Journal of International Money and Finance 133 (2023) 102829

Contents lists available at ScienceDirect

# Journal of International Money and Finance

journal homepage: www.elsevier.com/locate/jimf

# The interactive CNY-CNH relationship: A wavelet analysis

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ARTICLE INFO

*Article history:*
Available online 14 March 2023

*JEL classifications:*
F31
G14
G15
G18

*Keywords:*
RMB exchange rates
CNY
CNH
Wavelet
Information spillover

ABSTRACT

The extant literature has explored the linkages between the onshore (CNY) and offshore (CNH) Renminbi (RMB) markets, as well as the potential factors affecting their dynamic inter-relationship. However, these efforts were made on a stand-alone basis in terms of dimensions and perspectives. This paper hence adopts the wavelet methodology to comprehensively examine the CNY-CNH interactions over 2010–2022. We find information spillovers across the two RMB markets to be bi-directional and asymmetric, with the exact pattern depending upon the particular sample period and the focal data frequency. Moreover, major macroeconomic events such as China's exchange rate reform, US-China trade tensions, COVID-19 pandemic, and more recent global uncertainty can exert distinct impacts on the flow pattern of information. We further show that the CNY-CNH exchange rate difference alone serves as a key indicator for the complex relationship between the two markets. As expected, the CNH market is more sensitive to exchange rate difference fluctuations, indicating a powerful market mechanism in the offshore RMB market, or equivalently, a substantial policy impact of the counter-cyclical adjustment by China's central bank in stabilizing the RMB rate.



## 1. Introduction

The Chinese currency RMB has become an increasingly important vehicle for global use over the past two decades, as China's economic growth rate has miraculously outpaced the growth rates prevailing in many parts of the world. While there exists but a single RMB, the currency is traded in two sufficiently insulated markets: the CNH market, which includes RMB transacted in several offshore hubs, and the CNY market, where participants buy and sell RMB within an onshore environment.

Much of the RMB internationalization is attributable to developments in the CNH market that commenced officially in Hong Kong on July 19th, 2010, followed by the establishment of other RMB offshore hubs in Singapore, London, Toronto, Doha, etc. as replicas of Hong Kong in later years. The CNH market is almost if not completely free, with both spot and forward rates available for trade, and at the same time in the absence of trading limits, floating bands, or any other restraints imposed on trading activities. In contrast, although the People's Bank of China (PBoC) has been continuing to liberalize the onshore RMB market for years, it is still considered to be among those markets that are subject to the greatest extent of government interventions.

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https://doi.org/10.1016/j.jimonfin.2023.102829
0261-5606/

Since the CNY and CNH refer to the same underlying asset, without market controls, we expect them to be priced the same. However, this is not the case in practice. Given that the CNY market is strictly regulated by the PBoC via capital controls and central bank interventions, the divergence between the two RMB rates could not be speculated away easily, and their differentials naturally motivate the investigation of the CNY-CNH relation. Indeed, the CNY-CNH interactions attract increasing attention from policy makers, investors, and academics.

Traditional data analytical tools, such as time-series regressions, emphasize only one or two dimensions of this CNY-CNH relationship. In addition, those tools are methodologically limited, since they normally require strict assumptions (i.e., stationarity, no structural breaks, stable market activities, etc.) on the stochastic process of exchange rates that are hardly true. Instead, our paper employs the wavelet method which has been applied to a range of macroeconomic and financial topics (e.g., see Tiwari et al., 2013; Alzahrani et al., 2014; Cai et al., 2017; Yang et al., 2018; Fan et al., 2018). This approach not only can help overcome limitations inherent in the traditional methods, but it can also shed light on the economic significance of the omnibearing CNY-CNH interlinkages that the traditional ones fail to deliver. In particular, we take advantage of wavelets over the alternatives in the following three aspects. First, the wavelet method is flexible and does not require strong assumptions about the stochastic process of exchange rates. Second, the wavelet method provides information from both the time- and frequency-domain, so that we can look at multiple channels of information flow through which one RMB market may respond to the other. Last but not least, the wavelet method is endowed with the capability to locate discontinuities common in exchange rate series that are caused by policy changes and macroeconomic events.

Our results show that the information spillover between the CNY and CNH markets is bi-directional and asymmetric. This relationship is time-varying, with changes in response to the frequency chosen and strengthened by major macroeconomic events such as China's exchange rate reform, the US-China trade tensions, the COVID-19 pandemic, and more recent global uncertainty. We also find that the CNY-CNH exchange rate difference serves as a key indicator of RMB rates. The CNH rate is more closely connected with the exchange rate differential than with the CNY rate and is more likely to be influenced by macroeconomic events.

A bird's eye view of the two interactive RMB markets of interest is crucial for two reasons. First, since the onshore market is constrained by trading limits, regulations, and central bank interventions, a non-negligible part of the RMB pricing function operates offshore. Put another way, CNH activities deliver a significant proportion of information relevant to the Chinese currency's value, with varying levels of proportion determined in a variety of dimensions. So, without the help of a full evaluation of the CNY-CNH relation, the result on the informational role played by each RMB market wouldn't have been complete and unbiased. Second, given RMB's rising influential power in the Asia-Pacific region, there exists evidence that East Asian currencies' exchange rates co-move with the RMB exchange rate (Keddad, 2019), and the CNH market affects Asian currencies in a distinct way from its CNY counterparty (Shu et al., 2015). An overview of the dynamic relationship between the CNY and CNH markets hence would also help bring up further implications for the integration of the Asia economy.

The remainder of this paper is organized as follows. In section 2, we briefly review the literature related to CNY-CNH interactions. Section 3 first introduces the wavelet methodology, including the continuous wavelet transform, the wavelet coherence, and the phase difference. Then, we propose in this section several new indicators, constructed using wavelet-type of measures, to capture the interactions between CNY and CNH rates. Section 4 briefly describes our sample data. Section 5 presents the empirical results and discusses the economic implications of our findings, followed by section 6 which concludes.

## 2. Literature review

Our paper is complementary to the literature on exploring dual-RMB-market interactions. Maziad and Kang (2012) find that (i) during the last quarter of 2010, i.e., the quarter starting three months after the launch of CNH trading in mid-2010, developments in the then dislocated offshore market exert influences on both the level and volatility of onshore rates; whereas (ii) during normal times such as the first three quarters of 2011, changes in onshore spot rates drive price movement offshore mainly through volatility spillover channels. However, Ding et al. (2014), by grouping these two subperiods into an entire sample, conclude that CNY and CNH spot returns provide little cross-explanatory power for each other. As a result, mixed results emerge for spot markets in the early two years of 2010 and 2011 during our long sample period. It also implies that global public events that can divide exchange rate market price series into distinct segments play a critical role, necessitating subsample analysis or regime switching approach.

Turing to forward currency contracts, both studies mentioned above confirm the predictability of CNH non-deliverable forward returns. But unlike them, Leung and Fu (2014) emphasize the importance of the deliverable forward market, and provide evidence about two-way cross-RMB-market spillovers since 2013, with onshore-to-offshore effects looking much larger. Nevertheless, we deem forwards to be prone to speculative trades, thus leading to susceptible estimates of CNY-CNH linkages. In regard to follow-up works, one strand sticks with the GARCH family of models but focuses on specialized datasets. E.g., using the order-level data, Cheung and Rime (2014) discover an increasing impact of the CNH exchange rate on CNY dynamics over 2010–2013, and the predictive power of the CNH rate for the official RMB central parity rate.

Besides the above traditional tools, another strand seeks alternative analytical frameworks with the aim of better understanding the CNY-CNH relation from new methodology angles. Xu et al. (2017) resort to the thermal optimal path method that is known for identifying time-dependent lead-lag structure between CNY and CNH time series. They discover a weak alternate lead-lag pattern for CNY and CNH exchange rates at both daily and intraday levels from 2012 to 2015. While their method is good at finding which sequence is leading, our method is more exhaustive in finding how that sequence leads in all possible dimensions. Namely, we employ the wavelet method over the longest possible sample period 2010–2018 to provide comprehensive information in time-, frequency-, strength-, and causality-domain, simultaneously. These four dimensions are used to be approached separately by traditional time-series tools. Hu et al. (2023) use the dynamic conditional correlation multivariate volatility Copula and BEKK models, which is advantageous in studying the CNY-CNH relation at higher moments and during extreme market conditions. They find the two-way volatility spillover effect and identifies a positive time-varying dependence with gradual price convergence between the two RMB markets. However, both of the above alternatives cannot outweigh the two merits of wavelet analysis, i.e., no strong assumption required about and no arbitrary discontinuities specified for the underlying economic process. Like our paper, Xu et al. (2021) also employ wavelet analysis only to discover an enhanced connection following the 2015 reform of the CNY system. They conclude that the long-term association between CNY and CNH rates is greater than the corresponding short-term one. Their suggestion is that the CNH rate tends to lead the CNY rate across all frequencies. Our paper complements their research by pointing out the asymmetry in the whole sample period and the irregularity in event-segmented samples. Most importantly, our paper creates the difference between the CNY and CNH rates as an informational leading proxy for the CNY-CNH nexus.

Lastly, our paper is closely related to the literature on what determines RMB exchange rates and CNY-CNH interactions. From the macroeconomic perspective, Liang et al. (2019) address the policy issue and find that RMB currency market reforms increase the volatility of these differentials. In regard to microeconomic determinants, Funke et al. (2015) find that, among other fundamentals, market liquidity plays the most important role in explaining pricing differentials between CNY and CNH exchange rates. Zhang et al. (2013) argue that order flow, as a measure of excess demand pressure, explains a considerable part of RMB exchange rate fluctuations on a daily basis; Han et al. (2018) demonstrate that investor attention displays significant predictability in CNY-CNH spreads on weekly or even monthly basis. In this paper, we develop new wavelet indicators which enable us to investigate directional information spillovers as impact factors under various market circumstances.

## 3. Methodology

### 3.1. Wavelet definitions

Wavelets are mathematical functions that cut up data into different frequency components and allow researchers to study each component with a resolution matched to its scale. They have advantages over traditional Fourier methods in analyzing situations where the information flow contains discontinuities and sharp spikes. Originating from physics, wavelets have been developed and applied independently in many fields, such as mathematics, electrical engineering, and seismic geology, among others, and they worked exceptionally well for times series in economics and finance.

Consider a macroeconomic data sequence such as exchange rate in this paper, the wavelet analysis can decompose it into a collection of elementary functions, the wavelets $\psi_{\tau,s}(t)$, which can be defined as

$$\psi_{\tau,s}(t) = \frac{1}{\sqrt{|s|}}\psi\left(\frac{t-\tau}{s}\right). \tag{1}$$

In the above definition, $s$ is a scaling factor controlling the width of the wavelet, which is inversely related to input data frequency; $\tau$ is a translation parameter determining the location of the wavelet; and $\frac{1}{\sqrt{|s|}}$ denotes a normalization factor used to ensure that the wavelet has a unit variance. The requirement is $\|\psi_{\tau,s}\|^2 = 1$ so that the wavelets are comparable across different scales of the same underlying sequence or comparable even among different time series.

These wavelets $\psi_{\tau,s}(t)$ all result from a mother wavelet function, $\psi(t)$, which must satisfy several conditions, including (i) the zero-mean condition, $\int_{-\infty}^{\infty}\psi(t)dt = 0$; (ii) the condition that the mother wavelet function squared integrates to unity, $\int_{-\infty}^{\infty}\psi^2(t)dt = 1$; and (iii) the admissibility condition,

$$0 < C_\psi = \int_0^\infty \frac{|\Psi(f)|^2}{f}df < \infty.$$

In this paper, we choose the most commonly used mother-wavelet specification, i.e., the Morlet wavelet, because it involves the smallest requirements on how exchange rates are determined and because its results retain the temporal resolution of the original features of currency pricing series. The Morlet wavelet was first introduced and defined by Goupillaud et al. (1984) as

$$\psi^M(t) = \frac{1}{\pi^{1/4}}e^{i\omega_0 t}e^{-t^2/2}, \tag{2}$$

where $\frac{1}{\pi^{1/4}}$ ensures the unity energy of the wavelet and $\omega_0$ denotes the central frequency of the mother wavelet. $\omega_0$ is set to 6 in practice as it is shown that this number enables a balance between time and frequency localization (Grinsted et al., 2004; Rua and Nunes, 2009).

### 3.2. Continuous wavelet transform

Now we are ready to transform the concerned RMB exchange rate time series $y(t)$ into wavelets for further analysis. To model the continuity in CNY and CNH, we utilize the Continuous Wavelet Transform (CWT), a flexible tool that can provide overcomplete signal representation by making changes in the translation and scale parameters continuously. Given $y(t)$, its CWT with respect to any mother wavelet functional form $\psi$, $W_{y;\psi}(\tau, s)$, is given by

$$W_{y;\psi}(\tau, s) = \int_{-\infty}^{\infty} y(t) \frac{1}{\sqrt{|s|}} \psi^* \left( \frac{t-\tau}{s} \right) dt, \tag{3}$$

where the superscript * denotes the complex conjugate, defined in mathematics to be transforming into a new number with an identical real part as the original number and an equal but opposite-sign imaginary part.

Finding the inverse of the CWT definition function, the RMB exchange rate time series $y(t)$ can be reconstructed as follows

$$y(t) = \frac{1}{C_\psi} \int_0^{\infty} [\int_{-\infty}^{\infty} W_{y;\psi}(\tau, s) \psi_{\tau,s}(t) d\tau] \frac{ds}{s^2}. \tag{4}$$

The energy of this time series $y(t)$ is

$$\|y\|^2 = \frac{1}{C_\psi} \int_0^{\infty} [\int_{-\infty}^{\infty} |W_{y;\psi}(\tau, s)|^2 d\tau] \frac{ds}{s^2}, \tag{5}$$

where $|W_{y;\psi}(\tau, s)|^2$ is the wavelet power spectrum (WPS), which serves as a proxy for the local variance of $y(t)$ across different scales. In the formal expression, a WPS function has the below specification

$$(WPS)_y(\tau, s) = |W_y(\tau, s)|^2. \tag{6}$$

Torrence and Compo (1998) use Monte Carlo simulations to compute the white noise and red noise wavelet power spectra and derive the corresponding distribution for the local WPS under a hypothesis later used by Grinsted et al. (2004). In their paper, Grinsted et al. (2004) assess the statistical significance against the null that the time-series-generating process is given by an AR(1) stationary process with a certain background power spectrum. Both studies confirm that the local WPS distribution is given by the following:

$$D\left( \frac{|W_{y,t}(s)|^2}{\sigma_y^2} < p \right) = \frac{1}{2} P_f y^2, \tag{7}$$

where the so-called background power spectrum $P_f$ denotes the mean spectrum at the Fourier frequency $f$, which in turn roughly equals the reciprocal of the wavelet scale $s$ (i.e., $f \approx 1/s$).

### 3.3. Cross-wavelet transform, wavelet coherence, and phase differences

Since our focus is on the two RMB exchange rates, we need to extend the above wavelet analysis to a setup of multiple time series. Several measures introduced in this section are used to provide a comprehensive view of the CNY-CNH relationship in section 5. The cross-wavelet transform (CWT) of two sequences, $x(t)$ and $y(t)$, is defined by Hudgins et al. (1993) as $W_{xy} = W_x W_y{}^*$, where $W_x$ and $W_y$ are the respective wavelet transforms of $x(t)$ and $y(t)$, and $W_y{}^*$ is the complex conjugate of $W_y$. The cross-wavelet power (XWP) is thus given by

$$(XWP)_{xy} = |W_{xy}|. \tag{8}$$

This XWP describes the high common power area in the time–frequency space, providing information on the scale-by-scale local covariance. In light of its importance, Torrence and Compo (1998) have shown that the distribution of this XWP takes the form of

$$D\left( \frac{|W_{x,t}(s) W_{y,t}^*(s)|}{\sigma_x \sigma_y} < p \right) = \frac{Z_v(p)}{v} \sqrt{P_f^x P_f^y}, \tag{9}$$

where $P_f^x$ and $P_f^y$ are the background power spectra corresponding to $x$ and $y$, respectively, and $Z_v(p)$ is the confidence level with a given probability $p$ for the probability density function that is characterized by the square root of the product of two $\chi^2$ distributions.

In addition to XWP, a second measure for the behavior of multiple time series is called wavelet coherence, which is defined as the ratio of the cross spectrum to the product of each series' spectrum. This coherence measure can tell us the degree of the local correlation between any two chosen time series in the time–frequency space. According to Rua and Nunes (2009), the wavelet squared coherence (WTC) can be written as

$$R_{xy}{}^{2} = \frac{\left|S(s^{-1}W_{xy})\right|^{2}}{S(s^{-1}|W_{x}|^{2})S(s^{-1}|W_{y}|^{2})}, \tag{10}$$

where $S$ is a smoothing operator in both time and scale, ensuring that the smoothed WTC returns a value between the range of zero and one, i.e., $0 \le R_{xy}{}^{2} \le 1$. Intuitively, a returned value close to zero indicates a weak relationship, while a returned value close to one suggests a strong relationship between $x$ and $y$. Grinsted et al. (2004) use Monte Carlo simulations to derive the distribution of the WTC, for the purpose of estimating its statistical significance level.

The third measure, namely the phase difference, is used to demonstrate whether the correlation of these two times series is positive or negative, and which direction the lead-lag relationship between them is forward or backward. Mathematically, the definition of the phase difference $\phi_{xy}$ can be found below

$$\phi_{xy} = \arctan\left(\frac{\Im\{S(s^{-1}W_{xy})\}}{\Re\{S(s^{-1}W_{xy})\}}\right), \ with\ \phi_{xy} \in [-\pi, \pi], \tag{11}$$

where $\Im$ and $\Re$ are the imaginary and real parts of CWT between $\times$ and $y$, respectively. The explanation for the phase difference goes as follows. The above two time series of interests are referred to as moving in phase (this statement is analogous to two time series having a positive correlation) when $\phi_{xy} \in \left(-\frac{\pi}{2}, 0\right) \cup \left(0, \frac{\pi}{2}\right)$. Moreover, given that they move in phase, a $\phi_{xy} \in \left(0, \frac{\pi}{2}\right)$ means that $y$ leads $x$; if otherwise $\phi_{xy} \in \left(-\frac{\pi}{2}, 0\right)$, then $\times$ leads $y$. Similarly, a value of $\phi_{xy} \in \left(-\pi, -\frac{\pi}{2}\right) \cup \left(\frac{\pi}{2}, \pi\right)$ indicates an anti-phase relationship (analogous to a negative correlation) of $\times$ and $y$; if $\phi_{xy} \in \left(\frac{\pi}{2}, \pi\right)$, then $\times$ is leading in this relationship, whereas $y$ is playing the leading role if $\phi_{xy} \in \left(-\pi, -\frac{\pi}{2}\right)$.

### 3.4. An information spillover indicator: Phase difference ratio

Wavelet phase difference has the advantage that it can also be interpreted as a causality relation or information spillover (see Grinsted et al., 2004; Tiwari et al., 2013; Jiang et al., 2015). For instance, if $\phi_{xy,t|s} \in \left(-\frac{\pi}{2}, 0\right)$, that is to say, information transmits from the market where the asset's price is represented by the times series $\times$ to the market where the asset whose price is represented by the time series $y$ at time $t$ with scale $s$. With the aim of investigating to what extent information transmits from the market of $\times$ to the market of $y$, at a given scale $s$ and during a selected sample period $T$, we define the phase difference ratio conditioned on scale $s$ (CPDR) by

$$CPDR_{x \to y|s} = \frac{1}{T}\sum_{t=1}^{T} I\left(\phi_{xy,t|s} \in \left(-\frac{\pi}{2}, 0\right) \cup \left(\frac{\pi}{2}, \pi\right)\right), \tag{12}$$

where $x \to y$ denotes that the information transmits from the market of $\times$ to the market of $y$, and $I$ is an indicator variable. Then, we can proceed to define the phase difference ratio conditioned on scale $s$, as well as conditioned on the fact that $\times$ and $y$ move in phase. This conditional ratio is given by

$$CPDR_{x \to y|s,in\ phase} = \frac{1}{T}\sum_{t=1}^{T} I\left(\phi_{xy,t|s} \in \left(-\frac{\pi}{2}, 0\right)\right). \tag{13}$$

A higher value of the conditional phase difference ratio implies that the information transmitted accounts for a larger proportion of the total news at the given direction and scale of information flows. The above two ratios are employed to investigate the directional information spillover and these results are presented in Sections 5.2 and 5.3.

## 4. Data source and description

We collect for comparison the base spot RMB rate against US dollars, offered by the PBoC for the CNY market, and the corresponding spot RMB rate against US dollars in the CNH market from widely-used financial data vendors. Both CNY and CNH exchange rates are adopted in the direct quotation format. Our sample covers the period from October 2010 to October 2022, including 3,032 observations. The descriptive statistics are provided in Table 1. At a first glance, the CNH rate is more volatile than the CNY rate, partly because capital controls carried out by the PBoC constrain the up and down poten-

**Table 1**
Descriptive statistics of CNY and CNH exchange rates, and CNY-CNH exchange rate difference returns.

| | Mean | Std. Dev | Skew | Kurtosis | Max | Min | J-B |
|---|---|---|---|---|---|---|---|
| CNY | 3.30E−05 | 2.08E−03 | 0.397 | 11.599 | 0.0186 | −0.0144 | <0.001 |
| CNH | 4.06E−05 | 2.61E−03 | 0.340 | 12.599 | 0.028 | −0.0175 | <0.001 |
| DIFF | −5.68E−05 | 0.012 | −0.0130 | 11.763 | 0.0836 | −0.0993 | <0.001 |

Note: CNY, CNH, and DIFF denote returns of onshore and offshore Chinese RMB exchange rates, and the CNY-CNH exchange rate differences, respectively. J-B represents the p-value for the Jarque-Bera normality test for returns.

tials of CNY volatilities to a narrow corridor. The p-values of the Jarque-Bera (J-B) test show that both CNY and CNH market returns are non-normally distributed, suggesting the reasonableness of using wavelet methods to complement traditional regressions which require strict assumptions of return distributions.

Fig. 1 plots in one graph from top to bottom the price, return, and wavelet power spectrum for CNY rates in the left panel, CNH rates in the middle, and the CNY-CNH exchange rate difference in the right panel. One clear-cut observation is that both the onshore and offshore markets are relatively stable prior to 2015, whereas after this critical point in time, these two markets become much more volatile than ever before, not only in the long-term but also in the short- and mid-term. To substantiate these stylized patterns revealed by Fig. 1, we adopt the comprehensive wavelet methods to attack the rate volatility, relationship strength, time-domain, and frequency-domain issues at one time.

## 5. Empirical results

The existing literature has documented that the CNY-CNH relationship varies in different sample periods and data granularity (see Maziad and Kang, 2012; Ding et al., 2014; Cheung and Rime, 2014; Liang et al., 2019). However, research focused on the exact pattern of such varying relations is relatively sparse. In this section, we show that this relationship alternates in direction and varies in magnitude across both the time and frequency dimensions. Specifically, in the time domain, their interactions change according to specific periods; in the frequency domain, the mid- and long-term relationship between the two markets is generally positive but the short-term relationship is unstable. The two-way information spillover effect is evident at all frequencies.

### *5.1. A comprehensive view of CNY-CNH interactions*

Fig. 2 presents the wavelet coherence and the phase difference between the CNY and CNH markets, as well as the exchange rate difference. Wavelet coherence provides an intuitive way to analyze the twin RMB market relationship in three dimensions: time, scale (or frequency), and strength. The time dimension is shown in the horizontal axis, while the scale dimension is represented by the vertical axis. The higher the scale, the lower the frequency (i.e., a lower frequency equates to a longer term). The strength dimension is represented by different colors mapped with the degree of the CNY-CNH connection strength according to the color bar labeled on the right side of Fig. 2. The blue end means weaker relation while the yellow end means stronger. In addition, there are irregular boundaries, cone outline, and a bunch of arrows in the graph. First of all, the black and bold line enclosing all blue areas differentiates the 5% significant part of the WTC from other insignificant parts. Significant WTC implies a prominent economic relationship between the two markets at some given time and frequency. Secondly, only areas inside the cone of influence (COI) could be interpreted with economic meanings. At last, the

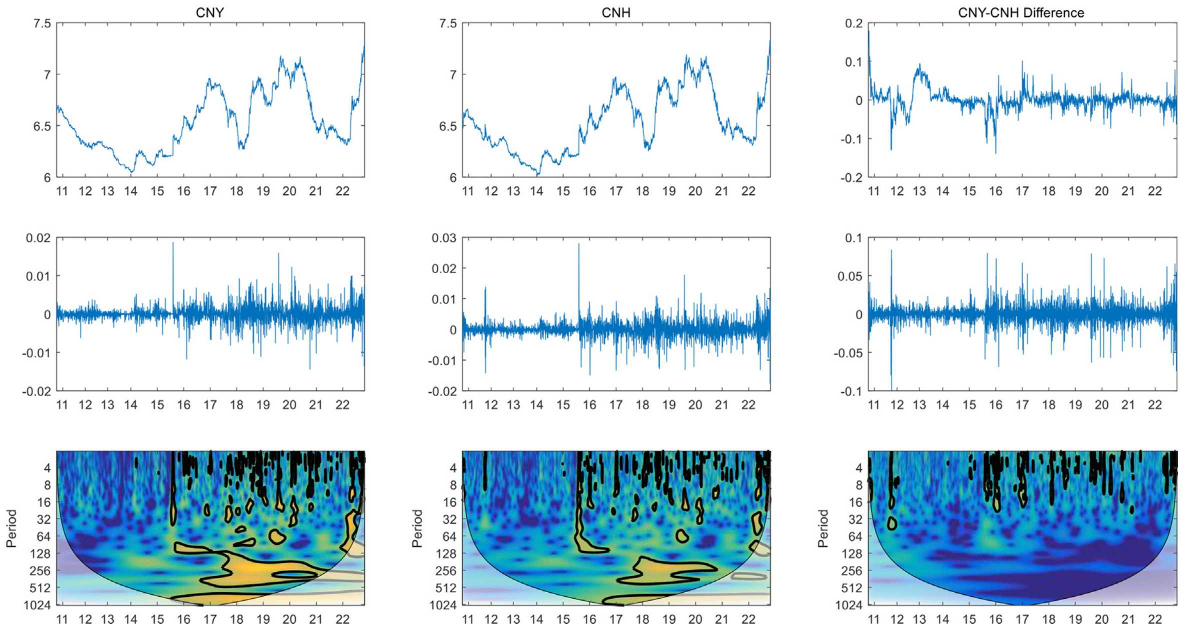
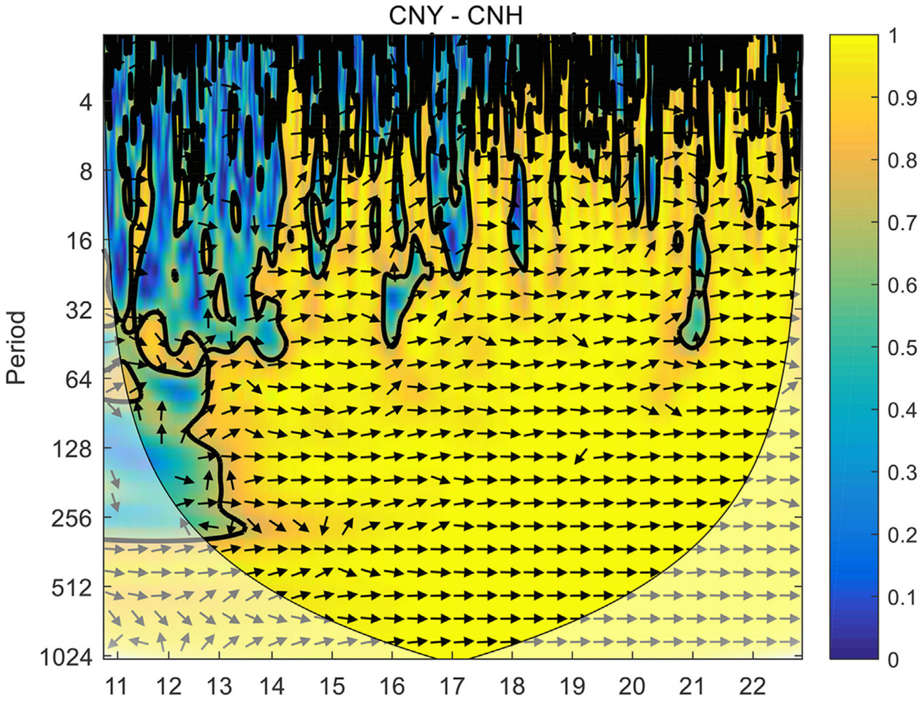
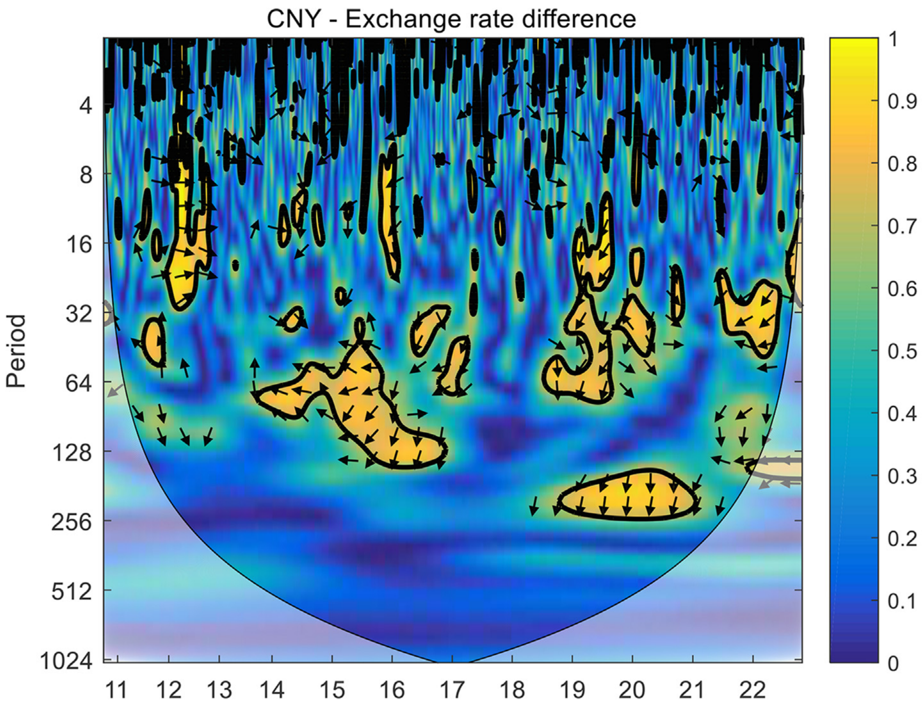



**Fig. 1. Price, return, and wavelet power spectrum for CNY, CNH, and CNY-CNH exchange rate difference.** Note: the graphs from top to bottom are the time series of price, return, and wavelet power spectrum. Price is quoted in the amounts of RMB in exchange for per unit of US dollar. The wavelet power spectrum shows the local variance of decomposed signals. The color shows the degree of volatility. The area enclosed in black and bold line is significant at 5% level.

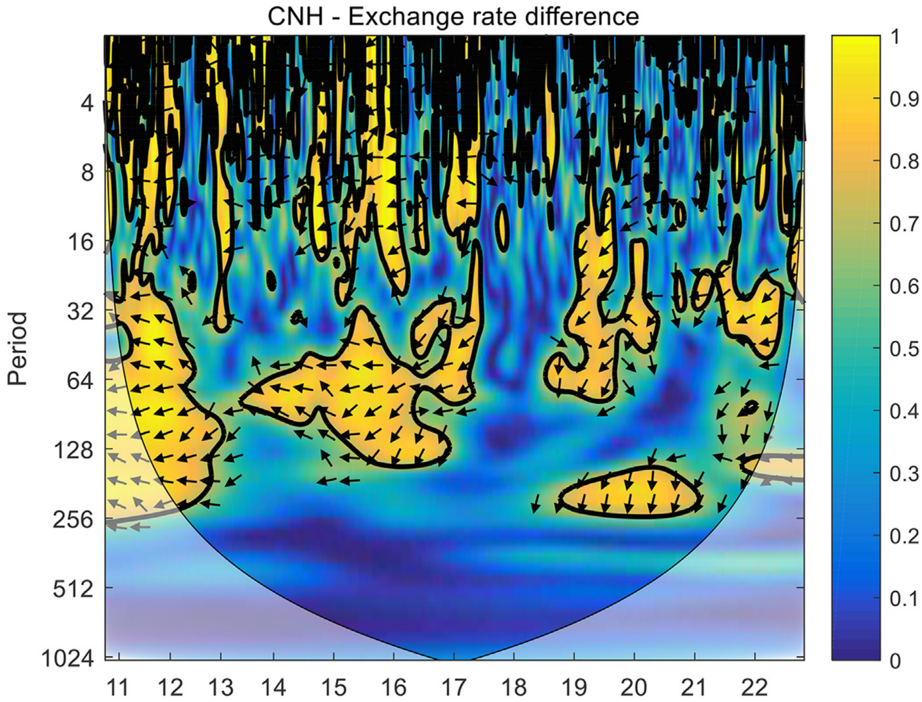



Panel A. Interactions between CNY and CNH exchange rates.




Panel B. Interactions between CNY and CNY-CNH exchange rate difference.

**Fig. 2. Interactions between CNY and CNH exchange rates, and their exchange rate difference.** Panel A. Interactions between CNY and CNH exchange rates. Panel B. Interactions between CNY and CNY-CNH exchange rate difference. Panel C. Interactions between CNH and CNY-CNH difference. Note: the horizontal axis represents time, while the vertical axis represents frequency. The warmer the color of a region, the stronger the relationship.




Panel C. Interactions between CNH and CNY-CNH difference.

**Fig. 2** (*continued*)

phase difference is indicated by the arrows here. The arrows point to the right (left) when the two RMB rates are in-phase (anti-phase), or positively (negatively) correlated. Arrows pointing down means CNY lead CNH by 90 degrees, whereas arrows pointing up means that CNH leads CNY by 90 degrees.

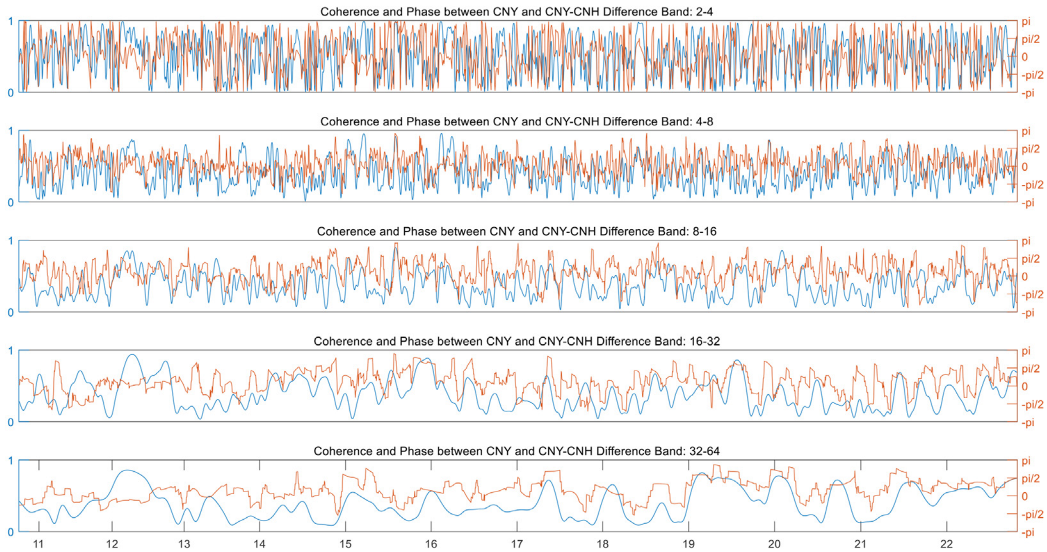
According to Fig. 2 panel A, although the CNY and CNH rates refer to an identical asset, their relationship is not necessarily strong. It is actually relatively weak in the mid- and long-term before the year 2015. Given the fact that the CNY market is intervened by the PBoC but there is no trading limit in CNH markets located worldwide, the price differentials between the CNY and CNH markets must have come from distinct market conditions caused by exogenous shocks specific to each market, and/or come from different responses made by market participants to the same set of fundamentals and announcements (Shu et al., 2015).

Nonetheless, conforming with the intuition, we indeed identify a prominent structural break at the beginning of 2015, after which the price co-movement between the CNY and CNH markets becomes much stronger than ever before. Despite this discontinuity, their relationship remains significant throughout the whole sample period in the mid- and long-term, and during most of the sample period in the short-term. Almost all the arrows point to the right in the mid- and long-term, indicating a strong positive relationship, whereas in the short-term, the relationship could be significantly negative, since some arrows point to the left. In other words, because of contrasting market conditions and the presence or absence of trading limits, the CNY and CNH prices could diverge or even go in opposite directions in the short run. However, since CNY and CNH refer to the same underlying currency asset, they are driven by a potent market power to co-move and eventually converge from the medium to the long run.

The link between the CNY-CNH exchange rate difference with the CNY and CNH rates, according to panels B and C, is significantly more convoluted. Essentially, the exchange rate difference can be a leader or a follower, causing both convergence and divergence of CNY and CNH rates. Given that the PBoC announces the CNY rate while market participants determine the CNH rate, we believe that the CNY-CNH difference is a key indicator that may affect both policymakers and investors. Furthermore, the association between the exchange rate difference and the CNH rate is significantly stronger than the relationship between the exchange rate difference and the CNY rate, implying that offshore market participants are more sensitive to the exchange rate differential than onshore market players under the supervision of the PBoC.

Fig. 3 displays the times series of coherence and phase difference between the CNY and CNH rates, as well as the Exchange rate difference in the top five scales. The blue line refers to their coherence, and the orange line refers to the phase difference. Obviously, in the short-term, the coherence and phase difference are very volatile, and they become more and more stable as the scale level rises, indicating that the short-term relationship is much more uncertain than the mid- and long-term relationships. That being said, the strength of this relationship could change sharply (almost range from the whole interval from

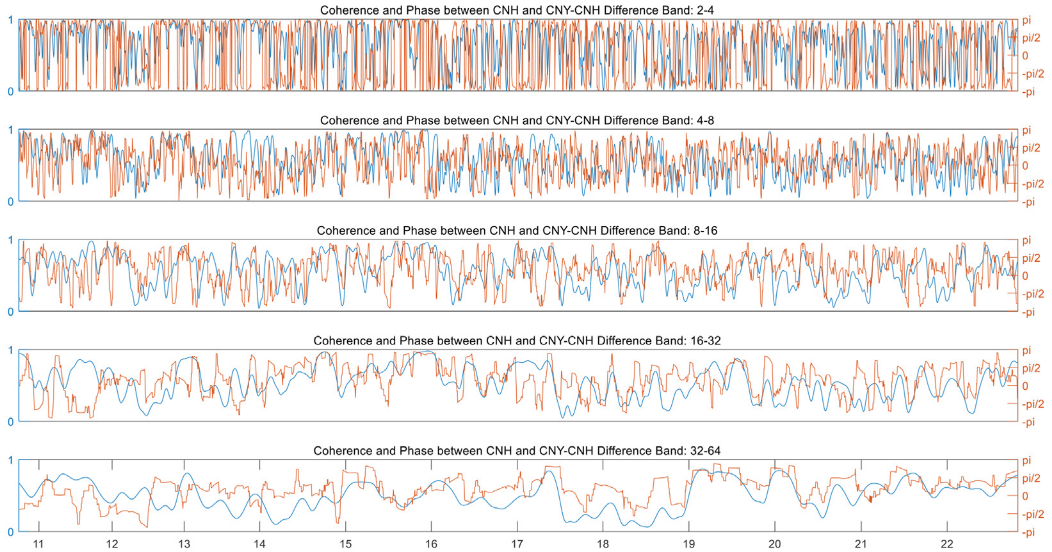

Panel A. Coherence and Phase between CNY and CNH exchange rates.




Panel B. Coherence and Phase between CNY rate and CNY-CNH difference.

**Fig. 3. Time series of wavelet coherence (left vertical axis and the blue line) and phase difference (right vertical axis and the orange line).** Panel A. Coherence and Phase between CNY and CNH exchange rates. Panel B. Coherence and Phase between CNY rate and CNY-CNH difference. Panel C. Coherence and Phase between CNH rate and CNY-CNH difference.

0 to 1) at all frequencies, even in the much more stable long-term. According to the orange phase difference line, in the first two sub-graphs with smaller scales (meaning in the short-term), the phase difference lies all over the four quadrants, suggesting the existence of both positive and negative relationships, as well as bi-directional information spillovers. However, according to panel A, based on the rest three sub-graphs with higher scales of 8–16 to 32–64, the orange line most of the time lies in the $(-\pi/2, \pi/2)$ range entirely, implying a positive relationship and a bi-directional causality between the two RMB markets.




Panel C. Coherence and Phase between CNH rate and CNY-CNH difference.

**Fig. 3** (*continued*)

**Table 2**
Mean and standard deviation of coherence and phase difference.

| Scale | | | D1 | D2 | D3 | D4 | D5 | D6 |
|---|---|---|---|---|---|---|---|---|
| **Panel A** | Coherence | Mean | 0.587 | 0.562 | 0.668 | 0.714 | 0.783 | 0.875 |
| CNY-CNH | | Std | 0.271 | 0.222 | 0.218 | 0.235 | 0.225 | 0.126 |
| | Phase | Mean | −0.075 | −0.149 | −0.161 | −0.165 | −0.078 | −0.057 |
| | | Std | 1.335 | 0.691 | 0.571 | 0.501 | 0.397 | 0.300 |
| **Panel B** | Coherence | Mean | 0.508 | 0.404 | 0.375 | 0.378 | 0.390 | 0.450 |
| CNY-DIFF | | Std | 0.261 | 0.198 | 0.178 | 0.204 | 0.205 | 0.197 |
| | Phase | Mean | 0.126 | 0.177 | 0.345 | 0.373 | 0.511 | 0.410 |
| | | Std | 1.565 | 0.911 | 0.966 | 1.011 | 0.865 | 1.152 |
| **Panel C** | Coherence | Mean | 0.648 | 0.577 | 0.563 | 0.544 | 0.496 | 0.567 |
| CNH-DIFF | | Std | 0.272 | 0.233 | 0.230 | 0.219 | 0.198 | 0.223 |
| | Phase | Mean | 0.187 | 0.301 | 0.503 | 0.528 | 0.601 | 0.474 |
| | | Std | 2.431 | 1.444 | 1.369 | 1.348 | 1.090 | 1.342 |

Note: D1, D2, D3, D4, D5, and D6 refer to 2–4, 4–8, 8–16, 16–32, 32–64, and 64–128 scales, respectively.

Table 2 represents the means and standard deviations of coherence and phase difference across all scales. Panel A shows that, in terms of coherence, by examining the respective means and standard deviations, the magnitude of coherence and its significance rise as the scale increases, indicating a stronger and more stable link in the long term than in the short term. Concerning the phase difference, our findings are that, on average, the values of phase difference fall into the category of $(-\pi/2, 0)$, and the standard deviation of phase difference decreases with an increase in scale. These results suggest that, although the related information is transmitted from the CNY market to the CNH market on average, this relationship is unstable and insignificant across all scales. In line with Fig. 3, results presented in Table 2 panel A confirm the presence of bi-directional information flowing channels, and provide collateral evidence that a relatively stable positive co-movement exists in the long-term rather than in the short-term. Panels B and C show that the coherence between exchange rate difference, and CNY and CNH rates are strongest in the short-term (D1). The values of phase difference fall into the category of $(0, \pi/2)$, suggesting that the exchange rate difference leads both CNY and CNH rates on average, however, this relationship is unstable across all scales. These results indicate the deterministic role of the exchange rate difference in influencing CNY and CNH rates. In addition, the relationship between the exchange rate difference and the CNH rate is stronger than that of the CNY rate at all frequencies, suggesting the more important role of the CNH market in price discovery.

### 5.2. Directional information spillover

As we find the bi-directional spillover effect at all frequencies in the previous subsection, it would be interesting to analyze the information transmission mechanism in detail. Specifically, we separate the phase difference into four quadrants: either a positive (in-phase) or negative (anti-phase) relationship, and bi-directional spillovers (either from CNH to CNY or from CYH to CNH). We calculate the conditional phase difference ratios in each quadrant at each scale according to equation (13). Table 3 reports these results calculated for the whole sample period.

According to Table 3 panel A, we can conclude that CNY and CNH move in phase most of the time. They are more likely to diverge in the short term when compared to the long term. In terms of information flow, the information transmission mechanism across our two RMB rates is bi-directional and asymmetric --- the CNY market sends much more abundant information than it receives from the CNH market at all scales. In absolute magnitude, the CNH market transmits a considerable amount of information, especially in the short term; but in relative magnitude, the information generated by the CNH market is still smaller than that generated by the CNY market. In the long term, we can say with confidence that the CNY market dominates the collection of CNH markets. According to Panels B and C, we can observe a bi-directional influence between exchange rate difference with CNY and CNH rates. Probabilities of the CNY rate diverging from the exchange rate difference (moving anti-phase), especially in the long term, show that the PBoC's offer rate plays a significant counter-cyclical adjustment function in maintaining the stability of the RMB rate. The convergence probabilities of the CNH rate and exchange rate difference (since CNY-CNH difference is defined as CNY rate minus CNH rate, moving anti-phase means the convergence) remain static across all frequencies, indicating a strong market mechanism in the CNH market.

### 5.3. Analysis in subsamples: The 8.11 exchange rate reform, US-China trade disputes, the COVID-19 pandemic, and the 2022 global conflict unfold

Since we have identified the time-varying and frequency-varying relationship between the CNY and CNH markets, it would be interesting to investigate how major events affect the information transmission mechanism. Thus, we separate the whole sample period into five subsamples: pre- and post-exchange rate reform, US-China trade tensions, the COVID-19 pandemic, and the 2022 global conflict and economic uncertainty periods.

Table 4 presents the descriptive statistics in five subsamples. Clearly, following the exchange rate reform, the volatility of CNY and CNH rates increased dramatically, and their exchange rate difference widened. The trade tensions between the United States and China prompted the RMB to depreciate sharply, increasing its volatility. During the COVID-19 pandemic, the RMB rate appreciated significantly and stabilized, due to a dramatic rise in China's medical devices exports (Wu et al., 2022) and ceased economic activities with China caused by fear of international spread risk (Lai et al., 2022). After that, the global conflict unfolding resulted in a severe decline and destabilization of the RMB rate.

Table 5 provides the estimates of coherence and phase difference between CNY and CNH rates in five subsamples. According to Panels A and B, after the exchange rate reform, the link between CNY and CNH rates rose considerably, suggesting that

**Table 3**
Directional information spillovers based on conditional phase difference ratios.

| | Scale | D1 | D2 | D3 | D4 | D5 | D6 |
|---|---|---|---|---|---|---|---|
| Panel A | Anti-phase CNY ← CNH | 0.126 | 0.125 | 0.079 | 0.065 | 0.042 | 0.013 |
| | In phase CNY ← CNH | 0.339 | 0.338 | 0.325 | 0.335 | 0.321 | 0.370 |
| | In phase CNY → CNH | 0.417 | 0.445 | 0.537 | 0.557 | 0.593 | 0.603 |
| | Anti-phase CNY → CNH | 0.118 | 0.091 | 0.058 | 0.044 | 0.044 | 0.014 |
| Panel B | Anti-phase CNY ← DIFF | 0.162 | 0.168 | 0.178 | 0.194 | 0.166 | 0.237 |
| | In phase CNY ← DIFF | 0.334 | 0.360 | 0.333 | 0.311 | 0.287 | 0.220 |
| | In phase CNY → DIFF | 0.296 | 0.262 | 0.205 | 0.186 | 0.193 | 0.154 |
| | Anti-phase CNY → DIFF | 0.209 | 0.210 | 0.283 | 0.308 | 0.354 | 0.389 |
| Panel C | Anti-phase CNH ← DIFF | 0.380 | 0.348 | 0.308 | 0.294 | 0.259 | 0.290 |
| | In phase CNH ← DIFF | 0.096 | 0.106 | 0.127 | 0.130 | 0.143 | 0.126 |
| | In phase CNH → DIFF | 0.080 | 0.086 | 0.077 | 0.087 | 0.099 | 0.098 |
| | Anti-phase CNH → DIFF | 0.444 | 0.460 | 0.489 | 0.490 | 0.500 | 0.486 |

**Table 4**
Summary statistics for CNY and CNH exchange rate returns, and price difference returns between the two during five subsample periods.

| | Mean | Std. Dev | Skew | Kurtosis | Max | Min | J-B |
|---|---|---|---|---|---|---|---|
| Panel A. Pre-exchange rate reform: 2010.10.11 ~ 2015.8.10 | | | | | | | |
| CNY | −5.91E−05 | 1.01E−03 | 0.086 | 7.661 | 0.005 | −0.006 | <0.001 |
| CNH | −4.37E−05 | 1.57E−03 | 0.497 | 21.039 | 0.014 | −0.014 | <0.001 |
| DIFF | −1.25E−04 | 9.23E−03 | −0.640 | 29.403 | 0.084 | −0.099 | <0.001 |
| Panel B. Post-exchange rate reform: 2015.8.11 ~ 2018.4.4 | | | | | | | |
| CNY | 2.16E−05 | 2.21E−03 | 0.520 | 13.007 | 0.019 | −0.012 | <0.001 |
| CNH | 1.68E−05 | 2.94E−03 | 0.634 | 16.899 | 0.028 | −0.015 | <0.001 |
| DIFF | 3.33E−05 | 1.41E−02 | 0.323 | 7.861 | 0.079 | −0.069 | <0.001 |
| Panel C. Trade tensions: 2018.4.5 ~ 2020.1.22 | | | | | | | |
| CNY | 2.03E−04 | 2.67E−03 | 0.415 | 7.118 | 0.016 | −0.011 | <0.001 |
| CNH | 2.10E−04 | 3.17E−03 | −0.055 | 7.031 | 0.018 | −0.013 | <0.001 |
| DIFF | −4.23E−05 | 1.31E−02 | 0.003 | 7.339 | 0.078 | −0.063 | <0.001 |
| Panel D. COVID-19 pandemic: 2020.1.23 ~ 2022.2.23 | | | | | | | |
| CNY | −1.63E−04 | 2.38E−03 | 0.094 | 8.072 | 0.012 | −0.014 | <0.001 |
| CNH | −1.64E−04 | 2.55E−03 | 0.271 | 4.765 | 0.012 | −0.009 | <0.001 |
| DIFF | 1.03E−05 | 1.13E−02 | −0.108 | 9.439 | 0.073 | −0.057 | <0.001 |
| Panel E. Global conflict unfolding: 2022.2.24 ~ 2022.10.31 | | | | | | | |
| CNY | 8.22E−04 | 3.37E−03 | −0.268 | 5.361 | 0.010 | −0.014 | <0.001 |
| CNH | 8.57E−04 | 4.39E−03 | −0.280 | 4.737 | 0.013 | −0.018 | <0.001 |
| DIFF | −2.11E−04 | 1.91E−02 | −0.031 | 5.941 | 0.065 | −0.074 | <0.001 |

**Table 5**
Relationship between CNY and CNH exchange rates during five subsample periods.

| Scale | | | D1 | D2 | D3 | D4 | D5 | D6 |
|---|---|---|---|---|---|---|---|---|
| Panel A. Pre-exchange rate reform: 2010.10.11 ~ 2015.8.10 | | | | | | | | |
| CNY-CNH | Coherence | Mean | 0.53 | 0.48 | 0.54 | 0.56 | 0.62 | 0.77 |
| | | Std | 0.27 | 0.21 | 0.24 | 0.24 | 0.26 | 0.13 |
| | Phase | Mean | −0.19 | −0.19 | −0.16 | −0.14 | 0.03 | 0.06 |
| | | Std | 1.55 | 0.82 | 0.73 | 0.66 | 0.56 | 0.38 |
| Panel B. Post-exchange rate reform: 2015.8.11 ~ 2018.4.4 | | | | | | | | |
| CNY-CNH | Coherence | Mean | 0.51 | 0.53 | 0.68 | 0.71 | 0.81 | 0.92 |
| | | Std | 0.27 | 0.21 | 0.18 | 0.22 | 0.13 | 0.07 |
| | Phase | Mean | −0.03 | −0.11 | −0.13 | −0.30 | −0.14 | −0.14 |
| | | Std | 1.38 | 0.68 | 0.50 | 0.48 | 0.26 | 0.26 |
| Panel C. Trade tensions: 2018.4.5 ~ 2020.1.22 | | | | | | | | |
| CNY-CNH | Coherence | Mean | 0.72 | 0.67 | 0.77 | 0.89 | 0.95 | 0.98 |
| | | Std | 0.23 | 0.20 | 0.12 | 0.08 | 0.04 | 0.01 |
| | Phase | Mean | 0.06 | −0.13 | −0.12 | −0.11 | −0.15 | −0.15 |
| | | Std | 0.97 | 0.53 | 0.34 | 0.26 | 0.19 | 0.07 |
| Panel D. COVID-19 pandemic: 2020.1.23 ~ 2022.2.23 | | | | | | | | |
| CNY-CNH | Coherence | Mean | 0.68 | 0.67 | 0.78 | 0.82 | 0.89 | 0.91 |
| | | Std | 0.24 | 0.20 | 0.15 | 0.13 | 0.13 | 0.09 |
| | Phase | Mean | −0.06 | −0.13 | −0.22 | −0.09 | −0.13 | −0.11 |
| | | Std | 1.02 | 0.53 | 0.48 | 0.31 | 0.20 | 0.24 |
| Panel E. Global conflict unfolding: 2022.2.24 ~ 2022.10.31 | | | | | | | | |
| CNY-CNH | Coherence | Mean | 0.59 | 0.62 | 0.80 | 0.92 | 0.97 | 0.97 |
| | | Std | 0.28 | 0.16 | 0.14 | 0.05 | 0.02 | 0.04 |
| | Phase | Mean | 0.10 | −0.14 | −0.21 | −0.14 | −0.18 | −0.04 |
| | | Std | 1.29 | 0.63 | 0.33 | 0.20 | 0.22 | 0.05 |

the marketization of the RMB rate boosted the efficiency of the exchange rate market. During the trade disputes between US and China, the COVID-19 pandemic, and the 2022 surging uncertainty amid global conflict, the CNY-CNH linkage strengthened further, suggesting a stronger CNY-CNH relationship during the periods of an unstable external environment.

Table 6 displays estimates of coherence and phase difference between the CNY rate and exchange rate difference for five subsamples. In comparison to Table 2, the strength of their association does not vary significantly between subsamples. In all subsamples, the average values and standard deviations of phase difference demonstrate bi-directional information spillover between the CNY rate and the exchange rate difference. Our findings reveal a consistent link between the CNY rate and the exchange rate difference, which was unaffected by key macroeconomic events, implying that the PBoC did a decent job of stabilizing the RMB onshore exchange rate.

**Table 6**
Relationship between CNY rate and CNY-CNH difference during five subsample periods.

| Scale | | | D1 | D2 | D3 | D4 | D5 | D6 |
|---|---|---|---|---|---|---|---|---|
| Panel A. Pre-exchange rate reform: 2010.10.11 ~ 2015.8.10 | | | | | | | | |
| CNY-DIFF | Coherence | Mean | 0.52 | 0.41 | 0.39 | 0.42 | 0.35 | 0.40 |
| | | Std | 0.26 | 0.21 | 0.18 | 0.22 | 0.19 | 0.18 |
| | Phase | Mean | 0.28 | 0.18 | 0.25 | 0.28 | 0.17 | −0.35 |
| | | Std | 1.50 | 0.87 | 0.96 | 0.95 | 0.72 | 0.95 |
| Panel B. Post-exchange rate reform: 2015.8.11 ~ 2018.4.4 | | | | | | | | |
| CNY-DIFF | Coherence | Mean | 0.48 | 0.40 | 0.37 | 0.36 | 0.33 | 0.45 |
| | | Std | 0.26 | 0.19 | 0.17 | 0.20 | 0.15 | 0.20 |
| | Phase | Mean | 0.18 | 0.06 | 0.38 | 0.41 | 0.45 | 0.77 |
| | | Std | 1.60 | 0.95 | 0.98 | 1.13 | 0.74 | 1.11 |
| Panel C. Trade tensions: 2018.4.5 ~ 2020.1.22 | | | | | | | | |
| CNY-DIFF | Coherence | Mean | 0.48 | 0.37 | 0.36 | 0.41 | 0.46 | 0.59 |
| | | Std | 0.26 | 0.19 | 0.17 | 0.19 | 0.25 | 0.18 |
| | Phase | Mean | −0.12 | 0.25 | 0.41 | 0.56 | 0.85 | 1.44 |
| | | Std | 1.66 | 0.96 | 0.87 | 1.00 | 1.13 | 0.57 |
| Panel D. COVID-19 pandemic: 2020.1.23 ~ 2022.2.23 | | | | | | | | |
| CNY-DIFF | Coherence | Mean | 0.54 | 0.41 | 0.34 | 0.28 | 0.42 | 0.46 |
| | | Std | 0.25 | 0.19 | 0.17 | 0.16 | 0.21 | 0.18 |
| | Phase | Mean | 0.05 | 0.29 | 0.41 | 0.27 | 0.83 | 0.42 |
| | | Std | 1.50 | 0.90 | 0.97 | 0.99 | 0.82 | 0.91 |
| Panel E. Global conflict unfolding: 2022.2.24 ~ 2022.10.31 | | | | | | | | |
| CNY-DIFF | Coherence | Mean | 0.50 | 0.39 | 0.40 | 0.41 | 0.61 | 0.38 |
| | | Std | 0.24 | 0.15 | 0.17 | 0.18 | 0.07 | 0.21 |
| | Phase | Mean | −0.23 | 0.10 | 0.45 | 0.67 | 1.10 | 1.14 |
| | | Std | 1.63 | 0.88 | 1.12 | 0.88 | 0.28 | 1.01 |

**Table 7**
Relationship between CNH rate and CNY-CNH difference during five subsample periods.

| Scale | | | D1 | D2 | D3 | D4 | D5 | D6 |
|---|---|---|---|---|---|---|---|---|
| Panel A. Pre-exchange rate reform: 2010.10.11 ~ 2015.8.10 | | | | | | | | |
| CNH-DIFF | Coherence | Mean | 0.71 | 0.66 | 0.61 | 0.59 | 0.49 | 0.61 |
| | | Std | 0.26 | 0.22 | 0.23 | 0.21 | 0.17 | 0.20 |
| | Phase | Mean | 0.45 | 0.30 | 0.41 | 0.41 | 0.16 | −0.41 |
| | | Std | 2.53 | 1.55 | 1.51 | 1.45 | 1.12 | 1.23 |
| Panel B. Post-exchange rate reform: 2015.8.11 ~ 2018.4.4 | | | | | | | | |
| CNH-DIFF | Coherence | Mean | 0.64 | 0.56 | 0.60 | 0.60 | 0.42 | 0.56 |
| | | Std | 0.28 | 0.24 | 0.23 | 0.24 | 0.18 | 0.26 |
| | Phase | Mean | 0.20 | 0.17 | 0.51 | 0.70 | 0.60 | 0.92 |
| | | Std | 2.50 | 1.47 | 1.35 | 1.43 | 0.88 | 1.28 |
| Panel C. Trade tensions: 2018.4.5 ~ 2020.1.22 | | | | | | | | |
| CNH-DIFF | Coherence | Mean | 0.58 | 0.52 | 0.51 | 0.47 | 0.49 | 0.63 |
| | | Std | 0.27 | 0.21 | 0.22 | 0.21 | 0.29 | 0.20 |
| | Phase | Mean | −0.17 | 0.38 | 0.54 | 0.65 | 1.00 | 1.58 |
| | | Std | 2.26 | 1.35 | 1.13 | 1.16 | 1.25 | 0.58 |
| Panel D. COVID-19 pandemic: 2020.1.23 ~ 2022.2.23 | | | | | | | | |
| CNH-DIFF | Coherence | Mean | 0.58 | 0.47 | 0.44 | 0.43 | 0.57 | 0.45 |
| | | Std | 0.26 | 0.20 | 0.21 | 0.15 | 0.15 | 0.20 |
| | Phase | Mean | 0.11 | 0.43 | 0.63 | 0.36 | 0.97 | 0.59 |
| | | Std | 2.19 | 1.28 | 1.27 | 1.20 | 0.88 | 0.99 |
| Panel E. Global conflict unfolding: 2022.2.24 ~ 2022.10.31 | | | | | | | | |
| CNH-DIFF | Coherence | Mean | 0.67 | 0.58 | 0.63 | 0.53 | 0.62 | 0.48 |
| | | Std | 0.21 | 0.22 | 0.16 | 0.23 | 0.08 | 0.17 |
| | Phase | Mean | −0.33 | 0.24 | 0.65 | 0.82 | 1.28 | 1.16 |
| | | Std | 2.43 | 1.34 | 1.30 | 1.04 | 0.44 | 1.03 |

Table 7 presents estimates of coherence and phase difference between the CNH rate and exchange rate difference for five subsamples. Similarly, the average values and standard deviations of phase difference show that bi-directional information spillover exists. In all subsamples and sizes, their link is stronger than the relationship between CNY and exchange rate difference. Unlike the CNY rate, however, this association fluctuates considerably between subsamples. These findings imply that the CNH market's functionary mechanism is quickly changed by large macroeconomic events.

**Table 8**
Directional information spillovers between CNY and CNH rates during five subsample periods.

| Scale | D1 | D2 | D3 | D4 | D5 | D6 |
|---|---|---|---|---|---|---|
| Panel A. Pre-exchange rate reform: 2015.8.11 ~ 2018.4.4 | | | | | | |
| Anti-phase CNY ← CNH | 0.20 | 0.18 | 0.13 | 0.10 | 0.08 | 0.02 |
| In phase CNY ← CNH | 0.24 | 0.30 | 0.31 | 0.32 | 0.37 | 0.53 |
| In phase CNY → CNH | 0.40 | 0.39 | 0.46 | 0.49 | 0.46 | 0.43 |
| Anti-phase CNY → CNH | 0.16 | 0.13 | 0.10 | 0.08 | 0.09 | 0.02 |
| Panel B. Post-exchange rate reform: 2015.8.11 ~ 2018.4.4 | | | | | | |
| Anti-phase CNY ← CNH | 0.12 | 0.12 | 0.05 | 0.08 | 0.04 | 0.01 |
| In phase CNY ← CNH | 0.32 | 0.37 | 0.33 | 0.33 | 0.34 | 0.33 |
| In phase CNY → CNH | 0.42 | 0.42 | 0.57 | 0.55 | 0.59 | 0.65 |
| Anti-phase CNY → CNH | 0.14 | 0.09 | 0.05 | 0.03 | 0.03 | 0.01 |
| Panel C. Trade tensions: 2018.4.5 ~ 2020.1.22 | | | | | | |
| Anti-phase CNY ← CNH | 0.04 | 0.07 | 0.03 | 0.01 | 0.01 | 0.00 |
| In phase CNY ← CNH | 0.47 | 0.36 | 0.34 | 0.33 | 0.26 | 0.10 |
| In phase CNY → CNH | 0.42 | 0.52 | 0.61 | 0.65 | 0.73 | 0.90 |
| Anti-phase CNY → CNH | 0.06 | 0.05 | 0.03 | 0.01 | 0.00 | 0.00 |
| Panel D. COVID-19 pandemic: 2020.1.23 ~ 2022.2.23 | | | | | | |
| Anti-phase CNY ← CNH | 0.07 | 0.07 | 0.07 | 0.02 | 0.01 | 0.01 |
| In phase CNY ← CNH | 0.43 | 0.34 | 0.33 | 0.36 | 0.29 | 0.35 |
| In phase CNY → CNH | 0.46 | 0.53 | 0.57 | 0.59 | 0.69 | 0.63 |
| Anti-phase CNY → CNH | 0.05 | 0.06 | 0.02 | 0.02 | 0.01 | 0.01 |
| Panel E. Global conflict unfolding: 2022.2.24 ~ 2022.10.31 | | | | | | |
| Anti-phase CNY ← CNH | 0.10 | 0.11 | 0.06 | 0.02 | 0.01 | 0.01 |
| In phase CNY ← CNH | 0.41 | 0.36 | 0.32 | 0.32 | 0.18 | 0.26 |
| In phase CNY → CNH | 0.35 | 0.45 | 0.60 | 0.65 | 0.81 | 0.72 |
| Anti-phase CNY → CNH | 0.14 | 0.08 | 0.02 | 0.01 | 0.00 | 0.01 |

Table 8 provides the results of directional information spillover between CNY and CNH rates during five subsamples. Evidently, the two rates are more likely to converge following the exchange rate reform, particularly during periods of international trade disputes between two major trading powers and periods of the COVID-19 epidemic forcing economic growth to grind to a halt, implying that the exchange rate reform considerably increased the efficiency of the RMB markets. The CNY market transmitted more information to the CNH market than it received in most cases; nevertheless, this relationship varied dramatically between subsamples, particularly in the long term. These findings highlight the two markets' intricate interaction, which may be considerably influenced by the external environment.

### *5.4. Economic implications*

The implications of our results are twofold. To begin, consider the perspective of investors. While it is easier for them to speculate in the CNH market due to the absence of trading limitations, investors with such intentions should avoid short-term trading. This is because the CNH and CNY exchange rates are more likely to diverge in the short term due to shocks, deviating from the common fundamentals, and large macroeconomic developments might have a substantial impact on this relationship.

Second, from the standpoint of policymakers in PBoC, it is not necessary for them to intervene in the RMB currency market, as any shortsighted intervention would increase market inefficiency, causing CNY and CNH prices to further diverge.

Since these two markets would finally converge in the long term, short-term market interventions play a lesser role in stabilizing the RMB rates. Currently, the CNH market absorbs almost all speculations of RMB rates. In sum, liberalizing the CNY market along with the RMB rate would with no doubt increase the market efficiency and the pricing power of the CNY market, reducing the significance of all CNH trading centers.

## 6. Concluding remarks

With the internationalization of RMB, the issue of "one currency, two markets" draws the attention of academics to take advantage of this setup to explore research questions centered around information spillover and pricing efficiency under different institutional arrangements. In light of the efforts made, it is now widely recognized that the CNY-CNH interaction is multi-dimensional and contingent, hence complicated in structure and magnitude. This paper provides a comprehensive investigation into this relationship using wavelets. We also develop new indicators based on wavelets, to understand how the CNY-CNH relationship changes under different situations.

We show that the information spillover between the CNY and CNH markets is bi-directional and asymmetric. This relationship varies in terms of time and frequency and is significantly strengthened by major macroeconomic events such as China's exchange rate reform, by then continuously escalating trade disputes between US and China, the COVID-19 pandemic, and the surging political and economic uncertainty amid global conflict. We also demonstrate that the exchange rate difference between CNY and CNH rates is a key indicator for investors and PBoC. The association between the CNH rate and the exchange rate difference is significantly greater than the relationship between the CNY rate and the exchange rate difference, and it is more likely to be impacted by key macroeconomic events. These results suggest that counter-cyclical adjustment by PBoC played an important role in stabilizing the RMB rate.

In regard to economic implications for monetary authorities in China, our results suggest the necessity of continuing liberalization of the RMB rate and deregulation in the CNY market for PBoC. Trading limits, central bank interventions and market regulations offer no help in stabilizing the RMB rate in the long term. On the contrary, these constraints decrease the efficiency and the pricing power of the CNY market in the short term. As for investors who are interested in including RMB currency in their portfolios, our results indicate that short-term speculations are not appropriate, since the short-term CNY-CNH relationship is highly variable and hence is deemed to be not persistent when we take their mid- and long-term relationships as benchmarks.

## CRediT authorship contribution statement

**Shuairu Tian:** Conceptualization, Methodology, Investigation. **Xiang Gao:** Validation, Supervision, Writing – review & editing. **Xiaojing Cai:** Data curation, Visualization, Writing – original draft.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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