, including CNH, and Bordo, Monnet and Naef (2019) compare the role of the offshore Hong Kong market with the London gold market during the internationalisation of the USD. We provide a more detailed description of the monetary and liquidity channels and policies of the offshore system.

[5] Segmenting markets to study exchange rates has a long tradition, e.g., Alvarez, Atkeson and Kehoe (2002). Onshore and offshore markets motivate a different set of assumptions behind that segmentation.

[6] Meese and Rogoff (1983) found no correlation between measures of money and exchange rates. 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). We estimate directly how much an increase in the stock of money in exchange for short-term bills changes the exchange rate.

that caused nine expansions in the offshore money supply that were exogenous, moderate in size (1.5% of deposits on average), and transitory (lasting a few weeks). Relative to the literature, we follow in the tradition of the narrative identification of shocks to the supply of money.[7] We find that the onshore-offshore exchange rate depreciated on average by 0.11 percentage points during these events, and the offshore-foreign exchange rate depreciated as well. While the literature has struggled to tightly estimate the interest elasticity of money demand, our model shows that there are two relevant elasticities: the elasticity of demand for reserves at the central bank and the elasticity of demand for bank deposits. We estimate that the former is approximately five times larger than the latter.[8]

Having described the institutions behind this successful peg, and understood and estimated the monetary channels that sustain it, the rest of the paper provides an anatomy of the peg. Section 4 estimates the policy rule for the money supply. The features of CNY-CNH-USD again suggest a novel identification strategy. We show that movements in the CNY-CNH exchange rate proxy for changes in the demand for CNH money, and that the PBoC's management of the CNY-USD exchange rate produces an instrument for these demand shocks. We find that, following an increase in demand for CNH money that raise the onshore-offshore exchange rate by 1%, the daily supply of CNH money increases by 2.6% over the next 5 days to help restore the peg. This gives a monetary anatomy of this particularly successful peg.[9]

Our estimated policy rule for money falls short of fully bringing the exchange rate back to parity. We show that a consequence of this partial adjustment is a negative co-movement between the CNY-CNH and the CNY-USD exchange rates. This implies that policy uses the offshore market as an escape valve to smooth changes in the exchange rate of the yuan with the dollar. We contribute to the literature on foreign exchange interventions by unveiling the use of offshore currencies as an effective tool.[10]

[7] Friedman and Schwartz (2008) is the classic reference. The closest studies are Velde (2009) that identifies three large contractions in the money supply in France in 1724, and Palma (2021) that uses major discoveries of precious metals in America raising the money supply in Europe. We complement this work by studying a recent experience with a modern central bank, and by identifying high-frequency shocks to reserves, as opposed to banknotes. Also, we estimate relevant elasticities within a model and the separate role of different monetary and liquidity policies.

[8] There is an enormous literature estimating the impact of monetary policy shocks to interest rates on exchange rates using time-series variation, e.g., Eichenbaum and Evans (1995). Differently, we use high-frequency narrative identification, within a peg, with policy set on the quantity of money, and in combination with other liquidity policies. Chodorow-Reich et al. (2019) is closer, by exploiting cross-regional variation during the Indian demonetization, but on banknotes as opposed to reserves.

[9] Typical pegs do not last long, and parallel currencies usually end in collapse, see Selgin (2020).

[10] Jermann, Wei and Yue (2022) inspect comprehensively the way the PBoC manages the CNY-USD ex-

Section 5 proceeds with a liquidity anatomy of the peg. It starts from an existing micro-founded model of the marginal benefit of liquidity, and extends it to the offshore context. It derives three predictions for the impact of our identified shocks to money demand on: money-market variables like interest rates, demand for bonds, and central bank lending.[11] The evidence supports all three.[12]

The model shows that liquidity policies over banks, like reserve requirements, access to a discount window, helicopter drops of money, and constraints on the flow of deposits and reserves all affect their willingness to create deposits (inside money). This provides a fresh take on a host of policies that affect the exchange rate.[13] We show that they have been used by the Chinese authorities, and that they may have accounted for a larger share of the control of the peg than conventional monetary policies did.[14]

Finally, section 6 concludes that our model, estimates, and anatomy of the peg give an optimistic counter to Goodhart's law. The Chinese policies create an incentive for financial innovation by banks to relax their liquidity constraints, which put pressure on the peg to break.[15] Our results tentatively suggest that a coherent monetary and liquidity framework can maintain the peg, keep the parallel onshore-offshore currencies, and provide new tools to affect the exchange rate with foreign currencies.

2 The offshore market and the CNH monetary regime

There is a single physical currency in China—the renminbi (RMB)—but 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 financial centres like Hong Kong.[16] A Chinese citizen or firm that deposits RMB banknotes into a

change rate, while we focus and go deeper on the use of the offshore-onshore currencies.

[11] We use the formulation of Poole (1968) by Bianchi and Bigio (2022) and Bianchi, Bigio and Engel (2021).

[12] Combining our estimates of liquidity benefits with the models of Engel (2016) and Engel and Wu (2023), which link them to convenience yields, would link monetary and liquidity policies to output or inflation.

[13] A complementary literature studies the role of capital controls and regulations on credit, capital allocation, and financial stability (Hachem and Song, 2023, Song and Xiong, 2018, He and Wei, 2023).

[14] Monnet (2014) uses time-series variation to identify the joint impact of a menu of liquidity policies on aggregate variables in France in 1948–73. We instead use high-frequency data and a model of each policy to provide an anatomy of the channels through which each of them affects the exchange rate.

[15] 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.

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

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 (RTGS) systems, have different interbank markets in which banks lend CNH or CNY to each other, and distinct retail markets where firms can borrow either currency from banks. Onshore CNY exchanges for offshore CNH one-to-one subject to restrictions leading to an unrestricted market exchange rate of E. This section describes these restrictions and the policies that support it.

2.1 Capital controls and restrictions on exchanging CNY and CNH

Only banks domiciled in China can supply CNY deposits and have access to the onshore China National Advanced Payment System to settle payments with reserve accounts at the PBoC. Only Chinese nationals can hold and use CNY deposits, with only a few exceptions for foreigners authorised by the government. Since CNY is required to buy and sell assets in mainland China, or more generally to transact in the onshore financial market, the limits in accessing CNY create a control over capital inflows.

The CNH can be held by anyone. It was first introduced to businesses in 2004, but only officially launched in July of 2010 as part of a package of financial reforms to create an offshore market, lower trade credit costs, and jumpstart the international use of the yuan.[17] Foreigners can hold deposits in CNH at will, make payments in CNH without restrictions, and convert CNH into foreign currency with no limits. Both Chinese and foreign banks with offshore branches or subsidiaries can issue CNH deposits. International financial centres settle transactions in CNH without constraints, and provide convertible deposit balances and trade credit without limits. Chinese firms that sell products or buy inputs from abroad can use CNH to make payments or to exchange it for another medium of payment, without any restrictions on quantity or composition. In short, access and use of the CNH is free, which has allowed the yuan to be used abroad and has contributed to making China the largest exporter in the world.

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. However, to invest abroad, Chinese citizens must exchange their CNY for another currency. Therefore, limits in accessing CNH create a control over capital outflows.

Official conversion of CNH for CNY, and vice versa, is one-to-one but is subject to

[17] See Bahaj and Reis (2020) on the jumpstart, and, more recently Chupilkin et al. (2023) on its recent rise.

many strict exchange limits. First, for purposes of investment, there are quotas on exchanging CNH and CNY 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). Restrictions also apply to firms trying to export or import capital.

Second, for consumption, households have an annual limit on how much they can transfer between CNH and CNY and vice versa. Shipping large quantities of RMB cash into and out of mainland China is forbidden.

Third, the Chinese firms that import or export using CNH or foreign currency can convert their CNH revenues to pay their CNY bills in mainland China only when they present the invoice behind their foreign sales (vice versa, they can convert CNY to CNH with an invoice for a purchase). These are the largest flows between CNH and CNY and their restrictions have led to large Chinese trading firms building up CNH deposits and associated invoices. They can earn CNH deposit rates or save in CNH bills, before converting these to CNY when there is an arbitrage opportunity.[18]

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. The fourth set of restrictions is on these cross-border interbank lending

All combined, since most capital flows can be thought of as ultimately exchanging CNY for CNH, by limiting this exchange, Chinese authorities can effectively enforce controls on the flow of capital in and out of mainland China. At the same time, if the exchange rate between the two currencies is not one, or if expected returns in financial investments in either are different, then there are avenues for arbitrage, mainly by firms and banks.

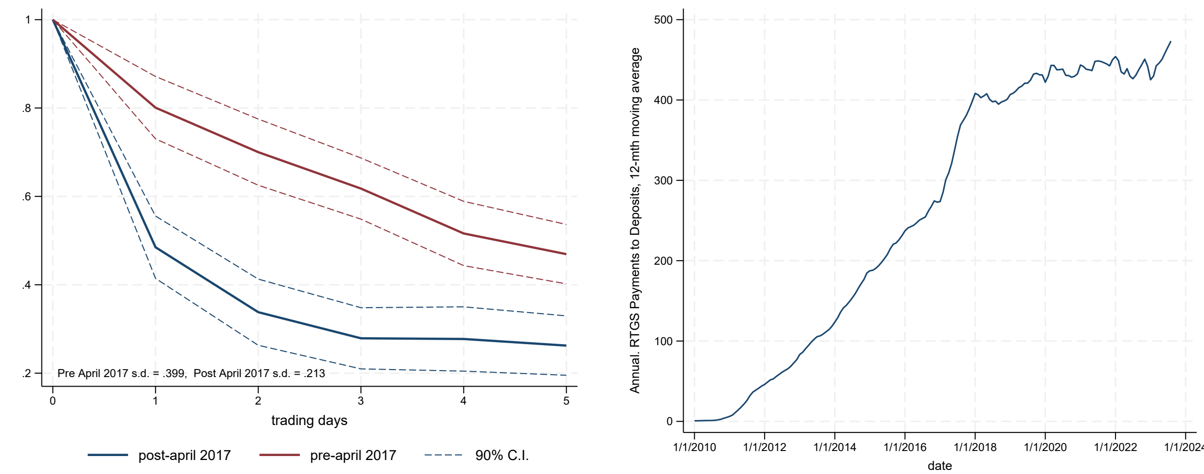
2.2 The survival of parallel currencies and the peg to parity

The limits to converting CNH and CNY constrain the arbitrage and allow for deviations from parity. However, if these deviations 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 capital controls would fail, and either arbitrage would bring about parity, or one of the currencies would disappear from circulation.

[18] Hu and Yuan (2021) and Liu, Sheng and Wang (2022) study firms exploiting the arbitrage opportunities.

Figure 2: The impact of the 2017 reforms

(a) Auto-correlograms of $\log(E)$ pre/post 2017 **(b)** CNH velocity



Note: Panel (a) compares the daily autocorrelograms in $\log(E_t)$ between October 2010 and March 2017 in red, and between April 2017 and May 2023 in blue. Panel (b) shows the ratio of annualized payments from the RTGS system to the stock of CNH deposits.

This imposes a necessary target for policy to keep the deviations of the CNY-CNH exchange rate from parity small and transitory. CNH monetary policy is subordinated to this goal. Figure 1 already showed its success over more than a decade: the daily standard deviation of $\log(E)$ was a mere 0.32% and only in a handful of days did it exceed 1%.[19] 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 number is evidence that the capital controls bind.

There was a structural break in the success of the peg in 2015–17. In August 2015, there was a reform in how the PBoC manages the exchange rate with the USD, which triggered a new framework for managing the CNH that was set up in 2016–17. The left panel of Figure 2 shows the improvement in maintaining the peg: the standard deviation of the exchange rate fell by half and the half-life of deviations went from 6 days to 1 day.[20] The right panel shows 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 significantly increased this velocity, which averaged 431 between 2018 and

[19] Appendix B lists all data sources and variable definitions.

[20] Figure D.1 in appendix D shows the autocorrelation function every thirty minutes. It declines moderately, and this is reversed at the end of the day, justifying a focus on a daily frequency.

2022. By comparison, the average velocity for the United States, equivalently defined as the annual ratio between Fedwire transactions and M1 less currency, was 450 on average between 2012 and 2019.

Because of this break, from now onwards, we discuss the post 2017 system and all the empirical tests that follow are for the sample from April 1st of 2017 until August 31st of 2023. Section 5 will discuss and analyse events in the 2015–17 period.[21]

2.3 The CNH monetary framework

To fix ideas, panel (a) 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.

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) 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) Deposits
(r) PBoC CNH Bills	(u) PLP Balances
(s) Loans, Others	(v) HKMA Facilities
	(w) Equity, Others

The first is an open market operation: buying government bonds from banks in ex-

[21] For descriptions of the pre-reform and reform periods, see Funke et al. (2015), McCauley and Shu (2018).

change for increasing 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 redemption of central bank bills at term, item (E), in exchange for reserves, item (D). The corresponding items for banks are (H) and (I). 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. Note that all three variants lead to a rise in item (I), the holdings of reserves by banks, for short the money supply. This may change the willingness of banks to make loans, item (J), and the interest they pay on deposits so that the private supply of money (K) rises further.

The supply of CNH money has two extra arms involved, displayed in panel (b) of table 1. The first of these is the offshore clearing banks. They are private entities, although they are all subsidiaries of 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 effectively the CNH reserves held by offshore commercial banks.[22] Each clearing bank operates its own RTGS system (which is then linked to the clearing banks' accounts at the PBoC and the onshore China National Advanced Payment System) and 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.[23]

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 CNY-CNH exchange rate have little impact on the unconsolidated PBoC balance sheet, but create (so far small) capital gains and losses for the clearing banks. This separation may be fiscally relevant if the peg is ever abandoned. But, integrating the two balance sheets makes little difference

[22] The offshore clearing banks also handle the offshore issuance of RMB banknotes.

[23] Banks domiciled in China can also access the Cross-border Interbank Payment System (CIPS) settlement accounts to make cross-border payments for approved reasons or to act as agents for foreign banks. The CIPS reserves are separate from the PBoC reserves, they are remunerated differently, and are subject to different liquidity policies. They are an alternative offshore clearing bank with a volume of cleared transactions that is an order of magnitude lower than the CNH-CNY flow.

for the PBoC's influence over the money supply.

The second new arm is the HKMA. In order to preserve financial stability in Hong Kong, the HKMA is also committed to the peg, together with liquidity regulations over these banks. It holds CNH balances at the clearing banks, and lends to the offshore commercial banks through two distinct programs. The first is a repurchase agreement, with up to ¥18bn available, that is open to nine select banks in Hong Kong, the primary liquidity providers (PLP), which are responsible for channelling liquidity to the CNH interbank and financial markets. When they borrow from the HKMA, they automatically increase the supply of reserves in circulation. The outstanding PLP volume averages about ¥3bn during the sample period, which is approximately 1/25th of the volume of CNH bills outstanding, with much variation day to day (see figure D.2 in appendix D).[24]

The other programs are repo facilities that supply CNH liquidity immediately, one intraday and one overnight. 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). 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 D.2 in appendix D).

Again, the fiscal risk, in this case from default by the banks that borrow CNH, does not lie 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.

In short, while its institutions and operations are peculiar, the CNH monetary framework can be unpacked into standard conventional monetary and liquidity mechanisms.

How large is the money supply? The average stock of CNH deposits in Hong Kong banks between January of 2018 and August of 2023 was ¥730bn. We do not have an accurate measure of CNH reserves, but we know that bank deposits at the clearing banks were on average ¥311bn, of which ¥80bn are absorbed by the stock of PBoC bills, and that the HKMA has a balance of at most ¥35bn.[25] This gives an estimate of reserves held by

[24]Left out of the table is a permanent 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 ¥800bn, about the same as the total stock of CNH deposits in Hong Kong.

[25]The HKMA's nine PLPs have a cap of ¥2bn each, while the two repo facilities have a cap of ¥10bn each, and the average amount outstanding in the PLPS was ¥3bn, giving: $2 \times 9 + 10 \times 2 - 3 = 35$bn.

banks of ¥196bn. This would imply a money multiplier of 3.7. By comparison, the ratio of M1 without currency to reserves in the United States was 13.3 over 2004–06 (when money was scarce) and 1.6 over 2021–23 (when reserves were ample).

2.4 How are CNH monetary and liquidity policies conducted?

The CNY-CNH peg is not enforced by law or regulation, but by deliberate policy actions that keep $\mathbb{E}(E') = 1$, where E' is the exchange rate next period.

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 endogenous, indexed to market interbank rates. Because the supply of CNH money is scarce, these interbank rates are well above zero.

Monetary policies. Open market operations in CNH are not appropriate as there is a limited stock of CNH government bonds. Instead 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 regular 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 weekly/monthly auctions, targets the money supply of CNH 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 a completely conventional repurchase operation of central bank bills.

The HKMA adjusts the money supply day-to-day 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. While the low-frequency PBoC policies could change the money supply exogenously, the high-frequency actions of the HKMA endogenously supply money to absorb shocks to demand.

Liquidity policies. The PBoC regulates the clearing banks and the HKMA regulates the commercial banks. These rules (and suasion) impose restrictions on the endogenous creation of private CNH money by financial intermediaries.

First, both authorities impose minimum balance requirements on banks. These reserve requirements on CNH deposits change at low frequencies.

Second, the HKMA sets the interest rate on its discount window. Currently, it is priced as a spread to the CNH interbank market rates in the previous three days, so the cost for banks of having CNH shortfalls and needing emergency liquidity increases as existing liquidity becomes scarce.

Third, beyond the controls on the composition of the capital flows, the PBoC can also limit the total flow of deposits and reserves between the onshore and the offshore interbank markets. These liquidity controls are heavy-handed policies since these flows vary widely every day depending on household and firms's liquidity needs.

Fourth and finally, the PBoC could do a helicopter drop of newly-issued CNH reserves by buying CNY government bonds. Conversely, it could do a helicopter drop of bills, for instance by lending out offshore bills in repos against onshore bills. On both directions, the media reports that Chinese State banks buy and sell CNH at the encouragement of the authorities, effectively doing FX interventions that are similar to helicopter drops.

2.5 Policies regarding the CNY and the USD

Mainland monetary policy is set entirely by the PBoC. It involves traditional channels, setting interest rates and controlling the supply of money, with a focus on mainland variables and domestic goals. The CNY money supply is much larger than CNH's: roughly 200 times larger on average between 2018 and 2023.[26]

There is no evidence that the PBoC has, in our sample, changed onshore monetary policy in response to the small daily fluctuations in the CNY-CNH exchange rate. CNH monetary policy is solely focused on the peg, precisely so that CNY monetary policy can ignore E almost entirely. Regressing the stock of monies on the CNY-CNH exchange rate, there is a quantitatively and statistically significant correlation only with CNH money, but not CNY money (table D.1 in appendix D.)

The PBoC actively interferes instead in the CNY-USD exchange rate, call it $\tilde{E}$. 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 the deviation $\log(\tilde{E}) - \log(\bar{E})$ does not exceed 2% in absolute value. This is a managed float that prevents large appreciations or depreciations within one day.[27]

[26] Back to panel (b) in table 1, line (c) is much larger than the sum of lines (i) and (j).

[27] The 2% limit has been in place since March of 2014, when it was widened from a 1% limit set in April of 2012. Prior to August 2015, the parity rate was close to being a constant, but since then it has changed

Jermann, Wei and Yue (2022) describe how the parity rate is set; importantly, for our purposes, the CNY-CNH exchange rate does not appear in their discussion, supporting an exclusion restriction that E does not enter the decision rule for $\bar{E}$, and so the latter can be used as an instrument for the former.

Most of the time, the parity rate adjusts 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 quickly 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. The CNH would trade below parity. In this sense, the CNY-CNH exchange rate mechanically acts as an escape valve for the appreciation and depreciation pressures over the CNY-USD.

Finally, and for completeness, the medium of exchange for transactions in Hong Kong is a separate currency, the Hong Kong dollar. The HKMA manages it independently of the CNH market, with a separate balance sheet, and a separate set of policies. The HKD is not subject to capital controls and is pegged to the USD via a currency board backed by the HKMA's substantial foreign exchange reserves, which are separate from China's own reserves. The HKD plays little role in understanding the CNY-CNH-USD setting.

3 Money and the exchange rate

We start with a simple model where banks create offshore deposits that are held by domestic and foreign households, and they hold offshore reserves partially against them. This matches the CNH-CNY-USD application, and illustrates why the CNH is a useful testing ground for fundamental principles of money and exchange rates. The model generates three predictions that we then test in the data.

3.1 A simple model of money and exchange rates

There are three agents, all risk-neutral and atomistic, taking returns as given: banks, domestic households, and foreign households.

over time through a countercyclical factor and by considering a basket of currencies beyond the USD.

The balance sheet of a bank. An onshore bank with equity capital c^o collects deposits d^o to either make loans l^o or hold reserves m^o. It can also go offshore to collect deposits d and hold reserves m.[28] The bank faces the resource constraint at the start of the day:

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

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

We assume (and later micro-found) that the $\phi(.)$ function has four properties. First, it is non-negative, reaching zero when the bank is narrow, $\phi(1) = 0$, and bounded above. Second, the function is decreasing in the reserve-deposit ratio, since liquidity costs are lower when the bank's assets are more liquid relative to its liabilities. Third, the marginal benefit $-\phi'(.)$ is non-negative, reaches its minimum of zero when the bank is narrow, $\phi'(1) = 0$, and is bounded above. Fourth, in equilibrium the costs are below the revenue from holding reserves, $\phi(.)d < R^m m$, so banks want to operate and supply positive deposits, and the marginal benefit $-\phi'(.)$ is decreasing in the aggregate reserve-deposit ratio, so there are decreasing returns to scale and the production of liquidity is finite.

Returns. Next period, the bank pays positive gross interest rates R^d and $R^{d,o}$ on deposits and earns R^l 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. All these returns are known today; the only unknown is the future exchange rate E'. The bank's expected payoff is:[29]

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

The demand for reserves by banks. A bank chooses l^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

[28] 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.

[29] The onshore variables, with a superscript o, play no role in the analysis, so we treat them as constants.

the two types of reserves give an uncovered interest parity (UIP) condition for reserves:

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

On the left-hand side are the expected returns from holding a marginal unit of onshore reserves; on the right are their offshore counterpart. These include both the final return as well as the marginal reduction in liquidity costs. Inverting the cost function gives a money demand function stating how many reserves banks want to hold relative to deposits as a function of the opportunity cost of holding reserves, which depends on the interest rate spread and the exchange rate. The interest rate semi-elasticity of demand for reserves is $\varepsilon_m = (R^m d)/(m\phi''(m/d))$ by the inverse function theorem.

The supply of deposits by banks. The first-order condition from the banks' optimisation with respect to offshore deposits is:

$$\left(\frac{\mathbb{E}(E')}{E}\right)\left[R^d + \phi(m/d) - \left(\frac{m}{d}\right)\phi'(m/d)\right] = 1. \tag{4}$$

They equate the expected cost of offshore deposits to the opportunity cost of capital.

The demand for deposits by domestic households. A representative household (or firm) located onshore derives liquidity services from holding offshore deposits with which it can make payments for imports.[30] The capital controls make offshore and onshore deposits be imperfect substitutes so that both coexist and have separate demand curves. The demand for deposits by domestic households D_{dom} is given by:

$$\left(\frac{\mathbb{E}(E')}{E}\right)R^d = k - vD_{dom}^{-\alpha}, \tag{5}$$

where k is a constant and v is a shock with mean 1. This demand function for money (deposits) has an interest semi-elasticity of $\varepsilon_d = (R^d\,\mathbb{E}(E')D^\alpha)/(vE\alpha)$.

The supply of deposits from foreign households. Foreigners hold offshore deposits in amount $\hat{D}$. They compare their returns, converted by the offshore-foreign exchange rate $\hat{E}$, to the alternative of a foreign deposit which earns an exogenous return $\hat{R}$.[31] At

[30] Appendix E.1 writes a microfoundation through the problem of the household. We abstract from the market power of banks or from financial repression suppressing deposits rates, so R^d clears a competitive market. It is not apparent to us how these would change the monetarist and liquidity conclusions here.

[31] This return $\hat{R}$ may include a UIP wedge as in Itskhoki and Mukhin (2021), Maggiori (2022).

the margin, they must be indifferent between the two, leading to a UIP condition for deposits:[32]

$$R^d = \left(\frac{\mathbb{E}(\hat{E}')}{\hat{E}}\right)\hat{R}. \tag{6}$$

Market clearing. The total supply of offshore reserves M is fixed by monetary policy. In equilibrium, $m = M$. In turn, supply and demand for deposits are the same: $d = D \equiv D_{dom} + \hat{D}$. The foreign deposits $\hat{D}$ are exogenous in equilibrium, which simplifies the model to focus on offshore variables, as opposed to the foreign ones.[33]

Equilibrium. An equilibrium of the model is a solution of the four equations (3)-(6) for the four variables $(E, \hat{E}, D, R^d)$ as a function of shocks to money supply M, and shocks to the demand for money, domestic v, or foreign $\hat{D}$. Taking as a benchmark the case of iid shocks and a credible parity peg, appendix E.2 formally proves the existence of an equilibrium with $E > 0$ and $M/D < 1$.

3.2 Model predictions

Appendix A.2 proves the following result.

Proposition 1. *Following a transitory increase in the supply of offshore reserves M:*

a) The offshore currency depreciates in value relative to the onshore currency, E falls.

b) The offshore currency depreciates in value relative to the foreign currency, $\hat{E}$ rises.

c) In the neighbourhood of the peg, the proportional change in the exchange rate is a weighted sum of the two elasticities of money demand: $(d\log(E)/d\log(M))^{-1} = \varepsilon_m + (M/D)\varepsilon_d$.

We could describe what happens to D and R^d after shocks, but since we do not measure these variables as well at a high frequency, we do not focus on these predictions. Appendix E.4 characterises what happens if the shock was anticipated several periods ahead: the predictions are the same. Here, we discuss the relevance of each of these three predictions, the difficulty with testing them, and why the CNY-CNH context provides strategies to make progress.

[32] This demand for money by foreigners is, for simplicity, infinitely elastic. Appendix E.1 extends the model to have an elastic supply of foreign deposits, mimicking that of domestic households.

[33] Appendix E.1 shows that this assumption can be interpreted as an outcome of the capital controls.

3.3 The causal link from money to exchange rates

All else equal, an increase in the supply of offshore money M satisfies some of the banks' demand for liquidity. Therefore, it raises $\phi'(M/D)$, and so lowers E in equation (3). That is, more offshore money supply depreciates the value of the offshore currency. Intuitively, with more offshore reserves, the liquidity premium on reserves is lower and banks require a higher return for holding them. The offshore exchange rate must be expected to appreciate, which for a credible peg implies that the current exchange rate must depreciate.

Money and its liquidity benefits. If $\phi'(.) = 0$, so there were no liquidity benefits to money, then the supply of money would be irrelevant for the equilibrium exchange rate for a fixed interest rate. Equation (3) becomes a standard UIP condition $E = \mathbb{E}(E')R^m/R^{m,o}$ that determines the exchange rate solely as a function of the gap between interest rates. Money in this case is a pure financial asset and the banks' demand for it is horizontal (or $\varepsilon_m = \infty$). The relative value of money is pinned down by its relative return, and the quantity of money is only relevant insofar as it is linked to the interest rate.[34]

Why it is hard to test for monetarism. The monetary theory of exchange rates (Mussa, 1976) relies on downward-sloping demand curves for money but testing for a finite ε_m is hard for several reasons.[35]

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 that respond 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.

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.

Fifth, 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.

[34] This is sometimes referred to as the cashless limit and has justified an ample reserves system where central banks using the size of their balance sheet and the interest they pay on reserves as independent policy tools.

[35] A survey of the early literature testing it is in Boughton (1988), with new developments in Rogoff (1999).

There are signalling effects that may be unrelated to the liquidity services of money.

The CNY-CNH testing ground. The CNH money supply M and the CNY-CNH exchange 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, $R^m = 1$ 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 $\mathbb{E}(E') = 1$. Because the PBoC only adjusts its component of M at weekly (or less) frequency 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, as we explained in the previous section. We can even normalize $R^{m,o} - \phi^{o\prime}(m^o/d^o) = 1$.

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. That is, we can take $\hat{R}$ as given when it comes to determining E after an M shock. This would certainly not be the case with respect to onshore monetary policy.

3.4 An empirical test

The remaining challenge is to find changes in M that are exogenous and transitory.

Exogenous shocks to CNH money supply. 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, in the summer of 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 (alongside a temporary 1 month bill issued on 28th June 2019). 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. By 2022 the stock converged to a level ¥80bn with any deviation closed within a very short window. The bill stock was expanded once again in August of 2023 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.[36]

The left panel of figure 3 plots the outstanding daily stock of bills. As a result of the variation in the schedule, at the nine dates indicated by the vertical lines, old bills rolled off without being immediately replaced by new bill issuances.[37] 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. These monetary expansions were temporary. The previous supply of bills was re-established with the new issuance. In five of the roll-offs, the increase in money supply lasted 5 trading days, while in the other four the impact on money supply lasted on average for 25 trading days.

The right panel of figure 3 confirms that reserves were scarce: these expansions in money supply lowered the private opportunity cost of holding reserves proxied here by the CNH one-week interbank rate. To assess statistical significance, the figure shows also a bootstrapped placebo distribution constructed by drawing nine non-overlapping events from other days in the sample. Finally, the blue and red lines show the average split between the roll-offs that were reverted in 5 trading days, and those that persisted for longer, respectively (the size of the roll-offs are similar in either case). Therefore, a shock to the quantity of money maps to the textbook shock to interest rates.[38]

At a monthly frequency, these 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 see this as 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 exogenous

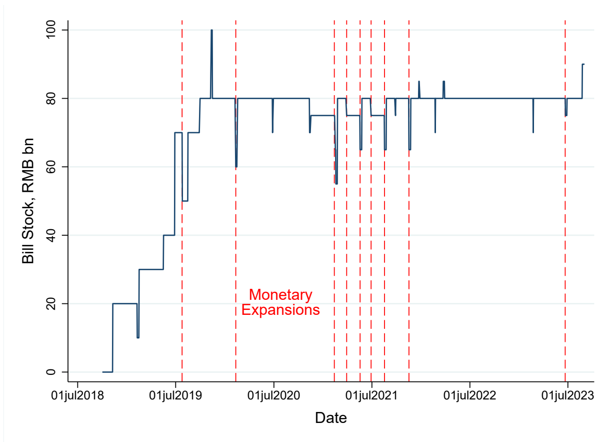
[36]This last event was partly due to an operational constraint having to do with the days of weekends in June of 2023. Our results are not sensitive to its inclusion.

[37]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 exclude the changes in the stock that arose immediately from the announcements on 20th of June 2019, 8 August 2019 and 6 November 2020. We further exclude rolls offs that were reverted within fewer than five trading days. Finally, we exclude periods when the stock of bills spiked due to a new bill being issued before an old bill maturing.

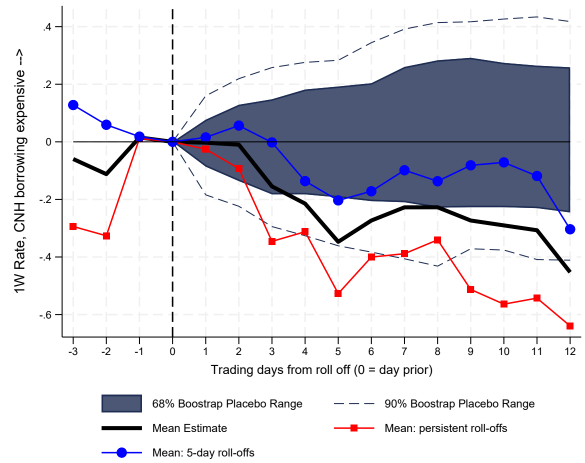
[38]A shock to the interest paid on reserves R^m also appreciates the exchange rate, as in the textbook model.

Figure 3: Exogenous money supply shocks

(a) Money supply shocks through bill roll-offs



(b) Interbank rates around the expansions in money supply



Note: Panel (a) shows the stock of PBoC bills outstanding and its short-lived fluctuations caused by the shift in maturity structure in June/August 2019 and in November 2020. Panel (b) shows the CNH one-week interbank rate relative to 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.

variation in the supply of money.[39]

Test of the causal effect of money on exchange rates. The left panel of figure 4 shows the average response of the offshore-onshore exchange rate to these monetary expansions (the black line).[40] Proposition 1a) predicts that E should fall, and the estimates confirm this prediction.[41] 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 over a 10-day horizon is 0.11%. Splitting by duration of the monetary expansions, the short-lived ones cause an immediate exchange rate movement of 0.12% that is temporary and rapidly reversed. The longer-lived monetary expansions have a less detectable immediate impact but lead to a larger CNH depreciation that persists beyond 12 trading days.

The right panel shows the response of the offshore-foreign exchange rate $\hat{E}$, which

[39] Appendix E.4 shows that the anticipation of the changes does not affect the validity of the test.

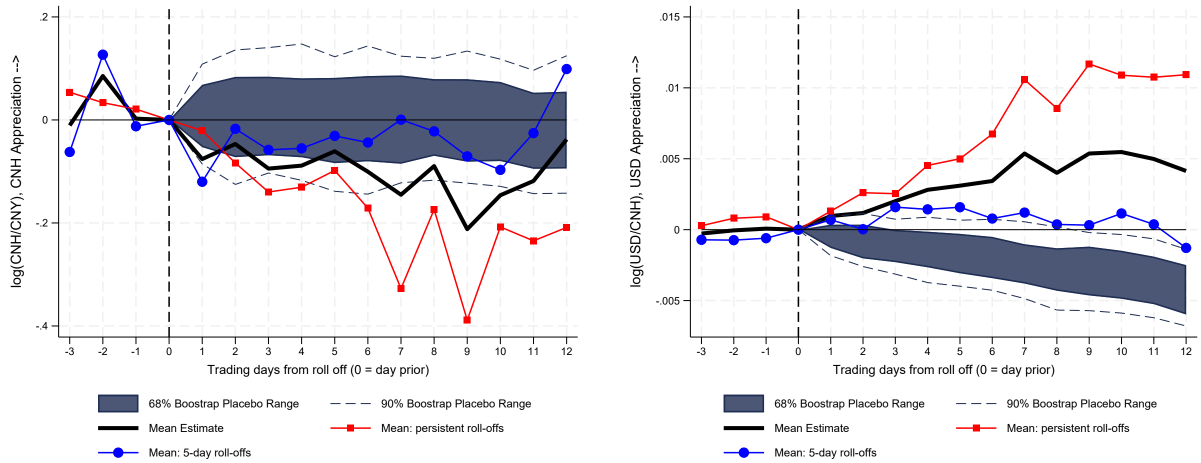
[40] Figure D.3 in appendix D shows the response after each event.

[41] The data five days before each event does not show clear pre-trends in the exchange rate, from either reversion from other shocks or because of anticipation of the rolloffs.

Figure 4: Exchange rates after an exogenous expansion in the money supply

(a) Response of the CNY-CNH exchange rate to money supply shocks

(b) Response of the CNH-USD exchange rate to money supply shocks



Note: Both panels show 100 times the cumulative change in the log of the daily exchange rate from the trading day prior to the bill roll off, averaged over the events, and bootstrapped placebo intervals from taking 10,000 random samples of an equivalent number of events dates between 1 July 2010 and 1 November 2021, excluding dates that overlap with the original event window and schedule announcements.

proposition 1b) predicted should rise. The evidence again confirms this prediction. The placebo happens to be declining because the yuan happened to be appreciating relative to the US dollar on average over the sample, making the effect of the shocks more noticeable.

In short, monetarism holds: raising the money supply depreciates the exchange rate.

3.5 The elasticity of money demand

The model makes clear that there are two separate elasticities of money demand: one for the reserves of banks at the central bank, and another for the deposits of households at banks. Combining the prediction in proposition 1c), the empirical estimate that the exchange rate depreciates 0.11% following an average roll off of ¥11bn of bills, and the average stock of reserves $M =$¥196bn and deposits $D =$¥730bn reported in section 2:

$$\varepsilon_m = \frac{11/196}{0.0011} - \left(\frac{196}{730}\right)\varepsilon_d = 51 - 0.27\varepsilon_d. \tag{7}$$

The upper bound for the interest semi-elasticity of demand for reserves of 51 in this expression is well below the cashless-limit assumption of infinity. For comparison, for the United States, Lopez-Salido and Vissing-Jorgensen (2023) estimate it to be 500 during the ample reserve system of 2009-2022, while Afonso et al. (2022) put it at approximately 50 in the early 2009-12 period. With scarce reserves, like in CNH, this should be lower, but since there is also a parallel currency to substitute into, this might make the elasticity higher. This elasticity is central in some of the key discussions of monetary economics: the welfare costs of inflation, the volatility of interest rates and monetary aggregates, and the optimal size of the central bank balance sheet.

A long literature has estimated time-series regressions of the log of the real stock of M1 on the log of the net nominal interest rate on short-term bonds. More recently Benati et al. (2021) reports coefficients across countries that lie between 0.1 and 0.5. Using the average 1-week CNH wholesale deposit rate of 2.75%, this implies $\varepsilon_d \approx 10$. Then $\varepsilon_m \approx 48$, or that banks are five times more elastic than depositors in their demand for money.

Alternatively, appendix D.1 describes a time-series regression of monthly CNH deposits on an aggregate instrument for CNH money demand shocks, described in the next section. This identifies ε_m imperfectly, given the limitation of having data only at a monthly frequency and not controlling for other variables that shift the demand function. Remarkably, the estimate of ε_m is 47, quite close to the estimates above, even though it relies on a different form of variation altogether.

4 A monetary anatomy of the peg

Systematic monetary policy avoids supply shocks and responds to demand shocks for money. A central bank committed to restoring the parity peg wants to follow a rule:

$$\log(M'/M) = \eta \log(E). \tag{8}$$

This captures the classic monetary prescription that, if the currency depreciates, the central bank should cut the money supply. A modern complement is that the central bank should raise its interest rate.

More formally, in our model:

Proposition 2. *Following an increase in the demand for offshore money (v or $\hat{D}$):*

a) *The onshore currency depreciates relative to the offshore currency, E rises. Offsetting it with an increase in offshore money supply brings that exchange rate back towards parity. Therefore $\eta > 0$ ensures that $E' < E$.*

b) *The offshore currency appreciates relative to the foreign currency, $\hat{E}$ falls. Therefore, the onshore-offshore exchange rate works as an escape valve: an equilibrium percentage change in the relative value of onshore versus foreign currency* $\log(\tilde{E}) = \log(E) + \log(\hat{E})$ *comes with a larger percentage change in the value of offshore versus foreign currency* $\log(\hat{E})$.

c) *A complement to depreciating the exchange rate after the shock is to employ liquidity policies that lower the marginal benefit of liquidity* $-\phi'(M/D)$ *for a given supply of money.*

This section interprets each of these three results and tests them by proposing an instrument for shocks to money demand.

4.1 Keeping a peg against money demand shocks

An increase in the demand for offshore deposits, domestic v or foreign $\hat{D}$, makes the offshore exchange rate appreciate. Intuitively, it raises the relative value of offshore reserves to provide liquidity, and the banks' portfolio shift from onshore to offshore reserves moves the exchange rate away from the peg. To keep the peg, the central bank can raise the supply of reserves, which brings the exchange rate back to parity.

Why it is hard to test for the monetary policies behind a peg. The correlation between either interest rates or measures of money supply with exchange rates for countries that peg their currency is close to zero in the monthly data.[42] At a monthly frequency, there are too many other shocks and too many deviations from UIP for these correlations to detect this monetary prescription for keeping a peg. Moreover, if the policy is successful, there will be no variation in exchange rates to test its effectiveness in the first place.

The CNY-CNH testing ground. At a daily frequency, it is challenging for a central bank to perfectly fine tune the money supply whenever the demand for bank 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 is re-established, holding at a lower frequency.

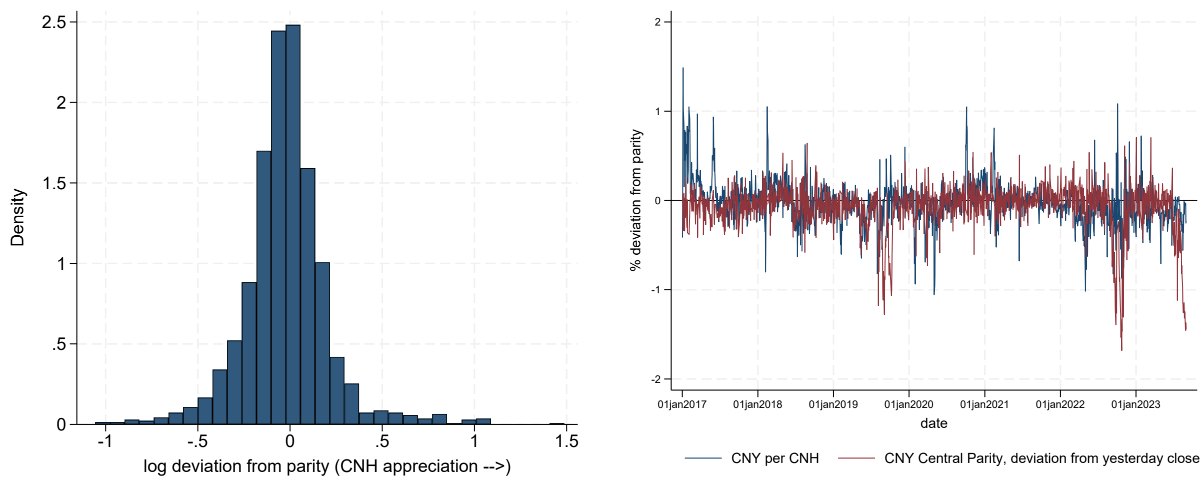
This implies that an appreciation of the exchange rate in one day reflects mostly a positive shock to the relative demand for CNH money. Mostly, because policymakers avoid shocks to money supply; and positive, because the appreciation reflects their inability

[42] Figure D.4 in appendix D 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.

Figure 5: Movements in the daily exchange rate as shocks to money demand

(a) Histogram of the log daily CNY-CNH exchange rate

(b) CNY-CNH exchange rate and the CNY-USD band deviation instrument



Note: Panel (a) shows the histogram of daily $\log(E_t)$ from April 2017 to August of 2023. Panel (b) shows the log deviation between the CNY-USD central parity band today and the CNY-USD exchange rate yesterday, together with the log of the CNY-CNH exchange rate today.

to accommodate the shock to money demand fast enough. 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. The left panel of figure 5 shows that indeed, deviations from parity are centred around zero with a bell shape. High-frequency movements in E proxy for money demand shocks.

Exogenous drivers of shocks to money demand. After an appreciation of the offshore currency, 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 immediately within the day, or there are other supply driven factors influencing the exchange rate, then these estimates would understate the strength of the response of the money supply to the exchange rate.[43]

We use an instrumental variable approach to correct for this downward bias in estimating η. Section 2 explained that the PBoC sets a central parity rate $\bar{E}$ for the CNY-USD exchange rate at the start of the day and allows $\tilde{E}$ to vary in a band of plus and minus

[43]Figure D.5 in appendix D confirms that PLP volumes respond during the day

2%. When the CNY is depreciating quickly and the band is close to binding, the escape valve result says that the offshore currency appreciates relative the onshore one, or that E rises. Since a good proxy for the band binding is whether the central parity rate tracked the previous close, then the deviation of the CNY-USD exchange rate today from the central parity rate tomorrow, $\log \bar{E}'/\tilde{E}$, is an instrument for the proportional change in the CNY-CNH exchange rate between today and tomorrow, $\log E'/E = \Delta \log(E_{t+1})$.

The instrument is a function of developments onshore and in the rest of the world, rather than monetary conditions offshore. Moreover since $\bar{E}$ is set in the morning, it is not contaminated by within-day PLP adjustments.[44] The right panel of figure 5 verifies that the two variables are strongly related: the F-statistic for the instrument is 20.

Test of the monetary prescription behind a peg. We estimate the local projection:

$$z_{t+h} = \alpha_h + \beta_h \Delta \log(E_t) + \gamma_h \log(E_{t-1}) + \delta_h z_{t-1} + \text{controls}_{t-1} + \text{error}_t^h, \tag{9}$$

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 $controls_{t-1}$ that include drawings from the HKMA's discount window facility and overnight and 1-week CNY and CNH interbank rates. The estimates of β_h are measures of the policy rule coefficient η at different horizons. If the estimates are positive, this confirms proposition 2a).

Figure 6 shows that 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 causes the offshore currency to appreciate by 1%, the HKMA's supply of money through the PLP rises by approximately ¥5bn to reestablish the peg, or a 2.6% increase in the money supply. Therefore, our estimate of the policy rule is $\eta = 0.026 > 0$.

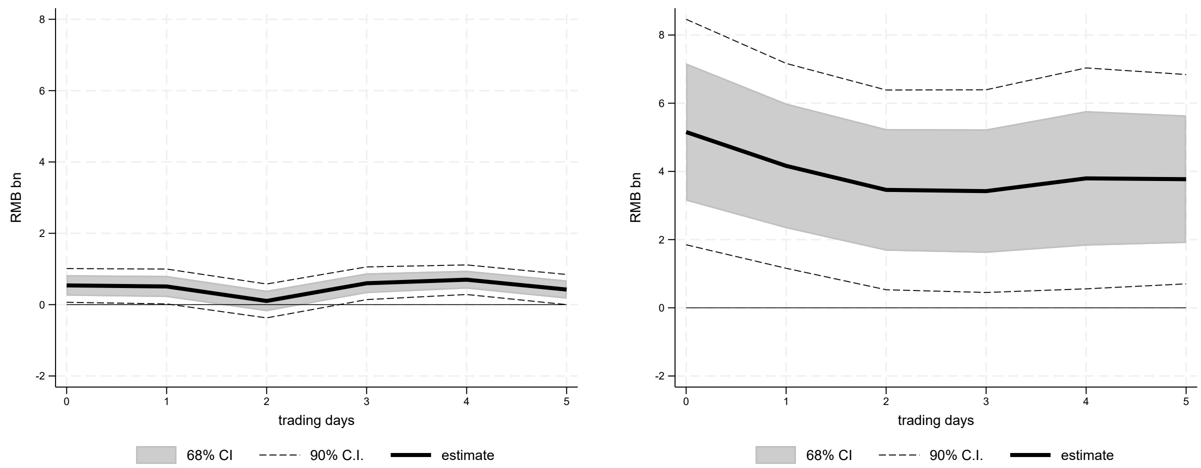
4.2 The offshore market escape valve for the foreign exchange rate

After a money demand shock, the central bank could reestablish the peg quickly by aggressively changing the money supply (a large enough η). The left panel of figure 7 estimates the same local projection as in equation (9) but now using the exchange rate on the left-hand side. The impulse response declines slowly, with a half-life of three days. After 5 days, 0.17 percentage points of depreciation are still missing to get back to parity.

[44] The central parity rate is announced at 11am, but considering PLP drawings only between 11am and end of day yields similar results; see figure D.6 in appendix D.

Figure 6: 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) for PLP drawings. The sample includes all trading days between April 2017 and August 2023. The confidence intervals use White 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.

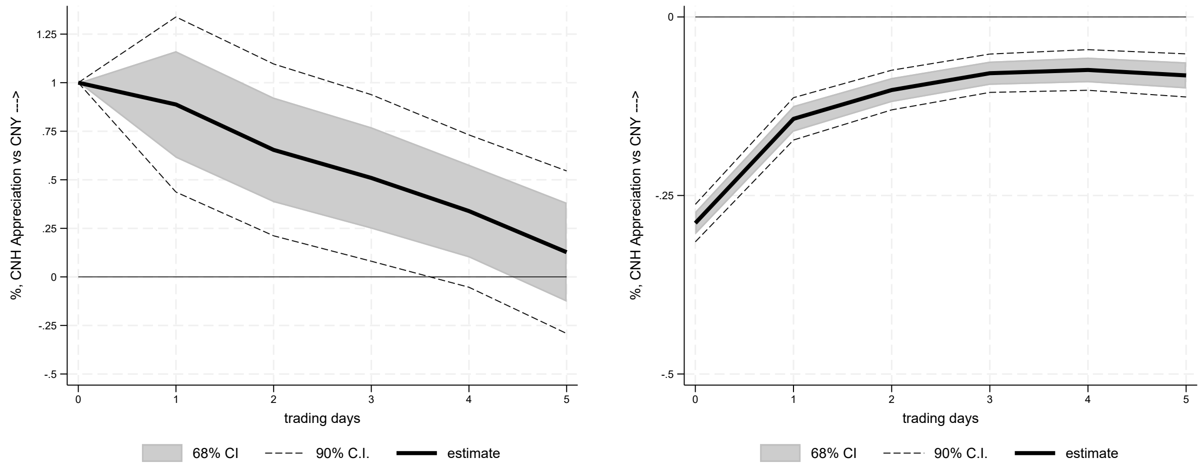
Proposition 2b) gives a reason for why policy only delivers an incomplete adjustment towards $E' = 1$. By not fully responding to the shocks, the central bank can use the onshore-offshore exchange rate to attenuate their impact on the onshore-foreign exchange rate. Intuitively, an increase in the demand for offshore deposits would, all else equal, raise the interest rate on deposits. Foreigners, seeing these higher returns abroad push the domestic exchange rate to appreciate up to the point where it is expected to depreciate, re-equating returns across borders. At the same time, the banks that supply these offshore deposits will increase their demand for reserves. If the central bank only partially satisfies this higher demand, then the offshore exchange rate will appreciate. Because it is expected to depreciate, back to its peg, domestic depositors are less willing to demand deposits. This lowers the pressure on the interest rate on deposits, and therefore reduces the adjustment of the domestic exchange rate.

In the case of the yuan, the PBoC has an explicit desire to smooth fluctuations in $\tilde{E}$, the onshore-foreign exchange rate. Having the onshore-offshore exchange rate E deviate from parity gives it a tool to do so. This offshore escape valve is subject to the limit that E cannot fall too far for too long from parity without putting pressure on the capital controls or falling foul of Gresham's Law. But, as a policy tool to absorb transitory fluctuations or

Figure 7: Dynamics of the two exchange rates

(a) CNY-CNH exchange rate after an expansion in money demand

(b) CNY-CNH exchange rate after a rise in the CNH-USD exchange rate



Note: Panel (a) shows estimates of equation (9) replacing z_t with $\log(E_{t+h})$, dropping the corresponding control, and instrumenting with our exogenous shift of money demand shocks. Panel (b) estimates the same local projection without an instrumental variable replacing $\Delta\log(E_t)$ with $\Delta\log(\hat{E}_t)$ and adding $\log(\hat{E}_{t-1})$ to the control set. In both panels, the confidence intervals use White robust standard errors, following Montiel Olea and Plagborg-Moller (2021). The sample goes between April 2017 and August 2023.

smooth permanent adjustments, this can be valuable.

The right panel of figure 7 confirms that it is so by plotting the conditional correlation between $\log(E)$ and $\log(\hat{E})$. At all horizons, this is negative. In line with Proposition 2b), the two exchange rates move in opposite directions, reducing the volatility of their sum. Unconditionally, across all shocks, the empirical correlation correlation of $\hat{E}$ with E between April 2017 and August 2023 was -0.19.

More generally, imagine that the onshore currency is, for whatever fundamental reasons, depreciating relative to the foreign currency. If the offshore currency is worth less than parity, then, mathematically, the relevant onshore currency must have depreciated less than it would have otherwise. The onshore-offshore exchange rate serves as an escape valve against these forces for a depreciation.

4.3 The role of liquidity policies

Five days after the shock that appreciated the exchange rate by 1%, it had depreciated back by 0.83% (figure 7a). In the model, following proposition 2c), this can be explained by: (i) the demand shock dissipating or $\hat{E}$ adjusting; (ii) *monetary policies* that expand the money supply either its target (by the PBoC in bills' auctions) or elastically to accommodate demand (by the HKMA in the PLP); and (iii) a shift in the liquidity function that reduces the marginal benefit of liquidity $-\phi'(M/D)$, which we refer to as *liquidity policies*.

On (i), the estimated dynamic correlation of the instrument for demand shocks suggests that, after 5 days, 0.53% of the depreciation is accounted for by the transitory nature of these shocks. To measure (ii), the estimated response of the money supply in figure 6 was ¥5bn. The estimates in section 3.5 of the potency of monetary policy were that each billion depreciated the exchange rate by 0.01%. Therefore, the monetary forces to re-establish the peg contributed a 0.05% depreciation. That leaves as a residual for (iii) that $1 - 0.05/(0.83 - 0.53) = 5/6$ths of the observed average depreciation brought about by policies is explained by liquidity policies. The next section unpacks this residual, decomposing it into shocks and policies, and presenting direct evidence from the CNH experience of its contribution to sustaining the peg to parity.

5 A liquidity anatomy of the peg

We start in section 5.1 with the Bianchi and Bigio (2022) microfoundation of the liquidity cost function $\phi(.)$ adapted to our setting, before expanding it in the following sections to deliver empirical predictions and consider a broader set of policies.

5.1 A model of the liquidity cost function

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

Withdrawal shocks. A bank is indexed by ω, an idiosyncratic shock standing for the fraction of start-of-period offshore deposits that are withdrawn by the end of the period. 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 receive net inflows $\omega > 0$. At the start of the period, 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. They must also satisfy at all times a 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 period, 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 period. 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 $\bar{\omega}$. Each individual bank takes the market tightness as given.

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 discount window facility at a given rate R^z.

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.

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 $1 - \Psi_-(\theta)$, the bank does not find a lender and must borrow from the discount window at the higher cost $R^z - R^m$. Expected liquidity costs are:[45]

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

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 at the top of the domain $\phi(1) = 0$.

5.2 Liquidity variables after a money demand shock

Appendix A.4 proves the following result:

Proposition 3. *The marginal benefit of liquidity evaluated at the equilibrium reserve-deposit ratio is:*

$$-\phi'(M/D) = (1 - \Psi_-(\theta))(R^z - R^m)\Omega(\bar{\omega}). \qquad (15)$$

A rise in money demand that is only partially offset by a rise in money supply (E rises) leads to:

a) an increase in the tightness in the interbank market θ;

b) an increase in the interbank rate $R^f(\theta)$;

c) greater use of the discount window liquidity facilities.

[45]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 $\mathbb{E}[\omega] = 0$.

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

Bill maturities	All	12M	6M	3M
	(1)	(2)	(3)	(4)
$\frac{1}{5}\sum_0^4 \log(E_{t-h})$	-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.

This proposition translates the shift in the marginal benefit of liquidity into three endogenous liquidity variables. We already identified at the end of section 4 a shift in $-\phi'(M/D)$ following a shock to money demand as a residual in the adjustment of the exchange rate. We now test this shift using these observable liquidity variables.

Tightness and bills auctions. Empirically, prediction a) would show up in a decline in the bid rate for CNH bills by banks. Intuitively, the missing supply of HKMA money means banks are less willing to hand CNH reserves to the PBoC in exchange for bills. As we discussed before, the PBoC runs regular auctions for bills at a lower frequency than the HKMA can act. Between the PBoC announcing an auction and taking bids, on average 6 trading days go by, so at high frequency, the quantity of bills supplied 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.

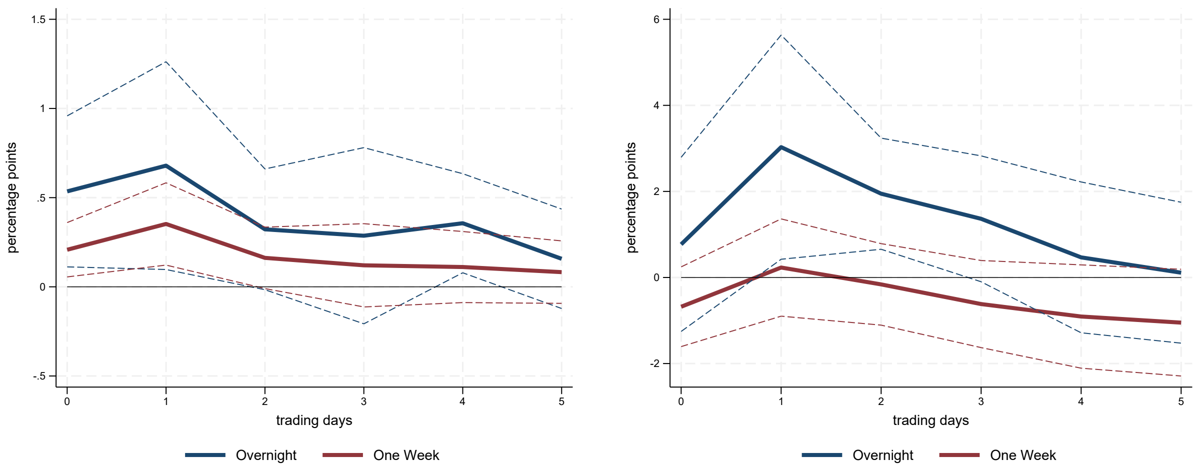
Table 2 tests this negative effect by regressing the subscription rate on the average deviation from the peg in the five days prior to the auction to capture the interval after an auction is announced and before it takes place. The estimated coefficients are negative.[46]

Interest rates. Prediction 3b) is that, when the overall money demand rises, banks need-

[46] Table D.2 in appendix D uses instead the exchange rate on the day of the auction. Because the auction results are only announced after the market closes, and the bills are settled two days later, they do not contaminate the exchange rate. The effect is less precisely estimated and weaker, but the conclusion holds.

Figure 8: Interbank rate response to a money demand shock

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



Note: Estimates of equation (9) for the overnight and one-week CNH interbank interest 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.

ing liquidity will turn to borrowing from other banks that have a liquidity surplus. This increase in demand in the interbank market raises the private-market price for liquidity.

In the data, the substitute for HKMA PLP balances is the interbank money market. Figure 8 estimates the same local projection as in equation (9), but with the overnight and one-week CNH interbank rate on the left-hand side. The least-squares estimates confirm the theory prediction that the rate rises. The effects are larger with the IV estimates on the right panel (note the change in the scale) but only at the overnight maturity.

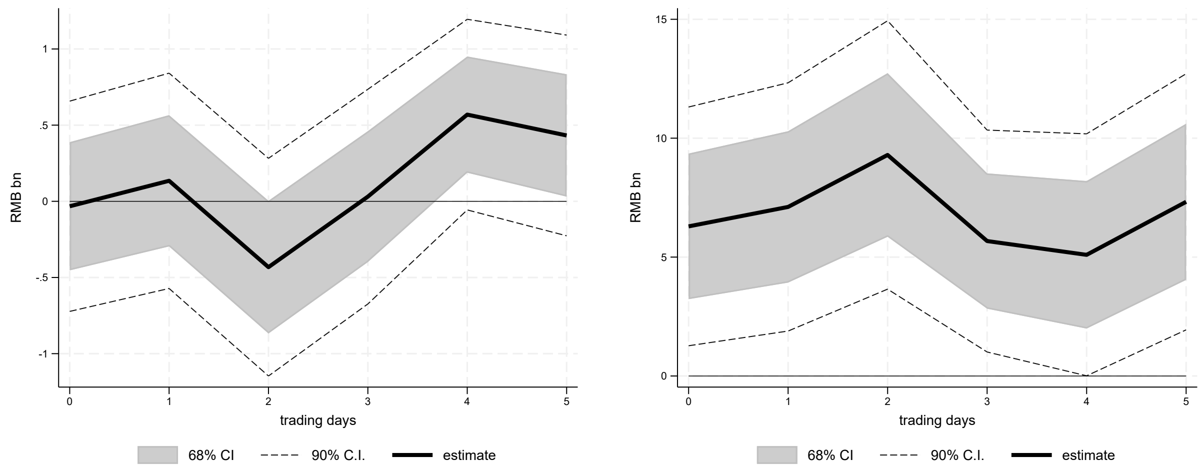
Discount window borrowing. The third and final prediction in the proposition arises because the money demand shock lowers the deficit threshold $\bar{\omega}$. With more demand for money, a bank is more likely to be in a liquidity deficit, not find a lender with probability $1 - \Psi_{-}(\theta)$, and go to the discount window.

In the case of CNY-CNH, by keeping the money supply scarce, the PBoC ensures that on aggregate banks find themselves routinely having to take this route. Figure 9 shows estimates of the same regression as in equation (9), but now with drawings from the liquidity facilities as the measures of z_{t+h}.[47] The increase in money demand generates a

[47]The results in figure 9 use only the intraday facility. Using the sum across the two facilities leads to

Figure 9: 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) for the liquidity facility drawings. The sample has all trading days between April 2017 and July 22nd 2022 when the terms on the HKMA lending facilities changed. The confidence intervals use White 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.

rise in discount window borrowing of around ¥6bn.[48]

5.3 Financial innovation shocks and low-frequency liquidity policies

Shocks to the marginal benefit of reserves put pressure on the peg. Conversely, liquidity policies that steer the marginal benefit of reserves can contribute to sustaining the peg and managing the escape valve. The next result identifies some of these shocks and policies.

Proposition 4. *The marginal benefit of liquidity rises when:*

a) the financial markets deteriorate: $\Psi_-(\theta)$ *falls or* $\Omega(.)$ *shifts up;*

b) reserve requirements are higher: ρ *is higher, which raises* $\bar{\omega}$*;*

c) the costs of emergency borrowing from the central bank is higher: R^z *rises.*

almost identical results. The sample ends in July 2022 because of a reform that we will discuss next.

[48]Figure D.5 in appendix D splits the impact between different times of the day. The use of the discount window rises as soon as the market opens and persists during the day.

The first prediction points to another source of shocks to the peg: financial innovation. A higher $\Psi_{-}(\theta)$ may be due to an increase in the efficiency of matching in the interbank market. A shift down of $\Omega(.)$ can arise from banks being better able to either retain depositors or to predict withdrawals. Either of them lowers the marginal benefit of reserves, depreciates the onshore-offshore exchange rate, and puts pressure on the peg.

Empirically, these shocks would show up as large fluctuations in the reserve-deposit ratio seemingly breaking the relation between monetary aggregates and the exchange rate (Goodhart's law). A plot of bank deposits in CNH relative to deposits in CNY on the lagged exchange rate using monthly data between April 2017 and April 2023 in figure D.7 in appendix D reveals a relation with an R^2 of just 0.04.

The second prediction states that raising reserve requirements will make it more likely that banks will find themselves scrambling for reserves. Therefore, it raises the marginal benefit of having reserves, and so pushes E up. Historically, central banks have changed reserve requirements in response to financial innovation that shifts the money multiplier. According to media reports, the PBoC does too, sometimes in the form of foreign risk reserve ratios, sometimes through other regulations and moral suasion. Yet, we have no direct empirical evidence to test it.

The third prediction notes that if the central bank makes its backstop liquidity more expensive, this will raise the marginal benefit of holding on to reserves beforehand. In the case of the CNH, the HKMA could do this by raising the rate it charges on its liquidity facilities, by lowering its own CNH reserves to lower the threshold at which it would have to resort to the swap line with the PBoC, or by raising the rate on that line. We have evidence to test this last prediction.

Evidence from two HKMA reforms. Initially, when the HKMA intraday lending facilities started, banks could borrow paying a rate of 50bp above the previous day's overnight interbank rate. On the 5th of April of 2016, the HKMA changed the lending rate to 50bp plus the average of the previous three days' overnight rates.

We estimate the following autoregressive distributed lag regression on a sample from the 4th of November of 2015 to the 1st of September of 2023, with a dummy variable $Post_t$ that takes the value one for observations after the 5th of April of 2016, and controlling for three lags of $\log(E_t)$, the onshore overnight rate, and the offshore and onshore three-month rates (in parentheses are Newey-West standard errors):

$$\begin{aligned}\log(E_t) = & \underbrace{-0.04}_{(0.23)} R^f_{t-1} - \underbrace{0.62^{***}}_{(0.23)} R^f_{t-2} - \underbrace{0.51^{***}}_{(0.12)} R^f_{t-3} - \underbrace{0.01}_{(0.17)} R^f_{t-4} \\ & + Post_t \times (\underbrace{0.57^{**}}_{(0.28)} R^f_{t-1} - \underbrace{0.52}_{(0.37)} \times R^f_{t-2} + \underbrace{\mathbf{1.25}^{***}}_{\mathbf{(0.29)}} \times \boldsymbol{R^f_{t-3}} + \underbrace{0.15}_{(0.27)} \times R^f_{t-4}) \\ & + \text{controls}_t + \text{error}_t. \end{aligned} \tag{16}$$

The key coefficient, in bold, is statistically significantly and positive. This says that, after the reform, ceteris paribus, a higher overnight rate three days ago is now associated with an appreciation of the CNH. Consistent with the model, once this lagged rate became an indicator for the cost of lending from the discount window, then a higher rate meant that emergency liquidity became more expensive. The ex ante marginal benefit of reserves was higher, and the relative value of the offshore currency rose.

On the 22nd of July of 2022 the HKMA announced a second reform and implemented it on the 27th. The HKMA cut the premium on lending from 50bp to 25bp, and raised the maximum quantity banks could borrow from ¥10bn to ¥20bn. By lowering the costs of emergency liquidity, this reform lowers the marginal benefit of reserves. Therefore, it should depreciate the value of the offshore currency and lower the difference between onshore and offshore overnight rates. Indeed, in the ten trading days after the new regime was in place, relative to the average in the ten trading days before, $\log(E)$ was on average 1.7bp lower and the interest rate differential was 10bp lower.

5.4 Higher-frequency liquidity policies

We modify the model to discuss three other liquidity policies.

Extended model. 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. Let G be the stock of central bank bills. We introduce them in the model by assuming that bills can be sold frictionlessly to obtain reserves, but only reserves can be used to settle meet withdrawals (and the interbank market is for reserves only). Second, we now allow banks to move onshore reserves to offshore reserves to lend in the interbank market. We denote this inflow of liquidity by W^m, and assume that it is exogenous because the PBoC has a tight control over the clearing banks through which these transfers happen. Third and finally, we allow offshore depositors that withdraw to move their funds to the onshore market and vice versa, instead of having to deposit them in another onshore bank. The mean of the distribution of withdrawals $\Omega(\omega, W^d)$ is no longer zero but rather equals this deposit flow W^d. Given the capital controls, we treat W^d as a policy tool of the central bank.

Appendix E.5 lays out the model and shows that interbank market tightness is now:

$$\theta = \frac{-\int_{-1}^{\bar{\omega}} s(\omega) d\Omega(\omega; W^d)}{\int_{\bar{\omega}}^{\infty} s(\omega) d\Omega(\omega, W^d) - G + W^m}. \tag{17}$$

This leads to the following result proven in appendix A.6:

Proposition 5. *With central bank bills (G) and exogenous constraints on reserve flows (W^m) and deposit flows (W^d) in the model for liquidity, the following policies raise tightness θ, the marginal benefit of reserves $-\phi'(M/D)$, and the exchange rate E:*

a) a cut in reserves that is paid for by issuing bills, so M falls but $M + G$ is unchanged;

b) a tightening of the restriction in reserve flows W^m;

c) a tightening of the restriction in deposit flows W^d.

Intuitively, a cut in the money supply that injects bills has no effect on the threshold for being in a liquidity deficit, $\bar{\omega}$, since banks can still meet withdrawals with their bills. However, now the interbank market is tighter, as there are fewer reserves for banks to offer there. This is why G appears in the denominator in equation (15) and so swapping M for G raises the marginal benefit of reserves. A cut in W^m works just in the same way, by making the interbank market for reserves tighter. Finally, a cut in W^d shifts left the distribution $\Omega(\omega)$ since it makes it more likely that banks will have a liquidity deficit.

Evidence from the 2015–16 financial crisis. In 2015–16, macro-financial forces led to a trend depreciation of the yuan relative to the dollar visible in panel (a) of figure 10. Initially, the PBoC held the central parity rate, $\bar{E}$ relatively constant. The CNY/USD exchange rate persistently traded at the lower bound of the trading band. 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 10. As predicted by the model, given its role as an escape valve, the CNH depreciated one additional percentage point against the USD. The CNH traded at an average 0.6% discount relative 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 sharp fall in the flows from the onshore to the offshore market in the Chinese current account, more than one fifth right away, and a further two fifths over the next few months.[49]

Panels (c) and (d) show the consequences for liquidity, which line up with our model and the identified empirical mechanisms. Panel (c) shows that the stock of CNH deposits (D in our model) fell by 20 log points relative to CNY deposits during the December 2015 tightening. Panel (d) shows that the PBoC's actions caused the 3-month CNH interbank rates ($R^f(\theta)$ in the model) 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). This intervention brought CNY-CNH closer to parity but the scarcity of CNH meant that the internationalisation of the RMB paused.

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 CNY-CNH that pushed it above parity (panels (a) and (c)). This ended at the start of 2017, partly helped by the stabilisation of the exchange rate with the USD, partly by setting up the framework described in section 2.

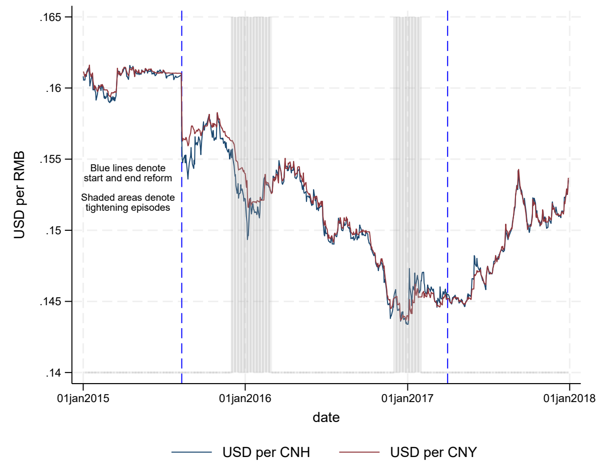
Evidence from the August 2023 devaluation. In the spring of 2017, the PBoC introduced a countercyclical factor in the central parity band and created the regular auctions of bills giving it greater control over the offshore money supply. Also, during 2016 and 2017, the HKMA reformed the automatic liquidity 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 CNY-CNH exchange rate much closer to parity, in spite of large fluctuations in the exchange rate with the USD (recall figure 1). This system was tested in the summer of 2023, when again the yuan depreciated relative to the dollar.

Figure 11 shows the financial variables during this time. 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

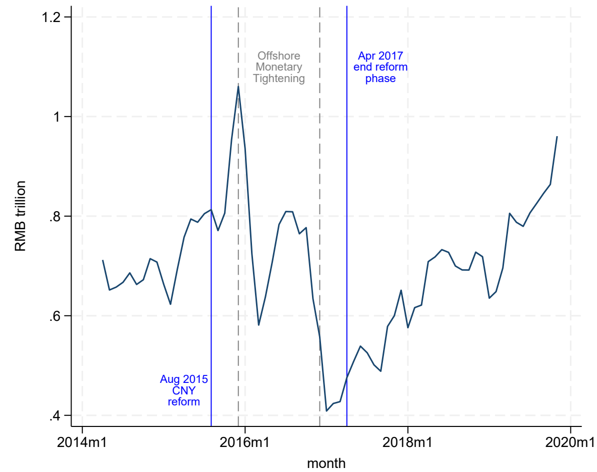
[49]The flows in the other direction are reported in appendix figure D.8.

Figure 10: The monetary tightenings of 2015 and 2016

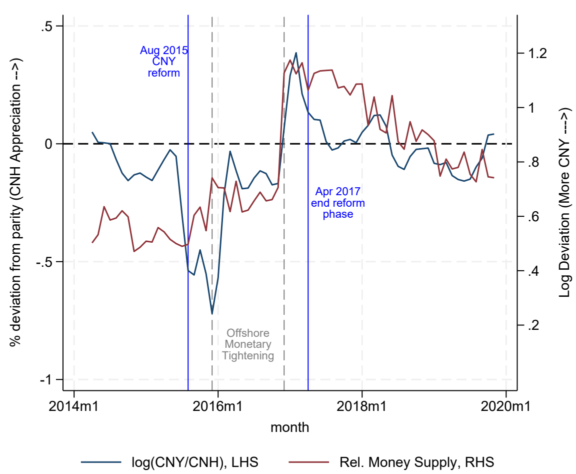
(a) CNH/USD and CNY/USD exchange rates



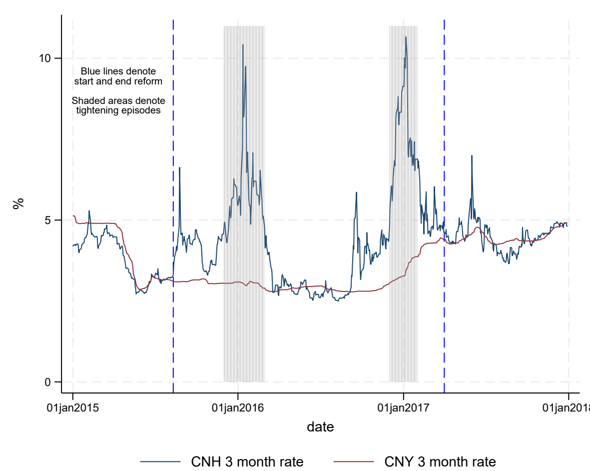
(b) RMB flows from onshore to offshore



(c) Relative CNY-CNH deposit stock and $\log(E)$



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



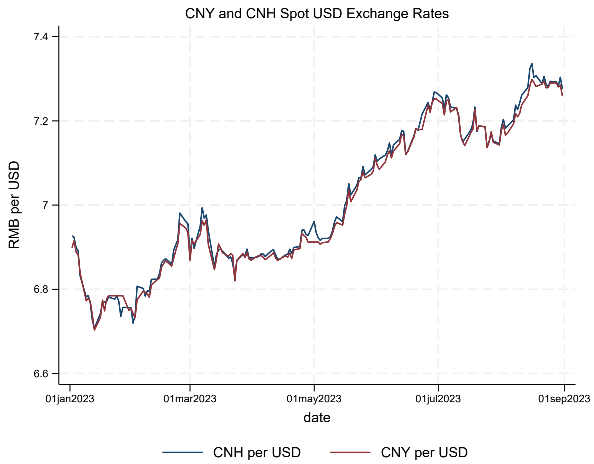
Note: Panel (a) shows yuan exchange rates. Panel (b) shows the conversion of CNH into CNY from the current account, at a monthly frequency. Panel (c) shows $\log(D_t^{\text{CNY}}) - \log(D_t^{\text{CNH}})$ against monthly average $\log(E_t)$. Panel (d) shows yuan interbank rates.

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.

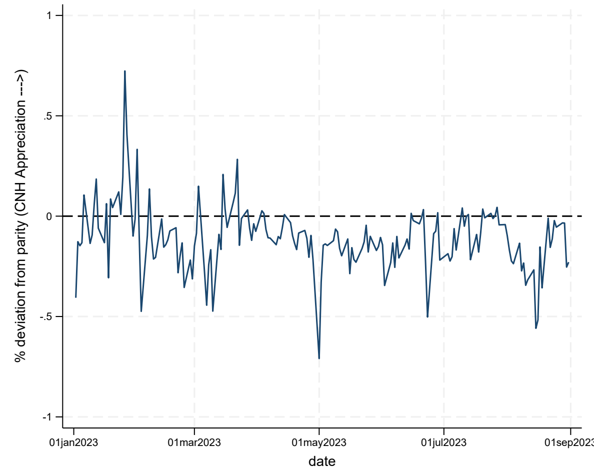
This time, the PBoC did not resort to draconian liquidity controls, and there was no crash in financial markets or damage to the growth of the yuan as an international currency. Instead, the PBoC responded by increasing the issuance of CNH 3M bills from ¥10bn to ¥20bn in the August auction, reducing the money supply. State banks sold USD reserves in a way similar to a sterilised foreign exchange market intervention, and

Figure 11: The August 2023 episode

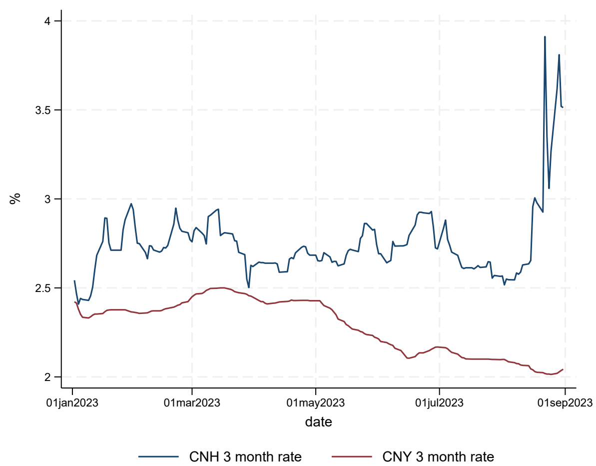
(a) CNH-USD and CNY-USD exchange rates



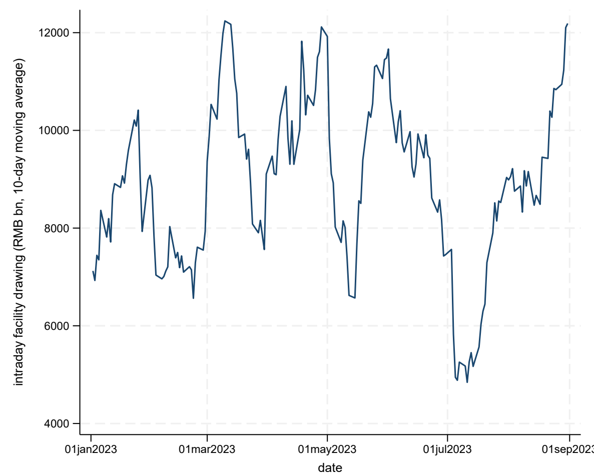
(b) CNY-CNH exchange rate



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



(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 $100 \log(E)$ so an increases is a CNH appreciation. Panel (c) shows CNY and CNH interbank rates. Panel (d) shows the 10-day moving average of maximum daily drawings from the HKMA's intraday RMB liquidity facility.

changed their holdings of CNH, which is akin to a helicopter drop. In the language of the model, the PBoC cut M, but also employed liquidity policies to raise $-\phi'(M/D)$. These policies complemented the movement in E shown in the figure, in order to prevent $\hat{E}$ moving as much as it would have otherwise. With the post-2017 framework that we analysed in this paper, the stress in the peg was smaller, with less of an increase in interbank rates and smaller and less persistent deviations from the peg.

6 Conclusion

More than a decade ago, Chinese monetary authorities created an offshore currency that could be used freely for foreign transactions, while imposing strict controls in the exchange of this offshore currency for its onshore counterpart. This was set up 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. It created a regime of parallel currencies, requiring a monetary and liquidity system that kept their exchange rate close to parity.

Institutionally, this paper explained this system. After unpacking its components, it made clear that there are conventional monetary and liquidity forces at play. Therefore, we can use the Chinese experience to understand the classic links between policies and exchange rates. At the same time, the use of this system to promote the internationalisation of the yuan, to enforce capital controls, and to aid in managing the exchange rate with foreign currency is more novel, and may be useful in other settings.

Empirically, we used this monetary experiment and its peculiarities to put forward some credible evidence on what drives exchange rates. We found that exogenous transitory increases in the money supply depreciate the exchange rate. The implied interest-rate elasticity of the demand for reserves at the central bank is 48, significantly less than the infinity of ample reserve frameworks or cashless-limit theories, but more than the zero of the simple quantity theory.

In the data, monetary policy has responded to increases in the demand for money by raising the money supply. This has kept deviations from the peg small and short-lived, helping to sustain the capital controls, while providing an escape valve when the yuan is depreciating relative to the dollar, helping to sustain the CNY-USD trading band.

We found a large and significant role for liquidity policies complementing monetary policies. Increases in the demand for money reduced the demand for bonds, raised interbank rates, and increased borrowing from the discount window in the data. Reforms to the emergency lending facility affected the exchange rate via the marginal benefit of an extra offshore reserve. Finally, a tightening of liquidity controls offset a large shock, but with severe consequences on liquidity measured by deposits or interbank rates. Altogether, monetary and liquidity policies have prevented the usual demise of parallel currencies from Gresham's law.

Theoretically, we proposed a model of exchange rates with offshore banks that create private money. The model gave an interpretation of the empirical results on the monetary drivers of exchange rates, and mapped the estimates into different elasticities. Merging it with a micro-founded model of liquidity management by banks provided a coherent framework to discuss the complementarities between monetary and liquidity policies, and to discuss the pressure that financial innovation puts on pegs.

The model and empirics combined suggest that the current institutional framework seems to be up to the task. As we showed, many shocks have hit the system, yet deft management of monetary and liquidity policies have preserved the peg. Still, by keeping the offshore supply of money scarce, the capital controls encourage financial innovation to satisfy the positive marginal benefit of liquidity. In the data, the link between monetary aggregates and exchange rates has broken often, as predicted by Goodhart's law. And yet, the parallel currencies have survived so far supported by a coherent monetary and liquidity framework. Our analysis provides future guidance for the PBoC on which shocks may burst the seams of its framework and how to reinforce them.

More intriguingly, this paper's results suggest that the international use of the yuan could still significantly increase. Also, other countries could try frameworks inspired by this experience. And finally, offshore arrangements can be used to temporarily relax the trilemma complementing foreign exchange interventions.

References

Afonso, Gara, Domenico Giannone, Gabriele La Spada, and John C. Williams. 2022. "Scarce, Abundant, or Ample? A Time-Varying Model of the Reserve Demand Curve." *Federal Reserve Bank of New York Staff Report 1019*.

Alvarez, Fernando, Andrew Atkeson, and Patrick J. Kehoe. 2002. "Money, Interest Rates, and Exchange Rates with Endogenously Segmented Markets." *Journal of Political Economy*, 110(1): 73–112.

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

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.

Boughton, James M. 1988. "The Monetary Approach to Exchange Rates: What Now Remains?" *Essays in International Finance*, 171: 1–28.

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.

Eichenbaum, Martin, and Charles L. Evans. 1995. "Some Empirical Evidence on the Effects of Shocks to Monetary Policy on Exchange Rates." *Quarterly Journal of Economics*, 110(4): 975–1009.

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, 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.

Genberg, Hans, and Cho-Hoi Hui. 2011. "The Credibility of Hong Kong's Link from the Perspective of Modern Financial Theory." *Journal of Money, Credit and Banking*, 43(1): 185–206.

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, Dong, and Robert N McCauley. 2012. "Offshore markets for the domestic currency: monetary and financial stability issues." In *The evolving role of China in the global economy.* , ed. Yin-Wong Cheung and Jakob de Haan, 302–338. Cambridge: MIT Press.

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.

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.

Lopez-Salido, David, and Annette Vissing-Jorgensen. 2023. "Reserve Demand, Interest Rate Control, and Quantitative Tightening." Federal Reserve 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.

Mussa, Michael. 1976. "The Exchange Rate, the Balance of Payments and Monetary and Fiscal Policy under a Regime of Controlled Floating." *Scandinavian Journal of Economics*, 78(2): 229–248.

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.

Rogoff, Kenneth. 1999. "Monetary Models of Dollar/Yen/Euro Nominal Exchange Rates: Dead or Undead?" *The Economic Journal*, 109(459): F655–F659.

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.

A Appendix: Proof of propositions

With iid shocks and a credible peg ($\mathbb{E}(E') = 1$) the equilibrium no-arbitrage condition in the reserves market is:

$$E = \frac{R^m - \phi'(M/D)}{R^{m,o} - \phi^{o\prime}}. \tag{A.1}$$

Combining supply and demand for deposits with market clearing and the credible peg delivers the equilibrium condition for the deposit market:

$$E(R^l - k + v(D - \hat{D})^{-\alpha}) = \phi\left(\frac{M}{D}\right) - \left(\frac{M}{D}\right)\phi'\left(\frac{M}{D}\right). \tag{A.2}$$

These two equations have two positive relations between two variables, E and D. Once they are pinned down, equation (5) gives R^d. Equation (6) then gives the exchange rate $\hat{E}$.

A.1 Comparative statics on the neighbourhood of a peg

We evaluate comparative statics around a steady state where: shocks are at their mean $M = \bar{M}, v = 1$, there are no offshore foreign deposits $\hat{D} = 0$, all gross interest rates are one $R^l \approx R^d \approx R^{m,o} - \phi^{o\prime} \approx 1$, and the peg is at parity: $E \approx \mathbb{E}(E') \approx 1$. Therefore, evaluating the equilibrium conditions and letting upper bars denote the steady state values: $\phi'(\bar{M}/\bar{D}) = R^m - 1$, and $\phi(\bar{M}/\bar{D}) = (\bar{M}/\bar{D})\phi'(\bar{M}/\bar{D})$, and $\bar{D}^{-\alpha} = k$, and $1 = \hat{R}$. Also, at this steady state $\varepsilon_m = 1/(\phi''(m/d)m/d)$ and $\varepsilon_d = D^\alpha/\alpha$.

Back to the two equilibrium conditions in equations (A.1) and (A.2), defining the composite exogenous variable $z = vM^{-\alpha}(1 - \hat{D}/D)^{-\alpha}$ and the endogenous inverse of the money multiplier $x = M/D$, the model can be reduced to a single equation:

$$\left(\frac{R^m - \phi'(x)}{R^{m,o} - \phi^{o\prime}}\right)\left(R^l - k + zx^\alpha\right) = \phi(x) - x\phi'(x).$$

which we solve for x as a function of the shocks z as: $x = x(z)$. With a slight abuse of notation, the solution for the exchange rate one is: $E(x) = R^m - \phi'(x)/(R^{m,o} - \phi^{o\prime})$.

Using the implicit function theorem to differentiate and evaluate on the neighbourhood of a peg:

$$\frac{dx(z)}{dz} = -\frac{x^\alpha}{\alpha z x^{\alpha-1} + x\phi''(x)} < 0.$$

Recalling the definitions of the elasticities and re-writing them in terms of x, we have

$\varepsilon_m = 1/(x\phi''(x))$ and $\alpha x^{\alpha}\varepsilon_d = M^{\alpha}$. Substituting out $\phi''(.)$ and α gives:

$$\frac{dx(z)}{dz} = -\frac{x^{\alpha}}{\frac{1}{x\varepsilon_d} + \frac{1}{\varepsilon_m}} < 0.$$

Since $z = vM^{-\alpha}(1 - \hat{D}/D)^{-\alpha}$, shocks to v and $\hat{D}$ will have the same comparative statics, and these will have the opposite sign of a shock to M. Moreover, in the neighbourhood of a steady state:

$$\frac{dE(x(z))}{dz} = -\phi''(x)\left(\frac{dx(z)}{dz}\right) = -\left(\frac{1}{x\varepsilon_m}\right)\left(\frac{dx(z)}{dz}\right) > 0.$$

A money demand shock raises E, and a money supply shock lowers E. This proves part a) of propositions 1 and 2

A.2 Proof of proposition 1

Part a) was proven in appendix A.1. For part b), It is clear from equation (6) that $\hat{E}$ moves in the opposite direction of R^d. Using equation (4), we can write the solution for the deposit rate as the function $R^d(E, x) = E/\,\mathbb{E}(E') - \phi(x) + x\phi'(x)$. Differentiating, evaluating in the neighbourhood of the peg, and using the implicit function theorem:

$$\frac{dR^d}{dz} = \frac{dE(x(z))}{dz} + x\phi''(.)\left(\frac{dx(z)}{dz}\right) = (1-x)\frac{dE(x(z))}{dz}$$

Therefore, since $0 < x < 1$ we have that R^d and E move in the same direction. Therefore, E and $\hat{E}$ move in opposite directions after a shock.

Finally, for part c), recall from appendix A.1 that:

$$\frac{dx(z)}{dz} = -\frac{x^{\alpha}}{\frac{1}{x\varepsilon_d} + \frac{1}{\varepsilon_m}} \quad \text{and} \quad \frac{dE(x)}{dx} = -\frac{1}{x\varepsilon_m}.$$

In turn, from the definition of $z(M) = vM^{-\alpha}(1 - \hat{D}/D)^{-\alpha}$ we have that in the neighbourhood of the peg: $dz/dM = -\alpha M^{-\alpha-1} = -M^{-1}x^{-\alpha}/\varepsilon_d$. By the chain rule, combining all these results:

$$\begin{aligned}\frac{MdE}{dM} &= M \times \left(\frac{dE(x)}{dx}\right) \times \left(\frac{dx(z)}{dz}\right) \times \left(\frac{dz(M)}{dM}\right) \\ &= M \times \left(-\frac{1}{x\varepsilon_m}\right) \times \left(-\frac{x^\alpha}{\frac{1}{x\varepsilon_d}+\frac{1}{\varepsilon_m}}\right) \times \left(\frac{-M^{-1}x^{-\alpha}}{\varepsilon_d}\right) \\ &= -\frac{1}{\varepsilon_m + x\varepsilon_d}.\end{aligned}$$

A.3 Proof of proposition 2

Part a) was proven in appendix A.1. The proof of part b) the same as in proposition 1, since z is a sufficient statistic for all shocks. For part c), from equation A.1 a shift down in $-\phi'(x)$ means that for any given x the exchange rate is lower.

A.4 Proof of proposition 3

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

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

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 expected benefit of participating in the interbank market is zero. Formally, the interbank market clearing condition is:

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

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

Note that it is again easy to verify the assumption we made earlier about $-\phi'(.)$ in equilibrium: 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.

Turning to the three comparative statics, take the case where $\eta = 0$ for simplicity, although the same logic would apply to a positive η. From proposition 2, the money demand shock raises E. From the reserves market equilibrium condition, this must come with an increase in the marginal benefit of reserves $-\phi'(M/D)$. From equation (15), this must come with an increase in $(1 - \Psi_{-}(\theta))$ and/or an increase in $\bar{\omega}$. From equations (12)-(13), it comes with both, and with a rise in $\bar{\omega}$ and in θ. Then, since θ rose, part a) is proven. Since by assumption $R^f(\theta)$ is an increasing function, that proves part b). Since the probability that a bank uses the discount window is $(1 - \Psi_{-}(\theta))$, that proves part c).

A.5 Proof of proposition 4

All three variables only enter the model through their impact on the marginal benefit of reserves in equation (15), taking into account equations (12)-(13) that define $\bar{\omega}$ and θ in terms of the other exogenous variables.

Then: a lower $\Psi_{-}(\theta)$, a shift up of $\Omega(\bar{\omega})$, or a higher R^z, all increase the right-hand side of equation (15), proving predictions a) and c). If ρ rises, then the liquidity threshold in equation (12) will rise. This raises tightness θ as well as the likelihood of being in a deficit $\Omega(\omega)$. Therefore, it raises the marginal benefit of holding on to reserves, proving prediction b).

A.6 Proof of proposition 5

A cut in M that leaves G unchanged, works just the same as in the previous model. However, if instead $M + G$ is unchanged, there is no longer an effect of the monetary expansion on $\bar{\omega}$. Instead, the cut in M works by raising G in equation (17) alone, changing θ and from there the marginal benefit of reserves. The same applies to cutting the constraint on reserve flows since $W^m - G$ are the sufficient statistic in this equation. Finally, a cut in W^d works just like a shift in the distribution $\Omega(\omega)$ discussed in proposition 3.

Online appendix

B Data appendix

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

FX data. Daily FX data are sourced from LSEG 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. All interbank rates were sourced from LSEG datastream. As an example, for 3-month tenors we use the 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. 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).

C 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 authorised 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 authorised 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 ¥20bn intraday and ¥20bn overnight to the same bank, and then convert the intraday borrowing into overnight for a total of ¥40bn. Overnight borrowing is repaid by 2pm the following trading day.

The term facilities operate on a $T + 1$ settlement cycle, and are funded using the HKMA's swap line with the PBoC 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.

D Complementary empirical results

Figure D.1 shows the persistence of the exchange rate deviations within one day.

Figure D.2 shows the daily usage of the different types liquidity facilities offered by the HKMA. The overnight repo is rarely used, likely because intraday borrowing converts into overnight borrowing automatically.

Table D.1 regresses the relative growth rate of the money stock in CNY and CNH on 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. 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 D.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 D.3 splits the response of the one-week interbank rates and the exchange rates to the exogenous shocks to money supply for each individual bill roll-overs.

Figure D.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) that have a USD market exchange rate in Bloomberg and that have a rating of 3 or 4 in the **?** scale of pegs gives an unbalanced panel of 26 countries from February 1979 to December 2015.

Figure D.2 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 D.5 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 occur at 11am then are stable throughout the day.

Figure D.6 is the equivalent of figure 6 panel (b), but using only drawings between 11am and 4pm to reflect that the central parity rate is announced at 11am.

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

Figure D.7 plots the data behind the regression in table D.1 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 D.8 shows the flows of RMB from offshore to onshore during 2015–16. They also show a contraction, in line with figure 10.

D.1 Time series identification of the elasticity of demand for deposits

The demand for reserves in equation (3) implies that in equilibrium:

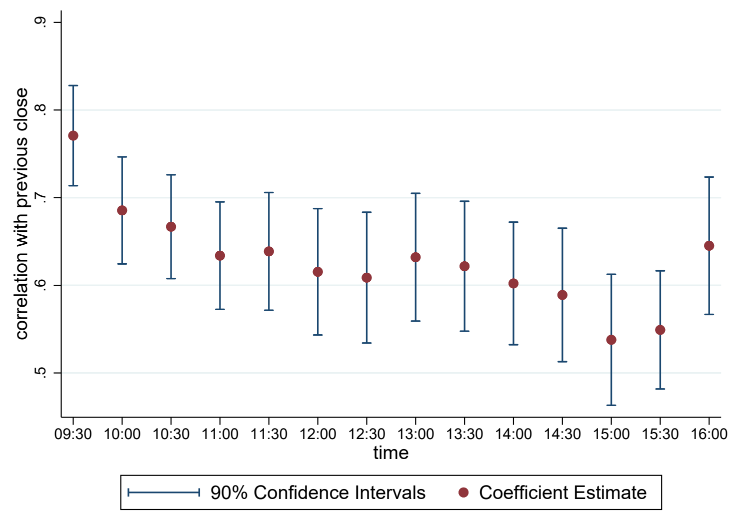
$$\phi'(M/D) = R^m - \left(\frac{E}{\mathbb{E}(E')}\right)\left(R^{m,o} - \phi^{o\prime}(m^o/d^o)\right). \tag{D.1}$$

The elasticity of M with respect to E is equal to $d(\phi'(.) - R^m)/(m\phi''(.))$. In the neighbourhood of a peg, this is equal to ε_m, since recall that $\varepsilon_m = (R^m d)/(m\phi''(.))$.

We measure E, and have an instrument for it that comes from shocks to the demand for deposits, discussed in section 4. Figure D.9 shows the estimates from a local projection of $\log(D_t)$ on $\Delta \log(E_t)$ and controls, including lagged deposits, at a monthly frequency using the monthly average of our daily measure of money demand shocks as an instrument for the exchange rate and control. This estimate of ε_m has three important caveats. First, we only have a monthly measure of D. Therefore, we need more observations, and so we extend the sample from the inception of CNH in 2010 until August 2023, which includes the pre-reform periods. Second, we do not have a monthly measure of M to control for. In the model, a shock to v or $\hat{D}$ is orthogonal to M, but in the data this is unlikely the case. Third, recall that part of our case for the exogeneity of the instrument was the high frequency of our data. At a monthly frequency identification is less sharp.

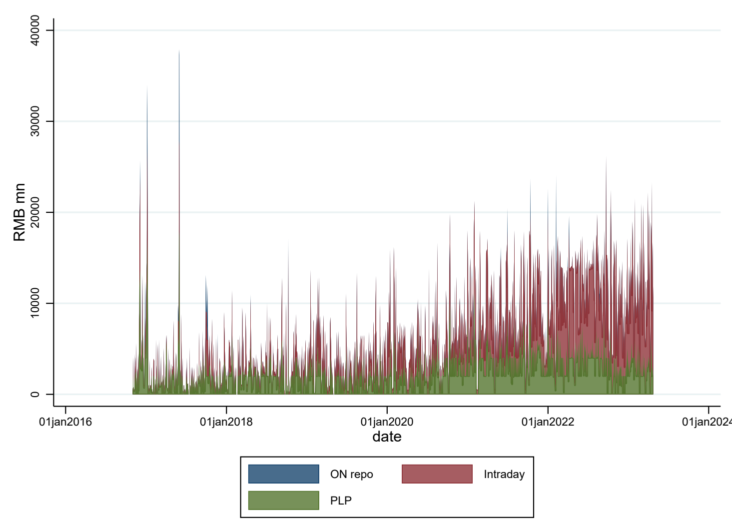
With these caveats in mind, we find that the impact of a money demand shock that raises the exchange rate by 1% is to is to raise deposits by 47% on average over the first six months.

Figure D.1: Intraday CNY-CNH exchange rate persistence



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

Figure D.2: 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 D.1: The correlation between the exchange rate and the relative stock of money

	$\Delta\left(\log(D_t^{\text{CNH}}) - \log(D_t^{\text{CNY}})\right)$	$\Delta \log(D_t^{\text{CNH}})$	$\Delta \log(D_t^{\text{CNY}})$
$\Delta \log E_{t-1}$	-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 CNY-CNH exchange rate on money growth offshore and onshore. See the notes to figure D.7 for a description of the data.

Table D.2: Bill Auction Subscription Rates

Bill maturities	All	1Y	6M	3M
	(2)	(4)	(6)	(8)
$\log(E_t)$	-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

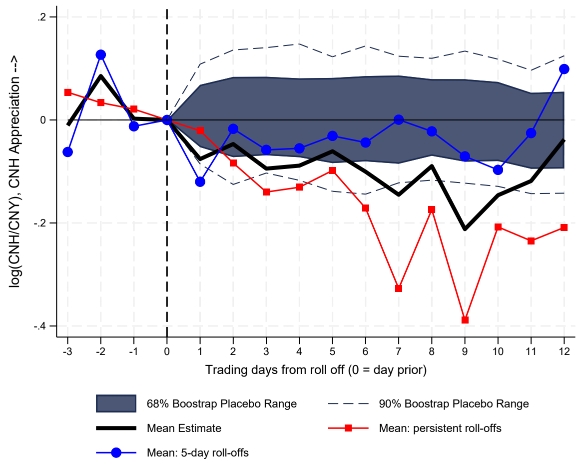
Heteroskedasticity robust standard errors in parentheses

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

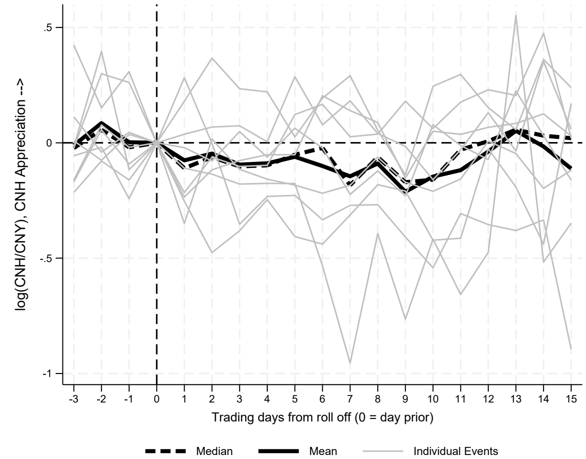
Note: Same as table 2 but using the exchange rate on the day of the auction.

Figure D.3: Response of exchange rates and interest rates to money supply shocks

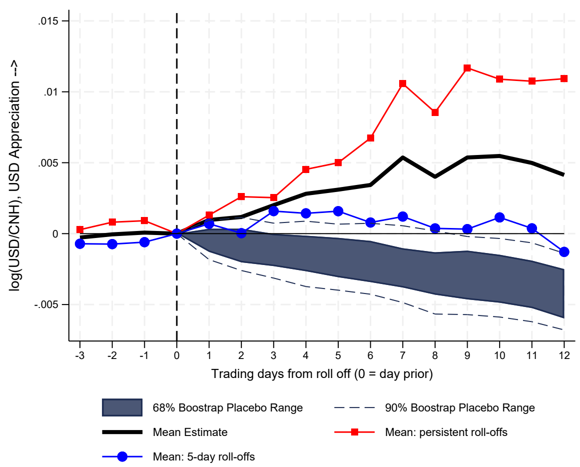
(a) E - mean



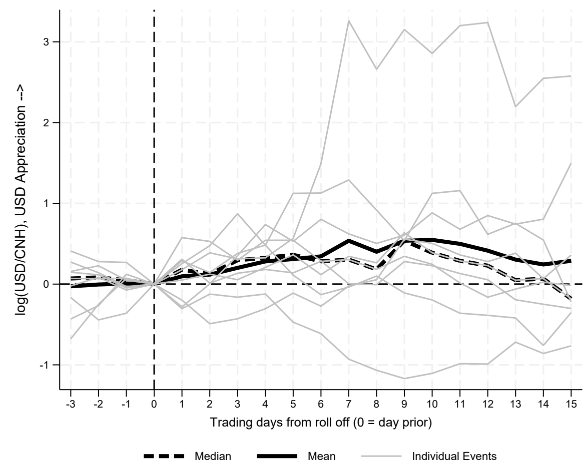
(b) E - individual



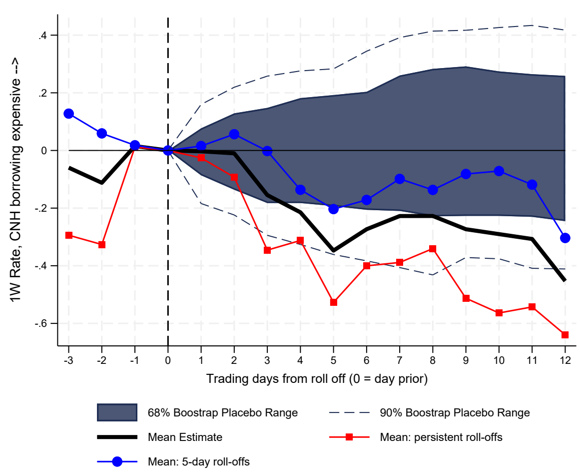
(c) $\hat{E}$ - mean



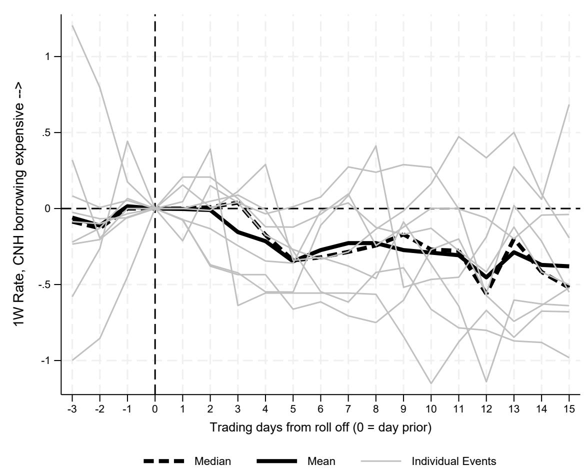
(d) $\hat{E}$ - individual



(e) R^f - mean



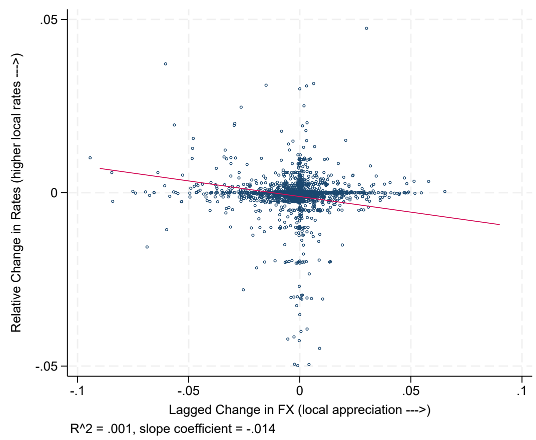
(f) R^f - individual



Note: This figure breaks the results in figures 3 and 4 into individual events.

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

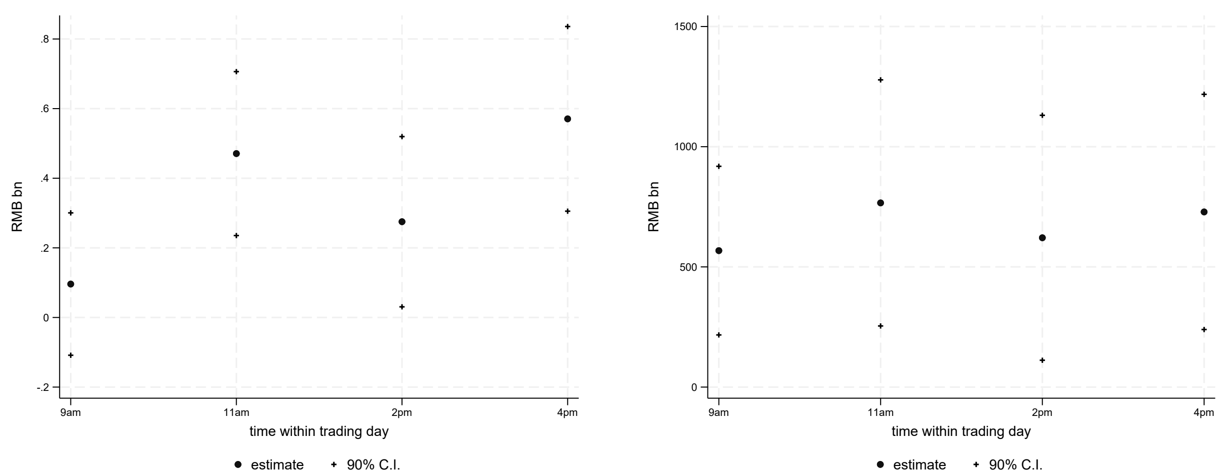
(a) Exchange rates and interest rates **(b)** Exchange rates and money stocks



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 **?** 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 D.5: Usage of the HKMA lending programs during the day

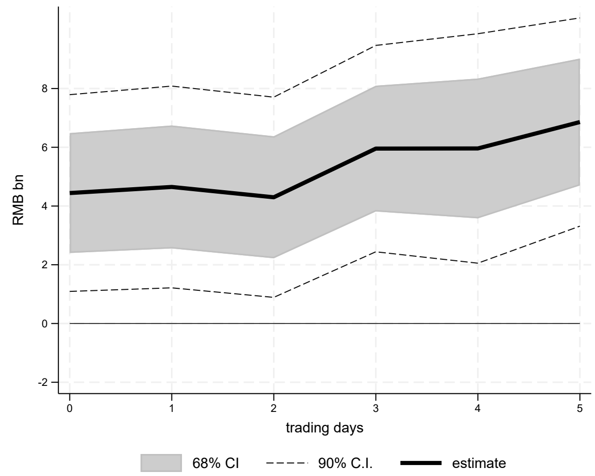
(a) PLP lending **(b)** Intraday liquidity facility



Note: Regressions of drawings from (a) the PLP liquidity facility and (b) the intraday facility at 9am, 11am, 2pm and 4pm on the deviation between the CNY central parity rate and the CNY-USD exchange rate at the previous day's close. The confidence intervals are constructed using White robust standard errors.

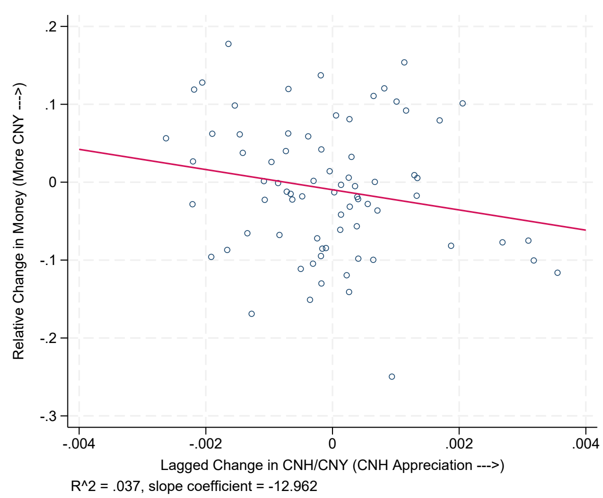
Figure D.6: Response of HKMA PLP facility to a money demand shock after 11am

(a) Local Projection - Instrumental Variables



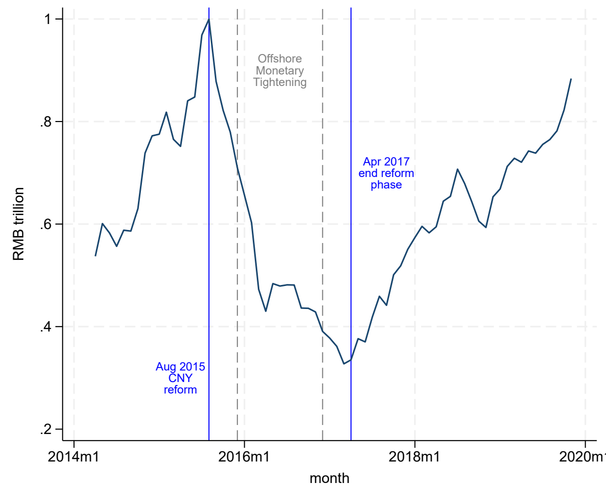
Note: Same as figure 6, but using only he flows between 11am and 4pm, inclusive.

Figure D.7: The CNY-CNH exchange rate and the relative stock of monies



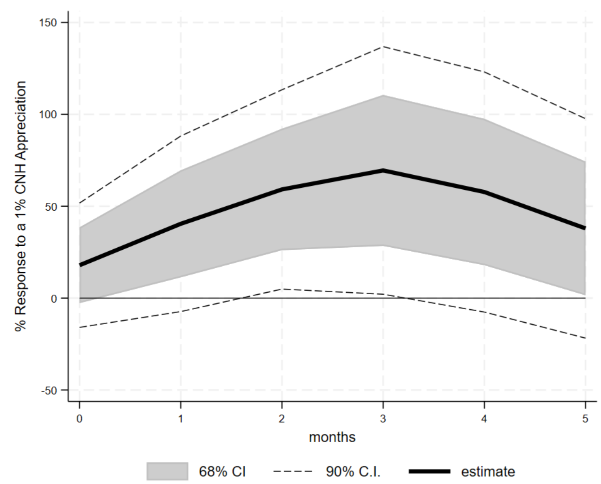
Note: Scatter plot of the lagged monthly change in the CNY-CNH exchange rate (horizontal axis) against relative money growth offshore and onshore (vertical axis). The horizontal axis show the average of the logarithm of the exchange rate across all trading days in the month, so an increase is a CNH appreciation.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

Figure D.8: RMB flows from offshore to onshore



Note: Plots the quantity of RMB flows from offshore to onshore through the Chinese current account between January of 2014 and December of 2019.

Figure D.9: Monthly response of deposits to money demand shocks



Note: Estimates of local projection in equation (9) by instrumental variables with $\log(D_t)$ at a monthly frequency left-hand side, the variable of interest is $\Delta \log(E_t)$ instrumented with the monthly average of our daily measure of money demand shocks. Controls include three lags of $\log(E_t)$, $\log(D_t)$ and the equivalent for onshore deposits. The sample is all monthly observations between October 2010 and August 2023. The confidence intervals are constructed using White robust standard errors.

E Additional theoretical results

E.1 Household problem

The domestic household is risk neutral and only values terminal consumption. Starting from an initial endowment Y, he can invest in bank equity C^o with return R^c, bank deposits onshore D^o, bank deposits offshore D_{dom}, and foreign deposits D^f, 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 asset: the household enjoys a liquidity service from their stock.

The household's problem is:

$$\max_{D^o, C, D_{dom}, D^f} R^c C^o + R^{d,o} D^o + \mathbb{E}(E') R^d D_{dom} + \mathbb{E}\left(E'\hat{E}'\right) \hat{R}^d D^f + \frac{(D^o)^{1-\alpha}}{1-\alpha} + \frac{vED_{dom}^{1-\alpha}}{1-\alpha}$$
$$+ \frac{v^f E\hat{E}(D^f)^{1-\alpha}}{1-\alpha} + \left(Y - C^o - D^o - ED_{dom} - E\hat{E}D^f\right)$$
$$\text{subject to:} \quad \hat{E}D^f \leq \bar{K}.$$

The constraint is the capital control: $\bar{K}$ is how many foreign deposits in domestic units the domestic households can hold.

There are five optimality conditions associated with the four choices and the budget constraint. Because of linearity in utility, we ignore the latter which would pin down consumption in equilibrium as a function of output. Likewise, we ignore the optimality condition that gives the demand for onshore deposits, which plays no role in the offshore equilibrium. The three conditions left are:

$$\begin{aligned} R^c &= 1, \\ E &= \mathbb{E}(E') R^d + EvD_{dom}^{-\alpha}, \\ E\hat{E} &= \mathbb{E}\left(E'\hat{E}'\right) \hat{R}^d + v^f E\hat{E}(D^f)^{-\alpha} \quad \text{or} \quad \hat{E}D^f = \bar{K}. \end{aligned}$$

The first equation gives the opportunity cost of capital, which because of linearity pins down the lending rate at 1, as well. The second equation is the demand for offshore deposits in equation (5). The third equation gives a demand curve for foreign deposits by domestic households.

Next, turning to the foreign household, she solves a similar problem but simplified to leave out features that play no role in our model. Namely, she behaves like an intermediary maximising returns, since considering her consumption with linear utility is irrelevant, and she chooses her offshore deposits $\hat{D}$ and her foreign deposits $\hat{D}^f$ only, since she has no access to the onshore markets. She also has some endowment $\hat{Y}$ and can store with return 1, just like the domestic households, but she faces no capital controls. Her problem is:

$$\max_{\hat{D},\hat{D}^f} \left\{ \hat{R}^d \hat{D}^f + R^d \hat{D} / \mathbb{E}(\hat{E}') + \frac{\hat{v}\hat{D}^{1-\alpha}/\hat{E}}{1-\alpha} + \hat{R}\left(\hat{Y} - \hat{D}^f - \hat{D}/\hat{E}\right) \right\}.$$

We assume away her liquidity preference shocks.

The two optimality conditions are:

$$\hat{R}^d = \hat{R},$$
$$\mathbb{E}(\hat{E}')\hat{R} = \hat{E}R^d + \hat{v}\,\mathbb{E}(\hat{E}')\hat{D}^{\alpha}.$$

The first condition simply pins down returns abroad. The second condition is the demand of offshore deposits.

We make two assumptions for simplicity. First, that there is no liquidity benefit from deposits by foreigners. Therefore $\hat{v} = 0$ and the second optimality condition for foreigners reduces to equation (6). Second, there is one missing equilibrium condition for cross-border holdings. This comes from market clearing in international trade. Since, with linear utility and no production, there is nothing interesting in the model about international trade, we assume that net foreign assets are zero at all times. Therefore:

$$\hat{E}D^f = \hat{D}.$$

The model is complete. Assuming that the capital controls bind, then the four equations in the main text, (3)-(6) give the solution for the four variables $(E, \hat{E}, D, R^d)$ as a function of $M, v, \hat{D}$ noting that $\hat{D} = \bar{K}$ and so is exogenous. The other variables then follow from the equilibrium conditions above as: $D^f = \hat{D}/\hat{E}, \hat{R}^d = \hat{R}, R^c = 1$.

Note that we only solve for $\hat{E}$ for a given expectation of its future value. Since there are no relevant dynamics in the model, we can simplify by setting that expectation to a constant, as would be the case if all shocks were i.i.d.

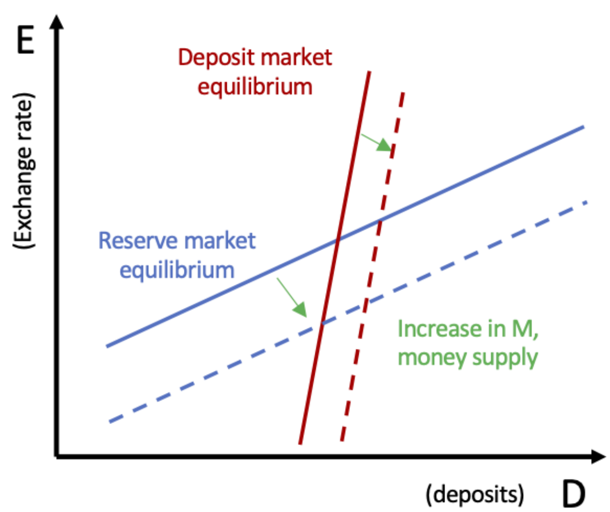
E.2 Existence and uniqueness of equilibrium in the monetary model

To prove that an equilibrium exists and that it is unique, we start by simplifying. Note that $R^m, R^{m,o}, \phi^{o\prime}, R^l, k$ are all either constant or exogenous in the model. Since they play no role, we normalise them to re-write equations (A.1) and (A.2) into two simpler mappings from D to E:

$$E = \mathcal{E}^{\text{reserves}}(D,.) \equiv 1 - \phi'(M/D),$$
$$E = \mathcal{E}^{\text{deposits}}(D,.) \equiv \frac{\phi(M/D) - \left(\frac{M}{D}\right)\phi'(M/D)}{v(D-\hat{D})^{-\alpha}}.$$

where the two endogenous variables are $(D,E) \in [M,\infty) \times (0,\infty]$. These two mappings are plotted in figure E.1.

Figure E.1: Simple model of exchange rates and deposits



Recall that we assumed (and later micro-founded) that the function $\phi(.)$ 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 reserve-deposit: $\phi_2 \equiv \partial\phi'(M/D)/\partial M/D \geq 0$. 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.

Existence. Since $\phi(1) = \phi'(1) = 0$, then $\lim_{D\to M}\mathcal{E}^{\text{reserves}}(D) = 1 > 0 = \lim_{D\to M}\mathcal{E}^{\text{deposits}}(D)$.

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 $\lim_{D\to\infty}\mathcal{E}^{\text{reserves}}(D) < \lim_{D\to\infty}\mathcal{E}^{\text{deposits}}(D)$. 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 $d\mathcal{E}^{\text{reserves}}(D)/dD > 0$. Taking derivative of the other equilibrium condition and simplifying:

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

Therefore, in figure E.1, both conditions slope upwards.

Uniqueness then requires that at any and all points in which they intersect, so $\mathcal{E}^{\text{reserves}}(D^*) = \mathcal{E}^{\text{deposits}}(D^*)$, it must be that $d\mathcal{E}^{\text{reserves}}(D^*)/dD < d\mathcal{E}^{\text{deposits}}(D^*)/dD$ (or vice versa), or:

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

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

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

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

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

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

E.3 General results for propositions

Part a) of proposition 1 can be shown more generally, using figure E.1, away form the neighbourhood of a peg. An increase in M shifts both curves to the right. For sure, D will rise, but we must show that E falls. 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 of $\mathcal{E}^{\text{reserves}}(D,.)$ and $\mathcal{E}^{\text{deposits}}(D,.)$ with respect to M, the condition is:

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

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

Likewise part a) of proposition 2 can be shows globally using figure E.1. An increase in v or an increase in $\hat{D}$ shifts the deposit equilibrium curve to the right, immediately it follows that both D and E will rise. Then from the policy rule in equation (8), we know that M' rises if $\eta > 0$. From proposition 1a), we know that this lowers E' relative to E.

Finally, part c) of proposition 2 also follow from figure E.1. A shift down in $-\phi'(M/D)$ means that for any given M/D the exchange rate is lower. A fall in $-\phi'(.)$ shifts the deposit equilibrium curve in figure E.1 down (or right), so it lowers both D and E.

E.4 Anticipation effects

In the model, we assumed iid shocks and a credible peg so that $\mathbb{E}(E') = 1$. Yet, the changes in the money supply due to the bill roll-offs were predictable weeks ahead and therefore led to predictable movements in the exchange rate. We drop that assumption to consider that case.

To simplify the analysis, we ignore the foreign exchange rate by setting $\hat{D} = 0$. The model then boils down to solving for the onshore-offshore exchange rate E_t and the offshore deposits D_t over time that solve the two equations:

$$E_t = \mathbb{E}_t(E_{t+1})\left(1 - \phi'(M_t/D_t)\right)$$
$$E_t D_t^{-\alpha} = \mathbb{E}_t(E_{t+1})\left[\phi(M_t/D_t) - \left(\frac{M_t}{D_t}\right)\phi'(M_t/D_t)\right]$$

taking as given the path for M_t and setting the other shock $v_t = 1$.

Assume that at date 0 we learn that $M_t = \bar{M}$ at all dates with the exception of $M_T = \bar{M} - R$ where R is the transitory bill roll over. Moreover, the peg is credible in that with $\bar{M}$ from T onwards, then for $t > T$, the equilibrium D_t is such that $\phi'(\bar{M}/D_t) = 0$ and so $E_t = 1$. The question is what happens to the exchange rate between 0 and T.

At date T, using the equations:

$$E_T = 1 - \phi'((\bar{M} - R)/D_t)$$
$$E_T D_T^{-\alpha} = \phi((\bar{M} - R)/D_T) - \left(\frac{\bar{M} - R}{D_T}\right)\phi'((\bar{M} - R)/D_T)$$

This is the problem covered in proposition 1 case a). The higher is R, then the lower is E_T and the lower is D_T. Call this value $E^* < 1$.

At date $T - 1$ instead, the equations are:

$$E_{T-1} = E^*\left(1 - \phi'(\bar{M}/D_{T-1})\right)$$
$$E_{T-1} D_{T-1}^{-\alpha} = E^*\left[\phi(\bar{M}/D_{T-1}) - \left(\frac{\bar{M}}{D_{T-1}}\right)\phi'(\bar{M}/D_{T-1})\right]$$

The equilibrium has a very similar representation to the one in figure E.1. If $E^* = 1$, then we would have $E_{T-1} = 1$ at the intersection as well. But since $E^* < 1$, then both equilibrium conditions are shifted to the left by proportionally the same amount. Given their slopes, this means that at the equilibrium $E^* < E_{T-1} < 1$.

At date $T - 2$ instead but by the same logic, $E_{T-1} = E_{T-2}$. By backwards induction the same applies all the way to date 0.

In other words, when the announcement happens at date 0, the offshore currency loses value (E falls). We only have two announcement dates and no guarantee that the announcements were not timed to coincide with other shocks. Therefore, we cannot test for these effects.

Then, at date T when the bills roll off, the scarcity of reserves makes the exchange rate appreciate further. This is anticipated and yet does not violate arbitrage. The reason is that this expected appreciation just offsets the increase in the liquidity premium of reserves. The return inclusive of those liquidity costs is indeed the same across dates and there is no scope for arbitrage. Or, in other words, money is not a pure financial asset, and its demand slopes downwards.

It is this appreciation of the onshore-offshore exchange rate that we test and find evidence for in the data.

E.5 Model with bills and capital flows

Any bank can hold bills, 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:

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

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:

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

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.

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:

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

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

Next, now assume it is possible for onshore reserves to move offshore reserves in order to be lent in interbank market. In reality, only the clearing bank can do this. So we think of this flow as the clearing bank lending into the offshore interbank market after raising funds from onshore, as opposed to individual banks making an optimal decision to move reserves in the intermediate period based on ω. 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. 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. Note that in the extreme where W^m was not limited, the clearing bank could freely borrow onshore reserves to lend offshore. Clearing banks acting competitively would equate the interbank rates, but the liquidity costs would not necessarily be equalized or go to zero.

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

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

Therefore, equation (13) is replaced by equation (17).

Finally, if offshore depositors can withdraw to and from the onshore market, equation (10) is replaced by:

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

The new term, W^d captures the flow of deposits from onshore to offshore during the day; before this was zero. 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. Note that 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.

All other equations in the model are unchanged.