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Money stock versus monetary base in time–frequency exchange rate determination ☆

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ABSTRACT

This study uses a time–frequency analysis to provide empirical evidence of the changing role of the money supply in the determination of the Japanese yen/U.S. dollar exchange rate. We demonstrate that in the short run, money supply has a stable significant effect on the exchange rate only after the introduction of quantitative easing policies, together with a remarkable difference between the money stock and the monetary base. Under quantitative easing policies, while money stock has a limited role, at best, in short-run exchange rate dynamics, increases in the monetary base cause the currency to depreciate in the short run. The notable role of the monetary base remains exceptionally stable over time only in quantitative easing regimes, while the exchange rate is unstably connected to other fundamentals. Moreover, in the long run, the monetary base outperforms the money stock in explaining the exchange rate, in general. Lastly, the growing role of the monetary base is shown to be robust to several checks.

1. Introduction

Although economists have long suspected that the relative money supply (stock) between two countries might play an important role in bilateral exchange rate dynamics, the global financial crisis and Great Recession in the late 2000s seemed to rekindle academic interest in the role played by the money supply in determining an exchange rate. In the 2000s, the Bank of Japan introduced an unconventional monetary policy, with central banks such as the Federal Reserve Bank and the European Central Bank later doing so as well. Prior to these policies (e.g., quantitative easing), the money stock tended to co-move with the monetary base in many industrialized countries (e.g., the euro area, Japan, the United Kingdom, and the United States). However, massive monetary injections through quantitative easing have broken this stable relationship, disrupting the co-movement of the money stock and the monetary base.

It is possible that quantitative easing policies have driven traders in the currency market to pay more attention to the monetary base than they did previously. While the main instrument of traditional monetary policies is short-term interest rates, which are no longer a policy indicator under the zero lower bound, the monetary base rather than the money stock is a

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direct indicator reflecting the policy stance under quantitative easing periods. If traders are concerned about monetary fundamentals, we would expect the introduction of quantitative easing policies to raise their awareness of the monetary base. Thus, the recent introduction of such policies invites several new questions: Do sharp increases in the monetary base cause currencies to depreciate, even without an increase in the money stock? Alternatively, is the money stock more relevant than the monetary base to exchange rate dynamics, even under a quantitative easing policy?

To answer these questions, we focus on the Japanese yen/U.S. dollar exchange rate. This is because Japan embarked on a quantitative easing policy before the rest of the world in the period March 2001 to March 2006, and the data are available for a longer time period than in other countries. Moreover, as shown in Fig. 1, the timing of these recent unconventional monetary policies following the global financial crisis differs between Japan and the United States. Immediately following the financial crisis, the Fed launched large-scale asset purchases (LSAP), before then tapering these off in January 2014. In contrast, the Bank of Japan introduced quantitative and qualitative monetary easing policies (the Abenomics monetary policy) in April 2013. In other words, the Abenomics monetary policy was launched more than four years after the Fed's LSAP. This difference in timing allows us to capture relative changes in the monetary base, and to identify the effect on the exchange rate of a massive increase in the monetary base.

Importantly, as can be seen in Fig. 1, there is a striking difference between the money stock and the monetary base after the 2000s. Specifically, the dominant behavior of the monetary base in both countries appears to change from low frequency (long run) to high frequency (short run) after quantitative easing policies are introduced. To the extent that a quantitative easing policy is implemented to counteract a recession, the business cycle frequency is likely to be more important under this policy than it was previously. In contrast, the dominant behavior of the money stock appears to remain at a low frequency (long run), even after quantitative easing policies are introduced. As depicted in the lower panels of Fig. 1, money multipliers directly indicate breaks in the stable short-run nexus between the two monetary aggregates.

Motivated by such complicated breaks, which occur over time and across frequencies, we use a time–frequency analysis to investigate the monetary approach to exchange rate (MAER) determination. The time–frequency analysis provides us with time-varying and frequency-dependent relationships between the exchange rate and the money supply. From an econometric viewpoint, our approach differs from the extant literature by resolving a common limitation. That is, the analytical frameworks in previous studies enable only a partial examination of the time and frequency aspects.[1] To overcome this limitation, we use a time–frequency analysis to investigate both aspects simultaneously.

The core of our argument is related to the effectiveness of unconventional monetary policies. The motivation for this study stems from recent works that highlight the role of monetary aggregates when the zero lower bound restriction for the policy rate is binding. Among others, Belongia and Ireland (2017) show empirically that the money supply works as a monetary policy indicator, even when short-term interest rates are at the zero lower bound. If a massive monetary injection is effective in stabilizing the macro economy, even at the zero lower bound, then aggregate demand augmentation through an exchange rate depreciation is a potential channel. Thus, it is important to test whether a monetary base expansion affects the exchange rate, even under the zero lower bound restriction.

Our main findings are summarized as follows. Overall, we find a weak and unstable nexus between the Japanese yen/U.S. dollar exchange rate and monetary fundamentals, consistent with the predominant view of exchange rate dynamics (known as the exchange rate disconnect puzzle).[2] However, we find that the money supply has a stable and significant effect on the exchange rate only after the introduction of a quantitative easing policy. Specifically, while the relative money stock is shown to have a limited role, at best, in short-run exchange rate fluctuations, the relative monetary base (the Soros chart) is shown to play an important role in the short run after a quantitative easing policy has been introduced. Importantly, this role of the monetary base remains exceptionally stable throughout quantitative easing regimes. These findings indicate that massive injections into the monetary base cause currencies to depreciate, even without an increase in the money stock. This implies that quantitative easing policies significantly enhance the role of the monetary base in short-run exchange rate determination. Moreover, the monetary base explains the long-run exchange rate, which the money stock fails to do. We check the robustness of our main results by using euro/U.S. dollar exchange rate data and vector autoregressive analyses, and find analogous results.

This study contributes to existing literature on the relationship between money supply and exchange rates in the following respects. First, in contrast to previous studies, we show that unconventional monetary policies result in profound structural changes to short-run relationships. Note that despite these structural changes occurring in the short run, most previous studies on the MAER disregard short-run relationships. Second, we provide formal evidence of the Soros chart, which is well known in the business world, but has not been investigated sufficiently in the academic literature.[3] Thus, because previous studies use the money stock to test the MAER, our analysis is the first to consider the monetary base, and to compare the money stock and the monetary base in an MAER framework. Our evidence of the Soros chart could shed new light on the role of the monetary base in out-of-sample forecasts of exchange rates, although since the pioneering work by Meese and Rogoff (1983), it is widely recognized that monetary models are difficult to outperform a simple random walk model.

[1] For example, time-varying cointegration models capture structural changes over time (e.g., Koop et al., 2011). However, they analyze the long run only, and do not investigate the frequency at which structural changes occur.

[2] See, for example, Sarno (2005) for the exchange rate disconnect puzzle.

[3] In the Soros chart, the nominal exchange rate is traced through the relative monetary base. For example, Dekle and Hamada (2015) and Kano and Morita (2015) state that the Soros chart is "a folk tale in the financial world" and "anecdotal evidence," respectively.

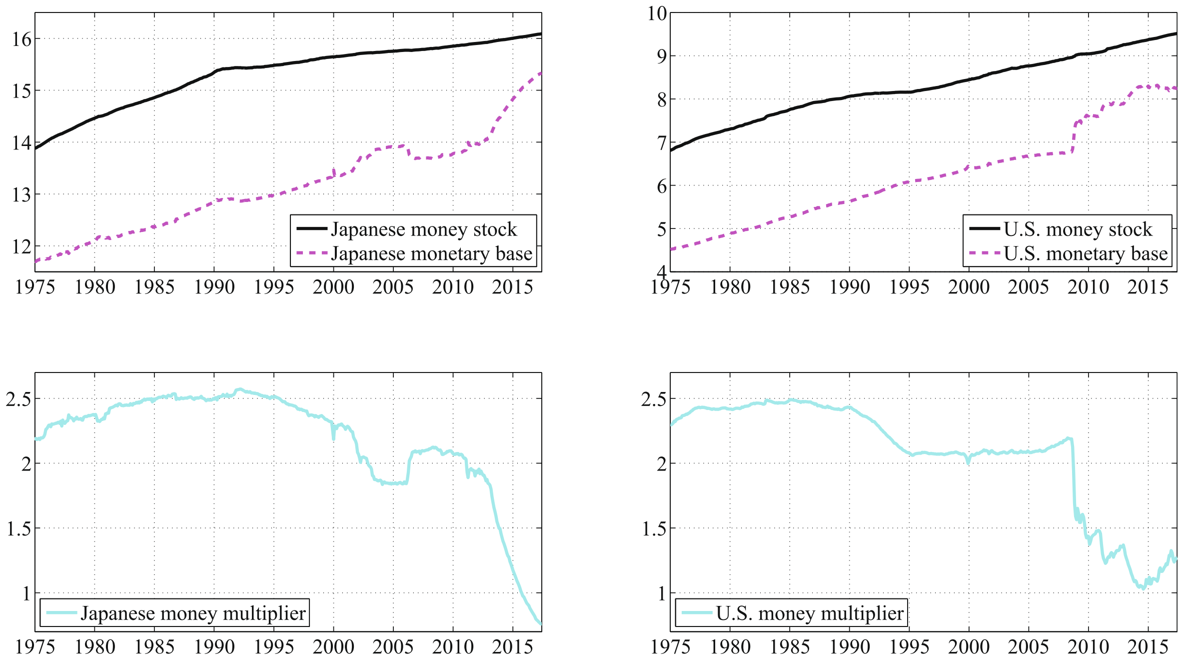

Fig. 1. Money supply and money multiplier in Japan and the United States (log level).

1.1. Related literature

This study relates to several strands of literature. First, we build on an empirical framework from the MAER literature, which is explained in subsequent sections. Since entering the post-Bretton Woods floating rate era, the MAER determination has garnered significant attention, pioneered by Frenkel (1976) and Bilson (1978). Most relevant studies since the 1990s assume the monetary exchange rate model holds in the long run and, accordingly, conduct a cointegration analysis using empirical models. These include, among many others, the works of Groen (2000, 2002) and Rapach and Wohar (2002, 2004).

Incidentally, while almost all MAER studies focus on the long-run relationships between exchange rates and monetary fundamentals, an important exception is that of Loría et al. (2010), who examine the short-run relationship as well. The authors employ a cointegrated structural vector autoregression (VAR) model to investigate the factors that determine the Mexican peso/U.S. dollar exchange rate. They find that the M2 money stock is related to the exchange rate in the short and long run, which means the model can be validated across various frequencies. Although the research issues examined in Loría et al. (2010) overlap with ours in the sense that we too include both the short and the long run in our analyses, unlike their study, our central concern is the short-run behavior of the monetary base under quantitative easing. In particular, whether a quantitative easing policy influences the exchange rate in the short run is an important monetary policy issue at the zero lower bound.

The second strand of related literature is that which emphasizes the temporal instability of the relationships between the exchange rate and fundamentals. For example, based on a parsimonious set of fundamentals, Park and Park (2013) use a time-varying cointegration model to show that the long-run relationship between the exchange rate and monetary fundamentals evolves over time.[4] Moreover, using a broader set of macroeconomic fundamentals, including the trade balance and net foreign assets, Sarno and Valente (2009) highlight frequent changes in fundamentals that can explain exchange rate movements. Using a survey of U.S. foreign exchange traders, Cheung and Chinn (2001) point out how the role of individual macroeconomic fundamentals varies over time in exchange rate dynamics. In contrast to the temporal instability documented in this strand of the literature, we show that throughout quantitative easing regimes, the monetary base works as a stable determinant of the exchange rate.

Finally, this study is related to the literature on the so-called Soros chart, which describes the relationship between the relative monetary base between two countries and the bilateral exchange rate. Although the Soros chart is well known in the business world, few academic papers on the topic adopt an approach other than the MAER to document the relationship between the monetary base and the exchange rate; see Dekle and Hamada, 2015; Hamada and Okada, 2009; Miyao and Okimoto, 2017. While the aforementioned studies provide evidence supporting the Soros chart, ours is the first study to show that the validity of the Soros chart depends on both time and frequency. That is, in the short run, the Soros chart holds

[4] See also Basher and Westerlund (2009), who find that the monetary exchange rate model fails unless multiple structural breaks are allowed, suggesting that the parameters of the model change over time.

only after introducing a quantitative easing policy; in the long run, it holds in general. Therefore, it is surprising that so few studies have assessed the effect of the monetary base on the exchange rate in a MAER framework.[5]

The rest of the paper is organized as follows. In Section 2, we explain our analytical framework and empirical strategy. In Section 3, we present the data and results. In Section 4, we demonstrate the robustness of our main results by using euro/U.S. dollar exchange rate data and VAR analyses. Section 5 concludes the paper.

2. Empirical framework

2.1. The monetary exchange rate model

Consider a parsimonious MAER model, as in Taylor (1995) and Loría et al. (2010), among others. First, purchasing power parity is assumed to hold:

$$\varepsilon = p - p^*, \tag{1}$$

where ε denotes the natural logarithm of the nominal exchange rate, and p and p^* denote the natural logarithms of the domestic and foreign price indices, respectively. Moreover, we assume money market equilibria in each country:

$$p = m - l, \tag{2}$$
$$p^* = m^* - l^*, \tag{3}$$

where m and m^* denote the natural logarithms of the domestic and foreign money supply, respectively, and l and l^* denote the domestic and foreign money demand, respectively. The money demand in each country is assumed to be proportional to the real income in that country, and inversely proportional to the interest rate in that country, such that

$$l = \gamma y - \delta r, \tag{4}$$
$$l^* = \gamma y^* - \delta r^*, \tag{5}$$

with $\gamma, \delta > 0$, where y and y^* denote the natural logarithms of domestic and foreign real income, respectively, and r and r^* denote domestic and foreign nominal interest rates, respectively. Note that we assume semi-elasticity of the nominal interest rate.

It follows from the above that

$$\varepsilon = (m - m^*) - \gamma(y - y^*) + \delta(r - r^*). \tag{6}$$

In summary, the monetary exchange rate model predicts that the nominal exchange rate is positively correlated with the money supply differential and the interest rate differential, and is negatively correlated with the real income differential.

Although prior studies use the M2 money stock as a proxy for m, our purpose is to assess the difference between the M2 money stock and the monetary base. Thus, we consider the following relationship between the two:

$$m_s = \mu + m_b, \tag{7}$$
$$m_s^* = \mu^* + m_b^*, \tag{8}$$

where m_s is the natural logarithm of the money stock, m_b is that of the monetary base, and μ is that of the money multiplier. Hence, our underlying empirical models can be written as follows:

$$\varepsilon = \beta_s(m_s - m_s^*) - \gamma(y - y^*) + \delta(r - r^*), \tag{9}$$
$$\varepsilon = \beta_b(m_b - m_b^*) + \beta_\mu(\mu - \mu^*) - \gamma(y - y^*) + \delta(r - r^*). \tag{10}$$

While other studies have presented theoretical models in which the money supply differential affects the exchange rate (e.g., Obstfeld and Rogoff, 1995), we express the exchange rate channel in the present MAER framework as follows. As in (2) and (3), we suppose that the price in a country rises when the money supply increases. Accordingly, if the variables in another country remain unchanged or the increases in the money supply are relatively small, the exchange rate depreciates through the purchasing power parity in (1). In this mechanism, expectation might also play an important role, especially in quantitative easing policies. According to the efficient market hypothesis, in a frictionless market, the exchange rate fully and immediately reflects all available information. If quantitative easing policies lead traders to become aware of the monetary base as a key monetary policy indicator for price stabilization, an expansion of the monetary base could increase the expected inflation and, thereby, depreciate the exchange rate.

[5] Several theoretical studies examine the relationship between unconventional policies and the exchange rate. For example, based on a two-country DSGE model, Adler et al. (2019) examines the effects of cooperative and self-oriented unconventional policies on exchange rates.

2.2. Decomposing the time–frequency coefficients

In almost all previous studies, the coefficients of (9) are estimated using traditional regression and cointegration analyses. However, as mentioned in the introduction, if money stock and the monetary base exhibit different behaviors at each time and frequency, then the coefficients can vary over time and across frequencies in the two Eqs. (9) and (10). To demonstrate this formally, as in Aguiar-Conraria et al. (2018), we use the partial wavelet gain as the regression coefficient for each time and frequency.

To explain the partial wavelet gain, we start with the continuous wavelet transform for the time series $x(t)$:

$$W_x(\tau, s) = \int_{-\infty}^{\infty} x(t)\bar{\psi}_{\tau,s}(t)dt, \tag{11}$$

where s denotes the scaling factor controlling the wavelet length, τ denotes the translation parameter controlling the wavelet location in time, the bar denotes a complex conjugation, and $\psi_{\tau,s}$ denotes the wavelet daughters obtained by scaling and shifting the mother wavelet ψ,

$$\psi_{\tau,s}(t) = \frac{1}{\sqrt{|s|}}\psi\left(\frac{t-\tau}{s}\right), \quad s, \tau \in \mathbb{R}, s \neq 0. \tag{12}$$

Note that the wavelet is compressed (stretched) when the absolute value of s is less (greater) than one. For our empirical purpose, we specify the mother wavelet as the Morlet wavelet, $\psi(t) = \pi^{-1/4}e^{6it}e^{-t^2/2}$, where i denotes an imaginary unit (i.e., $i^2 = -1$).

To introduce the partial wavelet gain, we now consider many time series, $x_1(t), x_2(t), \cdots, x_q(t)$, where q is an integer greater than 2. Suppose an integer j ($2 \leqslant j \leqslant q$), and the set such that $\boldsymbol{q}_j = \{2, 3, \cdots, q\} \setminus \{j\}$. Then, we can write the complex partial wavelet coherency of $x_1(t)$ and $x_j(t)$, after controlling for all other series, as

$$\varrho_{1j.\boldsymbol{q}_j} = -\frac{\boldsymbol{S}_{j1}^d}{\sqrt{\boldsymbol{S}_{11}^d}\sqrt{\boldsymbol{S}_{jj}^d}}, \tag{13}$$

where $\boldsymbol{S}$ is a $(q \times q)$ Hermitian matrix, such that $\boldsymbol{S} = \{S_{uv}\}_{u,v=1}^q = \{\Theta(W_{x_u x_v})\}_{u,v=1}^q$, and $\boldsymbol{S}_{uv}^d$ is the co-factor $\boldsymbol{S}_{uv}^d = (-1)^{u+v}$ det $\boldsymbol{S}_u^v$, in which $\boldsymbol{S}_u^v$ is the submatrix formed by deleting the uth row and vth column. Note that Θ is a smoothing operator in both time and frequency, and $W_{x_u x_v}$ is the cross-wavelet transform $W_{x_u x_v}(\tau, s) = W_{x_u}(\tau, s)\bar{W}_{x_v}(\tau, s)$.

Based on the complex partial wavelet coherency, the complex partial wavelet gain is

$$\mathcal{G}_{1j.\boldsymbol{q}_j} = \varrho_{1j.\boldsymbol{q}_j}\frac{\sqrt{\boldsymbol{S}_{jj}^d}}{\sqrt{\boldsymbol{S}_{11}^d}}. \tag{14}$$

Ultimately, the partial wavelet gain is given by the real part of the complex partial wavelet gain:

$$\widetilde{G}_{1j.\boldsymbol{q}_j} = \Re\left(\mathcal{G}_{1j.\boldsymbol{q}_j}\right) = \widetilde{R}_{1j.\boldsymbol{q}_j}\frac{\sqrt{\boldsymbol{S}_{jj}^d}}{\sqrt{\boldsymbol{S}_{11}^d}}, \tag{15}$$

where $\widetilde{R}_{1j.\boldsymbol{q}_j}$ is the partial wavelet coherency, as in Ko and Funashima (2019), such that

$$\widetilde{R}_{1j.\boldsymbol{q}_j} = \Re\left(\varrho_{1j.\boldsymbol{q}_j}\right) = -\frac{\Re\left(\boldsymbol{S}_{j1}^d\right)}{\sqrt{\boldsymbol{S}_{11}^d}\sqrt{\boldsymbol{S}_{jj}^d}}. \tag{16}$$

At each point in the time–frequency space, (15) and (16) correspond to the partial regression coefficients and partial correlation coefficients, respectively, in the multiple linear regression of a dependent variable x_1 over x_j, with $q-1$ explanatory variables $x_2, x_3, \cdots, x_q$.[6]

Owing to the continuous wavelet transform in (11), which extracts frequency and time information from the original time series, we are able to carry out a time-varying regression analysis at various frequencies using the partial wavelet gain in (15). For example, if structural changes are observed in a regression model, we can identify the frequencies at which the breaks occur. Therefore, if the partial wavelet gain suggests there are structural changes at a moment and frequency, we can obtain analogous results to those of regressions that use the specified frequency components in the subsample periods divided by the moment.

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[6] We use ASToolbox by Luís Aguiar-Conraria and Maria Joana Soares to estimate all wavelet measures. The ASToolbox can be downloaded at https://sites.google.com/site/aguiarconraria/joanasoares-wavelets/the-astoolbox. Note that the present partial wavelet gain and coherency differ from those in Aguiar-Conraria et al. (2018), because we consider the real part in order to evaluate the sign.

However, to the best of our knowledge, there remain several limitations to this approach; that is, we are not aware of a suitable significance test for the partial wavelet gain. For this reason, Aguiar-Conraria et al. (2018) argue that the results of the partial wavelet gain in (15) should be complemented with the significance of the partial correlation coefficients in (16). In addition, the edge effects must be considered, as noted in Aguiar-Conraria and Soares (2014), among others. The edge effects mean that the results at the beginning and end of a sample period are unreliable, owing to the finite length of the time series. Note that this problem stretches at lower frequencies; thus, to characterize longer-term relationships using the partial wavelet gain, we require longer time series.

3. Empirical analysis

3.1. Data description

For our estimation, we use monthly observations, and the sample is the post-Bretton Woods period January 1975 to June 2017. As a proxy for real income, we use industrial production. Except for the nominal exchange rate and interest rate, all series are seasonally adjusted. The nominal exchange rate of the Japanese yen/U.S. dollar (EXJPUS) is obtained from the St. Louis Fed FRED website. All U.S. data on the M2 money stock (M2SL), monetary base (AMBSL), industrial production (INDPRO), and interest rate (TB3MS), and Japanese data on the M2 money stock (MYAGM2JPM189S) and interest rate (INTGSTJPM193N) are also taken from the FRED website.[7] Data on the Japanese monetary base and industrial production can be found at the website of the Bank of Japan and Japan's Cabinet Office (Indices of Business Conditions), respectively.

Fig. 2 depicts our series of dependent and explanatory variables. In our analysis, the U.S. variables are denoted by an asterisk. Most of the series behavior related to the money supply differential is consistent with a visual inspection of Fig. 1. A casual observation indicates that the M2 money stock differential is stable in the short run, and that it traces the long-run movement of the exchange rate, in general. In contrast, the monetary base differential fluctuates at higher frequencies after the 2000s, and co-moves with the exchange rate in the short run. The monetary base differential exhibits a rapid increase in the period 2002 to 2006, owing to quantitative easing introduced by the Bank of Japan. However, following the late 2000s, it decreases significantly after the quantitative easing by the Fed. Thereafter, it increases considerably as a result of the Abenomics monetary policy and the concomitant Fed tapering.

3.2. Results on money supply

Having described the analytical framework and data, we now turn to the empirical results.[8] Before presenting the regression coefficients estimated in (15), we examine the estimated correlation coefficients over a time–frequency space, as in (16). To evaluate the positive and significant time–frequency regions, we use Monte Carlo simulations. Here, following Aguiar-Conraria and Soares (2014), among others, the surrogate series are generated from a fitted ARMA(1, 1) model, drawing errors that follow a Gaussian distribution.

Fig. 3 shows the partial correlation coefficients for the exchange rate and money supply. This figure shows the positive and significant regions at the 5% and 10% significance levels as orange and yellow contours, respectively. A dashed line denotes a border of a region affected by edge effects. In the following, as in the business cycle literature, we use "short run" to refer to higher frequencies with cycles shorter than eight years, and "long run" to refer to lower frequencies with cycles longer than eight years.

Notable findings emerge from both the time and the frequency perspectives. The structural changes over time are common to both the money stock and the monetary base. Specifically, for both monetary aggregates, we find larger significant regions after the 2000s than prior to this period. On the other hand, from a frequency perspective, this time-varying feature differs between the two: for the money stock, the larger regions emerge only in the short run; for the monetary base, they emerge in both the short and the long run.

To investigate more formally how the money supply affects the exchange rate, we next present the estimated coefficients for $(m_s - m_s^*)$ and $(m_b - m_b^*)$, in (9) and (10), respectively. These are calculated as the partial wavelet gain, as in (15). Fig. 4 shows the results. Note that in Fig. 4, we report the results for two frequency bands: short-run frequencies (1.5–8 years) and long-run frequencies (8–16 years). The short-run frequencies correspond to a typical business cycle range, as in Baxter and King (1999) and Christiano and Fitzgerald (2003). Unfortunately, as already stated, there is no appropriate significance test for the wavelet gain. As such, Aguiar-Conraria et al. (2018) recommend that statistically insignificant regions of coherency be disregarded when evaluating the gain. Following their recommendation, we consider the results of the wavelet gain by referring to the larger significant regions identified in Fig. 3.

As shown in the upper panel of Fig. 4, the short-run estimates of both the money stock and the monetary base are highly unstable over time before the 2000s, suggesting that the exchange rate disconnect puzzle applies to the money supply. On the other hand, the short-run estimates of both the money stock and the monetary base are stable and positive after the

[7] The Japanese M2 money stock series is linked after February 2017 using data from the website of the Bank of Japan.

[8] When estimating (10), the money multiplier differential is divided into each country's money multiplier, because there is a strong positive correlation between the monetary base differential and the money multiplier differential.

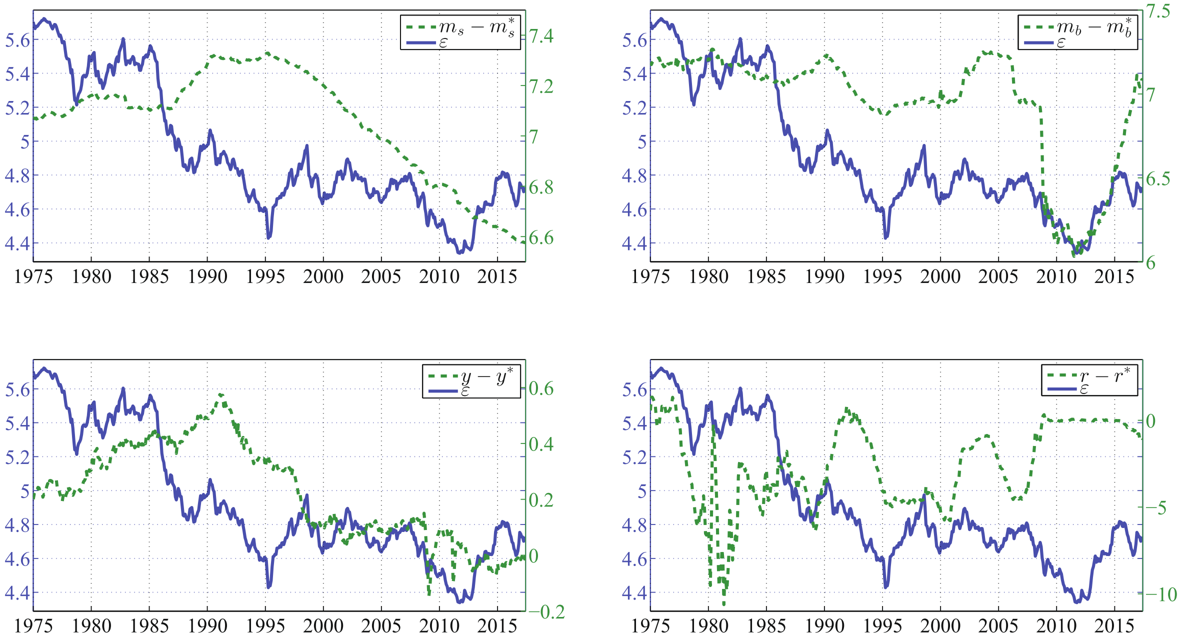


Fig. 2. Japanese yen/U.S. dollar exchange rate and explanatory variables.

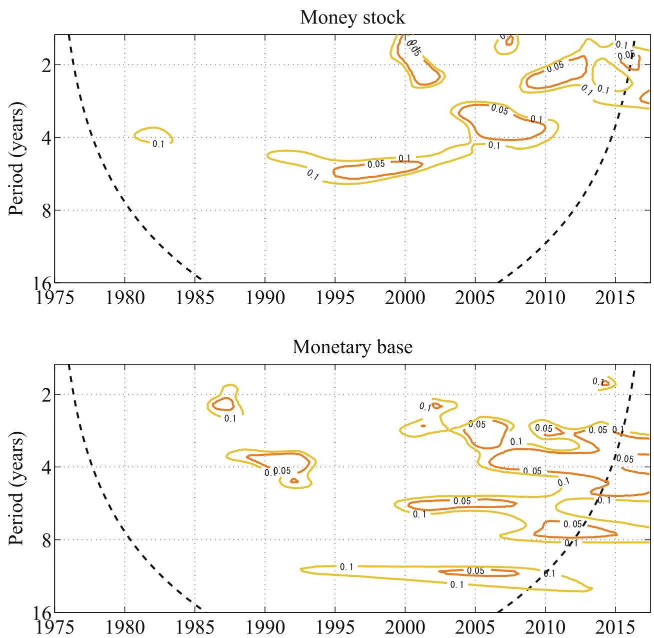


Fig. 3. Significantly correlated regions of the money supply. Notes: The positive significant regions at the 5% and 10% significance levels are depicted as orange and yellow contours, respectively. The dashed lines are borders of regions affected by edge effects. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2000s. Moreover, it is worth emphasizing that the estimated coefficients for the monetary base are larger than those for the money stock after the mid-2000s, corresponding to the period in which the Bank of Japan and the Fed pursued quantitative easing policies. These short-run results are consistent with those of Fig. 3. In the long-run results plotted in the lower panel of Fig. 4, excluding the period before the 1990s, the estimated coefficients for the monetary base are positive, but those for the money stock are negative, as expected from Fig. 3.

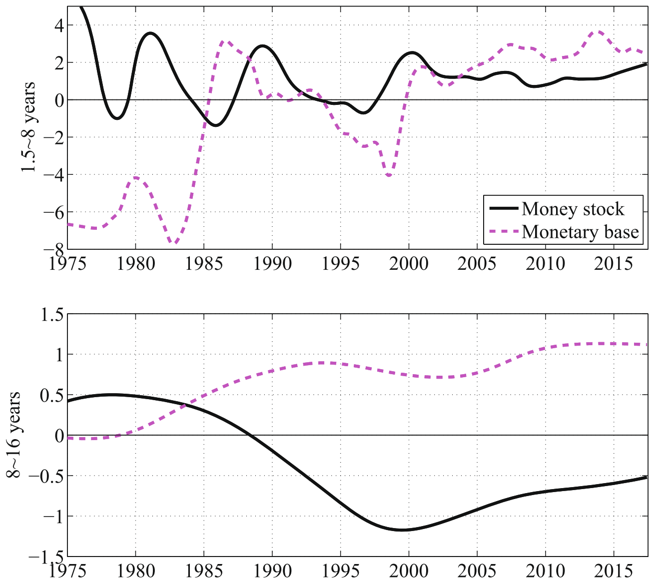


Fig. 4. Estimation results for the money supply coefficients.

It should be noted that the above short-run results are obtained using a typical business cycle range (1.5–8 years). However, another strand of the literature uses a narrower range, namely three to eight years, as a business cycle frequency band. Such works include, among others, those of Kydland and Prescott (1990) and Levy (2000). Moreover, especially in the long-run results, wide edge effects occur, as shown in Fig. 3. Hence, as a robustness check, Fig. 5 reports the results on a narrower frequency band, in which the short-run frequencies are set to three to eight years, and the long-run frequencies to eight to 12 years. For the most part, the results reinforce the above conclusions. In the short run on this narrower frequency band, the difference between the monetary base and the money stock is more evident after the mid-2000s. Although the short-run estimates for the money stock exhibit larger values before the early 1980s, they are not statistically significant, as shown in Fig. 3. We notice that the long-run results mirror the above.

Summarizing the above, we find the following. First, and most important, there is a significant break in the role of the monetary base in both in the short and the long run around the early 2000s. In particular, we detect a remarkable break in the short run, rather than in the long run. This finding can be interpreted as the consequence of introducing a quantitative easing policy. Specifically, the introduction of such a policy enhances substantially the relative role of the monetary base in the macroeconomic fundamentals; accordingly, the monetary base gains importance to traders as playing a more prominent role in price stabilization after the implementation of a quantitative easing policy. Because quantitative easing is used to stabilize the macro economy, the effect on the exchange rate is more marked in the short run than it is in the long run.

Second, there is a significant break in the role of the money stock, in the short run only, around the early 2000s. While the short-run break is less noticeable than in the case of the monetary base, this can also be attributed to the introduction of a quantitative easing policy. In other words, after the introduction of such policies, traders emphasize the short-run behavior of broader monetary aggregates as well, although quantitative easing policies are straightforwardly reflected in the monetary base, not the money stock. On the other hand, in the long run, there is no positive correlation between the exchange rate and the money stock throughout the period. Thus, the exchange rate fluctuation is disconnected from the money stock in the long run. Although most previous works in the MAER literature employ cointegration analyses to study the long-run relationship between the exchange rate and the money stock, our analysis reveals that such attempts are likely to fail to find a significant link.

3.3. Results on other fundamentals

Next, we present our results for real income and interest rates. Although our primary interest is the money supply, it is meaningful to investigate whether these fundamentals can explain exchange rate dynamics over time and across frequencies. This investigation revisits the exchange rate disconnect puzzle, which is the discrepancy between the nominal exchange rate and the macroeconomic fundamentals.

Fig. 6 plots the significant regions of the partial correlation coefficients for $(y - y^{*})$ and $(r - r^{*})$, as before. Panel A shows the correlation between the exchange rate and real income; the expected sign is negative in the MAER model. Panel B shows the correlation between the exchange rate and the interest rate, which is expected to be positive. Hence, negative significant regions are shown in Panel A, and positive significant regions are shown in Panel B.

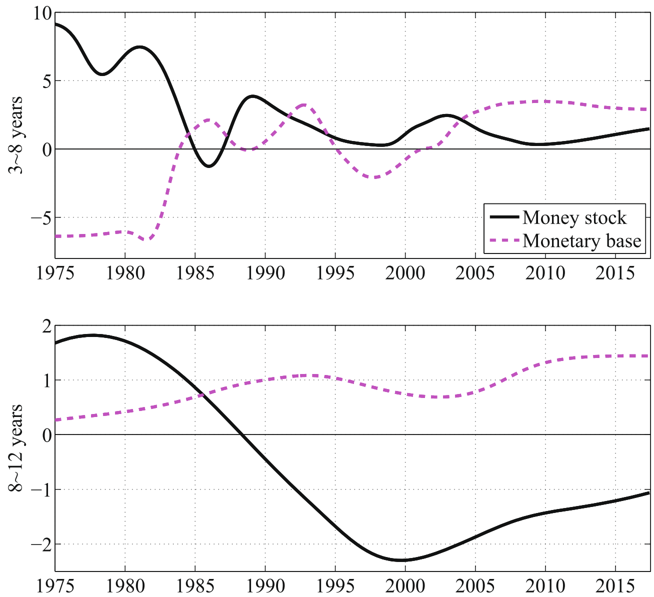


Fig. 5. Estimation results for the money supply coefficients in a narrower frequency band.

In examining the real income results for the money stock model, negative and significant correlations are observed only in the short-run region from 1990 to the mid-2000s. This suggests that when using the money stock, no long-run relationship between the exchange rate and real income is evident. Thus, the exchange rate disconnect puzzle arises if we focus only on the long run money stock. However, for the monetary base model, there are additional significant short-run regions in a more recent period. Furthermore, albeit at the 10% level, we can see a negative significant region after the 1990s in the long run.

For the interest rate results, regardless of whether we employ the money stock or the monetary base model, we find few large significant regions in the time–frequency space, excluding those regions affected by edge effects. Overall, the relationship between the exchange rate and the interest rate seems to be unstable and weak.

In summary, we do not find a stable and strong correlation with the exchange rate, especially in the case of the interest rate, even when conducting analyses from both short- and long-run perspectives. In other words, as the extant literature on the exchange rate disconnect puzzle suggests, real income and interest rates are shown to be unstably connected to the exchange rate.

4. Robustness

In this section, we examine the robustness of our main results. First, we investigate the euro/U.S. dollar exchange rate. Thus far, we have considered the Japanese yen/U.S. dollar exchange rate in order to ensure a larger sample size. However, despite the shorter time series, it is important to confirm whether the above findings are also observed in euro area economies, where quantitative easing policies were implemented after the Great Recession. Second, we use VAR models to examine the robustness of the main results. If our main findings are dominant in exchange rate dynamics, we expect to find an increasing importance of the monetary base under quantitative easing regimes in standard time-series analyses.

4.1. Euro/U.S. dollar exchange rate

Fig. 7 plots the series for the euro/U.S. dollar exchange rate and the explanatory variables.[9] Note that an asterisk denotes U.S. variables, as before. The monthly observations span the period January 1999 to March 2017. The monetary base differential declines after the Great Recession, owing to the Fed's LSAP in the late 2000s. On the other hand, we find two positive spikes in the first half of the 2010s due to European Central Bank money injections (the Security Market Program, and Outright Monetary Transactions). In January 2015, the European Central Bank introduced the Asset Purchase Programme, after which, the monetary base differential began to increase. Importantly, after the Great Recession, it seems that the exchange rate co-moves with mon-

[9] All euro area variables are obtained from the St. Louis Fed FRED website. As before, the nominal exchange rate (EXUSEU) and interest rate (EUR3MTD156N) are not seasonally adjusted, but the M2 money stock (MYAGM2EZM196N), monetary base (ECBASSETS), and industrial production (EA19PRMNTO01IXOBSAM) are seasonally adjusted.

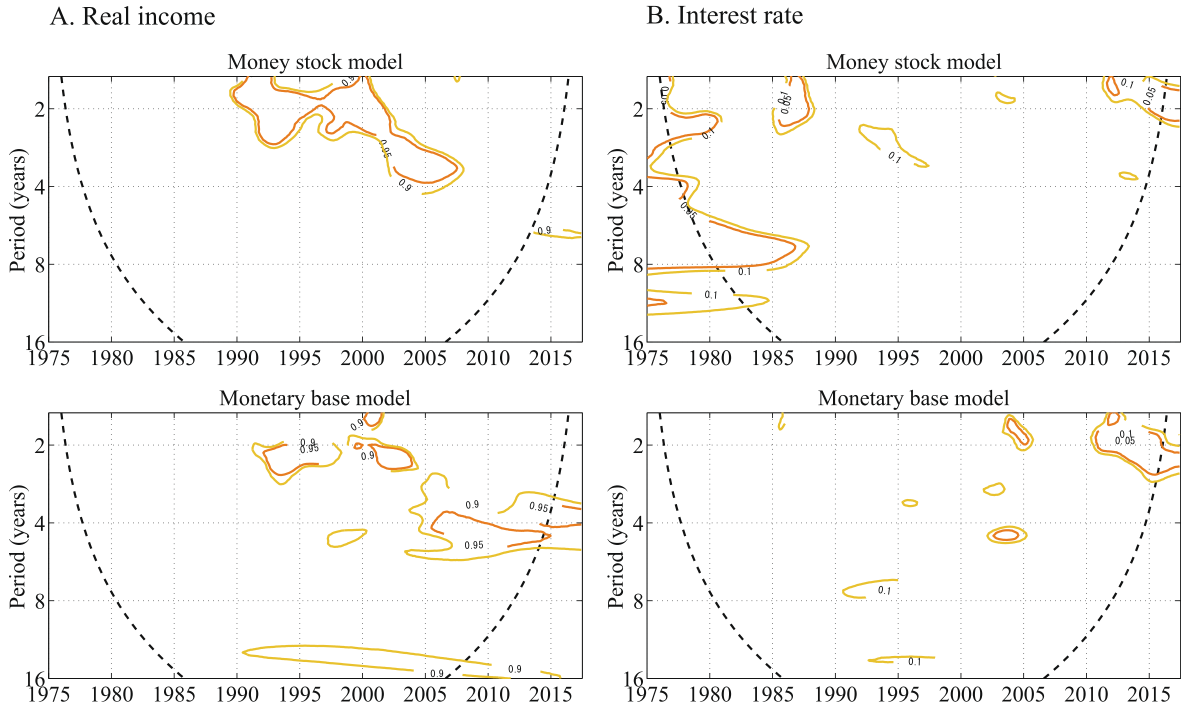


Fig. 6. Significantly correlated regions of real income and interest rate. Notes: The negative (positive) significant regions at the 5% and 10% significance levels are depicted as orange and yellow contours in Panel A (B), respectively. The dashed lines are borders of regions affected by edge effects. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

etary base differential in the short run, but does not do so with the money stock differential. These observed relationships between the exchange rate and the money supply foreshadow the consistent results found throughout this paper.

To formally test this observational hypothesis, as before, Fig. 8 explores the partial correlation coefficients for the exchange rate and the money supply. Note that long-run evaluations cannot be conducted, owing to the smaller sample size. However, the results support the observational hypothesis drawn from the visual inspection of Fig. 7, and are consistent with those for the Japanese yen/U.S. dollar exchange rate. The relevant time-varying pattern in the monetary base can be found at frequencies in the vicinity of four-year cycles; that is, there is a large significant region after the late 2000s. In contrast, such structural changes cannot be observed in the money stock case. Moreover, focusing on the time-varying pattern at a narrower frequency band, Fig. 9 provides the estimated coefficients for $(m_s - m_s^*)$ and $(m_b - m_b^*)$ in (9) and (10), respectively, calculated as the partial wavelet gain.[10] Unlike the money stock results, the estimated coefficients for the monetary base are stable and positive. In summary, at least in the short run, the monetary base plays a significant role in explaining the euro/U.S. dollar exchange rate in a quantitative easing period.

4.2. VAR analysis

Based on the MAER model, we use a simple VAR framework to measure the effects of the money supply differentials on the nominal exchange rate, and check whether the effects increase in quantitative easing periods. To do so, we consider two four-variable systems: $(r - r^*, m_s - m_s^*, y - y^*, \varepsilon)$, and $(r - r^*, m_b - m_b^*, y - y^*, \varepsilon)$. In all VARs below, the optimal lag length is chosen as two, using the Schwarz criterion. Our way to identify structural shocks is to use a Cholesky decomposition to orthogonalize the reduced-form shocks; thus, we suppose a benchmark Cholesky ordering, as described above. In the MAER model, the exchange rate ε is assumed to be the most endogenous variable in the benchmark ordering, meaning that the exchange rate responds immediately to all other variables as new information about the state of the macro economy is revealed. We report the benchmark results below. Note that these are robust to the choice of ordering.

Panel A of Fig. 10 shows the impulse responses of the exchange rate to money supply differential shocks for the Japanese yen/U.S. dollar exchange rate, and Panel B shows those for the euro/U.S. dollar exchange rate. In these figures, the deep blue (red) line and blue (red) shaded area are the point estimates and the one-standard-error bands, respectively, in the former (latter) subsample. The start date of the latter subsample periods is determined by the beginning period of the quantitative easing regimes, as follows. In Panel A (Japan and the United States), subsamples are selected by dividing the full sample per-

[10] The long-run results are unreported, because most occur under edge effects (see Fig. 8).

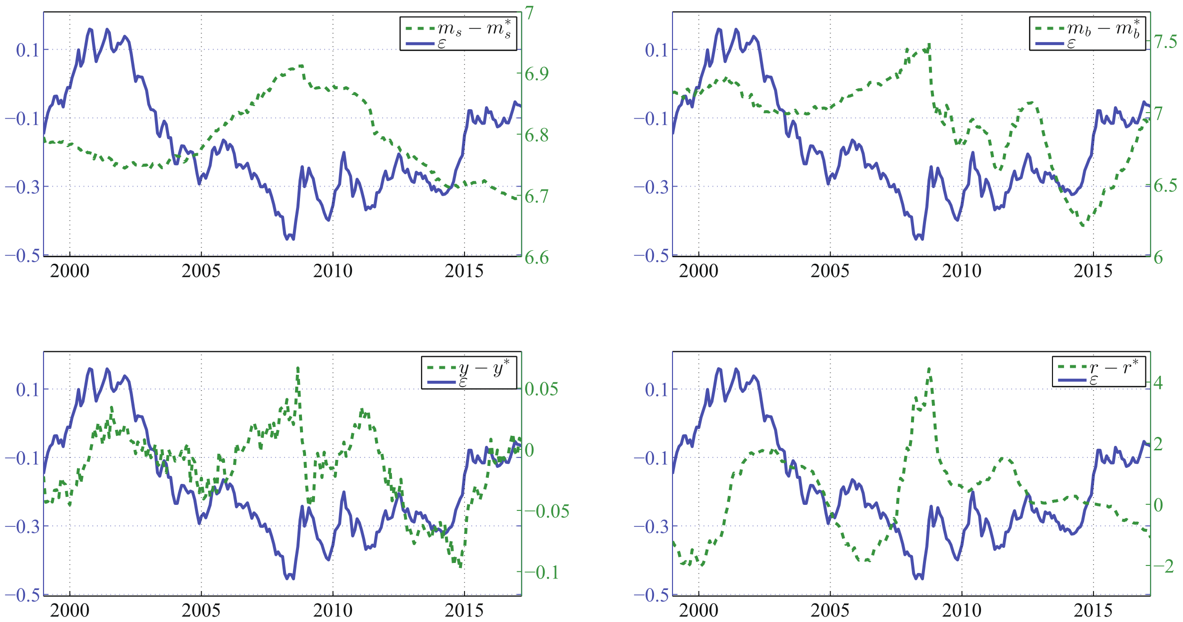


Fig. 7. Euro/U.S. dollar exchange rate and explanatory variables.

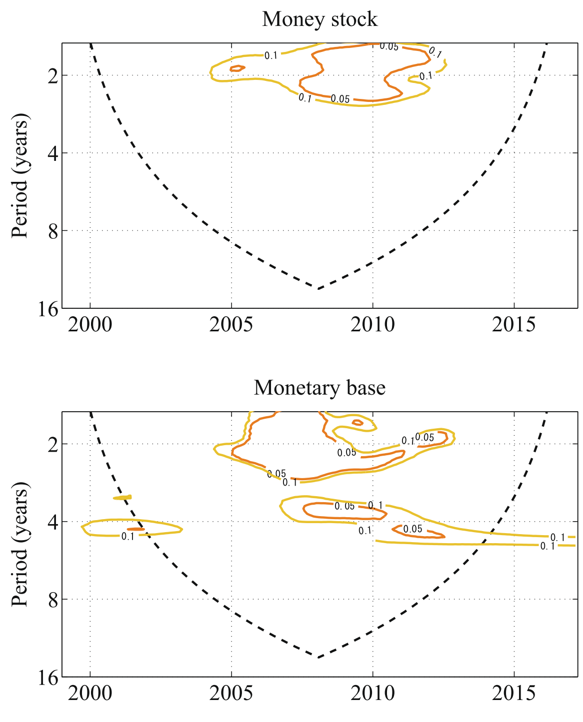


Fig. 8. Significantly correlated regions of money supply in euro/U.S. dollar exchange rate. Notes: The positive significant regions at the 5% and 10% significance levels are depicted as orange and yellow contours, respectively. The dashed lines are borders of regions affected by edge effects. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

iod before and after March 2001, when the Bank of Japan embarked on its first quantitative easing policy. Accordingly, the former subsample is 1975:1–2001:2, and the latter subsample is 2001:3–2017:6. In Panel B (the euro area and the United States), the subsamples are divided by the starting month of the Fed's LSAP (i.e., November 2008); that is, the former subsample is 1999:1–2008:10, and the latter subsample is 2008:11–2017:3.

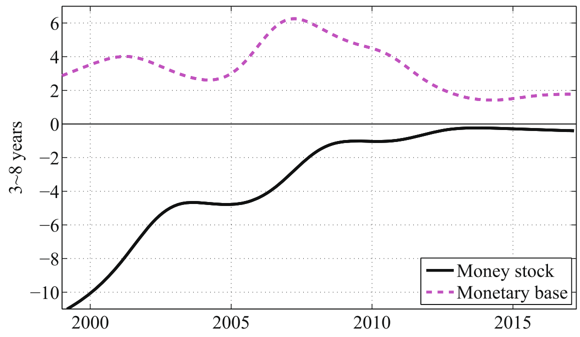


Fig. 9. Estimation results of money supply coefficients in euro/U.S. dollar exchange rate.

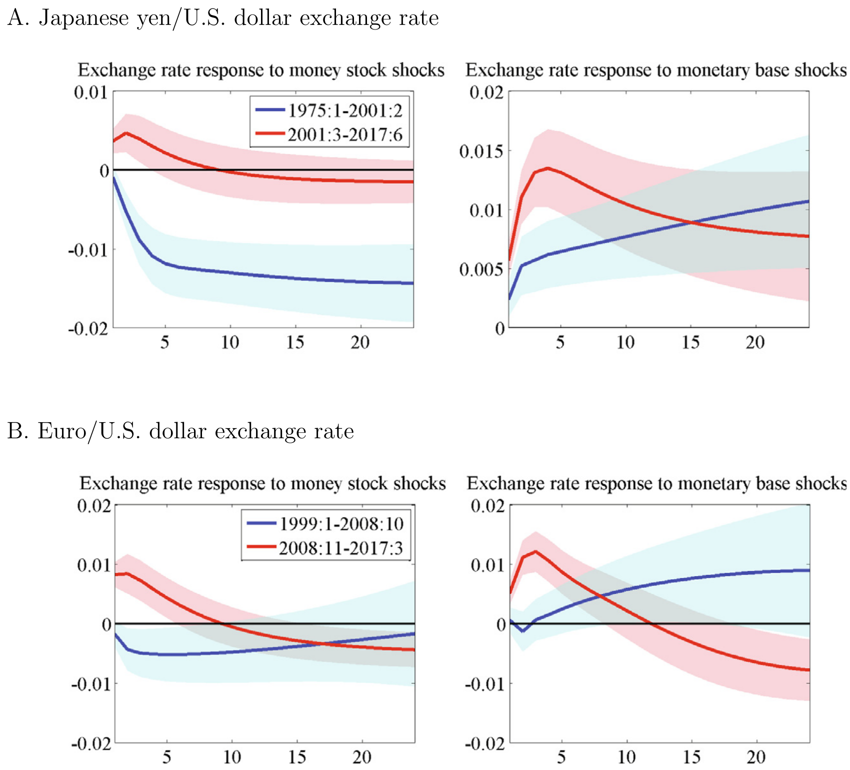
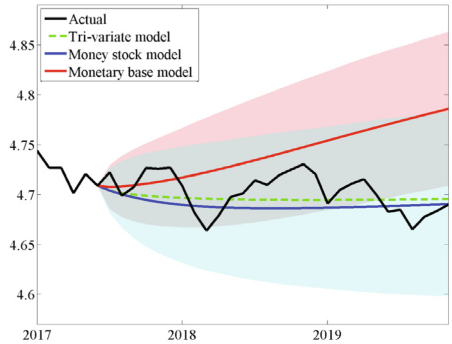


Fig. 10. Impulse response of exchange rate to money supply differential shock. Notes: The deep blue (red) line and blue (red) shaded area are the point estimates and one-standard-error bands, respectively, in the former (latter) subsample. In Panel A, the former subsample is 1975:1–2001:2, and the latter subsample is 2001:3–2017:6. In Panel B, the former subsample is 1999:1–2008:10, and the latter subsample is 2008:11–2017:3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Panels A and B suggest the following results, most of which reinforce our earlier conclusions. First, regardless of whether we use the money stock or monetary base, their effects on the exchange rate are larger in the latter periods than they are in the former. This is consistent with our wavelet outcomes that the role of the money supply increases in quantitative easing periods. More importantly, especially for the monetary base, the effect for the latter period is positive and significant.

As a final analysis, we perform an out-of-sample forecast evaluation for the exchange rate. If the above evidence is true, the money supply (notably, the monetary base) might enable accurate predictions for recent exchange rate behavior. Panel A of Fig. 11 shows the forecast results for the Japanese yen/U.S. dollar exchange rate, and Panel B shows those for the euro/U.S. dollar exchange rate. The estimation period corresponds to the latter subsamples above, and the prediction period is after the periods. In this figure, the actual nominal exchange rate is depicted by the black line from January 2017 to November 2019. The green dashed line shows the point estimates from the tri-variate model $(r - r^*, y - y^*, \varepsilon)$. The deep blue line and blue shaded area show the point estimates and the one-standard-error bands, respectively, in the four-variable model

A. Japanese yen/U.S. dollar exchange rate



B. Euro/U.S. dollar exchange rate

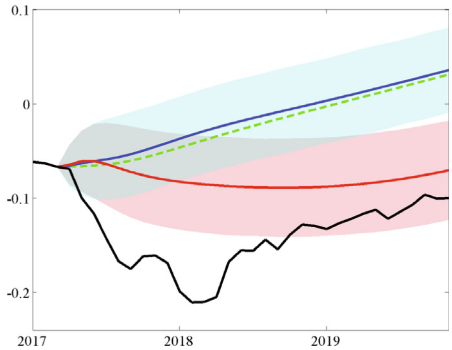


Fig. 11. Forecast of exchange rate. Notes: The black line is the actual nominal exchange rate. The green dashed line shows the point estimates in the tri-variate model $(r - r^*, y - y^*, \varepsilon)$. The deep blue line and blue shaded area are the point estimates and one-standard-error bands, respectively, in the four-variable model $(r - r^*, m_s - m_s^*, y - y^*, \varepsilon)$. The deep red line and red shaded area are the point estimates and one-standard-error bands, respectively, in the four-variable model $(r - r^*, m_b - m_b^*, y - y^*, \varepsilon)$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$(r - r^*, m_s - m_s^*, y - y^*, \varepsilon)$. Similarly, the deep red line and the red shaded area are the point estimates and the one-standard-error bands, respectively, in the four-variable model $(r - r^*, m_b - m_b^*, y - y^*, \varepsilon)$.

Overall, we find that the four-variable model that includes the monetary base outperforms the other models. In particular, the inclusion of the monetary base is likely to improve the accuracy of short-run forecasts. In contrast, the four-variable model that includes the money stock provides approximately the same prediction as that of the tri-variate model, in which the money supply is excluded from the system. For the euro/USD exchange rate dynamics, the two models that exclude the monetary base, $(r - r^*, y - y^*, \varepsilon)$ and $(r - r^*, m_s - m_s^*, y - y^*, \varepsilon)$, fail to provide a prediction. While recognizing the need for further analysis of the out-of-sample forecast, these findings suggest that, under a quantitative easing regime, using the monetary base could improve the accuracy of such forecasts for the exchange rate.

5. Conclusion

The money supply is considered a relevant determinant of exchange rate behavior. However, the introduction of a quantitative easing policy results in breaks in the money stock–monetary base nexus, heightening the need to reconsider the role of the money supply in exchange rate determination. Thus, the use of quantitative easing policies invites new questions: Do sharp increases in the monetary base cause currencies to depreciate, even without increases in the money stock? Alternatively, is the money stock more relevant to exchange rate dynamics than the monetary base is, even in quantitative easing periods? Against the backdrop of quantitative easing policies introduced in many industrialized countries in the past few decades, we argue that the correct methodology to answer these questions requires both time and frequency perspectives.

Our time–frequency results reveal that quantitative easing policies drive currency market traders to pay attention to the monetary base in the short run. One notable point in the results is that the significant role of the monetary base is exceptionally stable throughout quantitative easing periods; however, in general, we find a weak and unstable relationship between the exchange rate and monetary fundamentals, as in the exchange rate disconnect puzzle literature. This implies that quantitative easing policies persistently enhance the role of the monetary base in determining short-run exchange rates. Moreover, although the MAER literature focuses on the long-run role of the money stock, our results show that the monetary base outperforms the money stock in explaining the long-run exchange rate as well, supporting the long-run validity of the Soros chart.

Finally, our results are limited to assessing the recent period, especially at long-run frequencies, owing to edge effects. This limitation can be overcome by updating the data as they become available. This should be pursued in future research.

CRediT authorship contribution statement

Yoshito Funashima: Funding acquisition, Project administration, Supervision, Visualization, Writing - original draft, Resources, Investigation, Formal analysis, Validation, Conceptualization.

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