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# Time-frequency volatility spillovers between Chinese renminbi onshore and offshore markets during the COVID-19 crisis

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This article investigates the time-frequency volatility spillovers between Chinese renminbi onshore and offshore markets during the COVID-19 crisis. By employing wavelet analysis, we find that: (i) As the timescale increases, the volatility spillovers between renminbi onshore and offshore markets are gradually significant and bidirectional, and they have increased significantly after the COVID-19 outbreak. (ii) The significant volatility spillovers of the two markets are decomposed into many sub-spillovers on different timescales, most possibly precipitated by heterogeneous behaviors across various investment horizons. (iii) During the COVID-19 crisis, the onshore market has the dominant position on price discovery and leads the offshore market.

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## Introduction

China is the world's largest emerging market economy, accounting for more than 15% of global trade (Li, He & Zhou, 2020). On October 1, 2016, China's renminbi joined the Special Drawing Rights (SDR) currency basket with a weighting of 10.92%, becoming the third largest international reserve currency after the US dollar and the euro. This move greatly enhanced the attention and the confidence of renminbi investors in the foreign exchange market, leading to the increasing usage of Chinese renminbi in cross-border trade settlements. By the first quarter of 2020, the proportion of renminbi in the global allocated foreign exchange reserves rose to 2.02%.

The advancement of renminbi internationalization cannot be enhanced without the fundamental supporting role of the renminbi offshore and onshore markets (Ho, Shi & Zhang, 2018). Under the background that the renminbi current account has been liberalized and the renminbi capital account continues to be liberalized, the renminbi offshore and onshore markets are linked and influence each other through various channels, such as in the form of Shanghai and Shenzhen and Hong Kong stock connections and bond northbound connections (Li et al., 2021). On the one hand, the renminbi offshore market is characterized by rich types of market participants, less trading restrictions, and sensitive to market information, thus having a significant impact on onshore market (Ding, Tse & Williams, 2014; Ho, Shi & Zhang, 2018). On the other hand, with its huge stock scale, the onshore market is the "central bank" of the renminbi offshore market, and it has a comparative advantage in reflecting the fundamental information of renminbi, thus affecting the offshore market (Owyong, Wong & Horowitz, 2015). Therefore, exploring the relationship between the renminbi offshore and onshore markets is important for policy formulation in the process of renminbi internationalization and for who was in the dominant position in the price discovery process.

However, on March 11, 2020, the novel coronavirus (COVID-19) was officially declared a worldwide pandemic by the World Health Organization (WHO). The COVID-19 outbreak exacerbates the risk of volatility in the Chinese renminbi exchange rate, as the renminbi is an emerging currency with the nature of a risky asset. In 2020, the central parity rate of renminbi against the US dollar shows a downward and then upward trend, as illustrated by Fig. 1. From December 31, 2019, to May 29, 2020, it shows a depreciation trend with an overall decrease of 2.2%, while it turns to appreciate rapidly between May 29, 2020, and the end of 2020, with a cumulative appreciation of 8.5%. However, due to the sensitivity of the foreign exchange market and its financial risk contagion characteristics, the risk of renminbi onshore exchange rate fluctuations will be transmitted to the offshore market, thereby potentially causing serious systemic risks. Therefore, it is necessary to focus on the volatility spillovers between the renminbi onshore and offshore markets during the COVID-19 crisis.

As a major public emergency, the COVID-19 epidemic can affect the linkages among international financial markets through investor sentiment, cross-market contagion, and real economy feedback. First, a major public emergency can affect the risk expectations and investment sentiments of economic agents (Sun, Bao & Lu, 2021). For example, the occurrence of a major unexpected public event can cause investors to demand a higher risk for risky currencies premiums or chase relatively safe safe-haven currencies. Second, based on the common exposure mechanism, in the event of an external shock from a major unexpected public emergency, investors will speculate on changes in other markets based on changes in one market (Kollias, Papadamou & Arvanitis, 2013). Furthermore, based on the asset allocation adjustment mechanism, different financial markets provide different investors with asset allocation channels to meet different risk averse investors' needs (Liu et al., 2021). Meanwhile, the allocation of assets in different markets can also provide investors with financial asset risk hedging, causing risk spillover effects among financial markets (Liu et al., 2021). Third, some major public emergencies can have a knock-on effect on the real economy, which in turn affects financial markets (Jia, Wen & Lin, 2021). For example, on the supply side, the COVID-19 epidemic was accompanied by mandatory containment policies, such as travel bans and factory closures, which led to a reduction in corporate labor and a decrease in output of goods and services. From the demand side, the containment policies have led to a decline in people's income, a decline in purchasing power, a decline in consumption levels, etc. However, the existing studies have explored the impact of the COVID-19 epidemic on the stock markets, oil markets, bond markets, and cryptocurrency markets,


**Fig. 1** The trend for central parity rate of renminbi against the US dollar in 2020.

few have studied the influence of the COVID-19 epidemic on the foreign exchange markets. Therefore, the objectives of this paper inquire about the following questions.

(1) Will the COVID-19 outbreak increase the volatility spillovers between Chinese renminbi onshore and offshore markets?

(2) During the COVID-19 crisis, who was in the dominant position in the price discovery process? The renminbi offshore market or onshore market?

## Literature review

The literature review mainly involves the following five research fields.

(i) The influence of the COVID-19 outbreak on the international financial markets

The existing studies have explored the impact of the COVID-19 on the stock markets, oil markets, bond markets, and cryptocurrency markets. In terms of the stock market, Zhu et al. (2021) highlighted that there are significant risk spillovers from the US and Chinese stock markets to the oil markets during the COVID-19 outbreak. Ashraf (2020) found that stock markets responded negatively to the growth in COVID-19 new cases by using data from 64 countries. Awadhi et al. (2020) demonstrated that COVID-19 has significant negative effects on all Chinese stock returns for the same period. Phiri, Anyikwa & Moyo (2023) applied wavelet coherence analysis to find co-movements between global COVID-19 indicators and stock returns in major stock markets. Bai et al.(2023) studied that the intensification of the COVID-19 epidemic adversely affects the stock market. Regarding the oil market, Zhang & Hamori (2021) found a significant volatility spillover between the crude oil market and the stock market in the long-term during the COVID-19 pandemic. Heinlein, Legrenzi & Mahadeo (2021) concluded that there were significantly higher correlations between oil and stock markets returns during the COVID-19 outbreak. Abuzayed, Al-Fayoumi (2021) confirmed that the effect of oil price systemic risk on GCC stock market returns was significantly larger during COVID-19 than before the pandemic. Ding, Huang & Wang (2023) found that the crude oil futures RV can significantly affect future stock volatility for each equity index except SSEC, by using a sample of 19 international stock markets. For the bond markets, Papadamou et al. (2020) revealed that the COVID-19 affects the correlation between stock and bond markets. Yi et al. (2021) concluded that the COVID-19 pandemic has significant impacts on China's green bond market and increases the cumulative abnormal return (CAR) of the green bonds greatly. Chen et al. (2021) found that the COVID-19 pandemic has a significant positive impact on the bond market. Wei et al. (2023) highlighted that the COVID-19 pandemic changed the relationship between oil market shocks and the green bond market. In terms of the cryptocurrency markets, Caferra, Vidal-Tomás (2021) confirmed that the COVID-19 caused a short-term impact on co-movements between stock and cryptocurrency markets. Lahmiri & Bekiros (2021) showed that the COVID-19 pandemic significantly affected long memory in return and volatility of international stock and cryptocurrency markets. Salisu & Ogbonna (2021) found that fear-induced news triggered by the COVID-19 pandemic increases the return volatilities of the cryptocurrencies compared with the period before the pandemic. Khalfaoui et al. (2023) showed that the COVID-19 Uncertainty Index has a complex interconnection with the green bond market and the cryptocurrency market.

(ii) The lead-lag relationship between the renminbi onshore and offshore markets

Kou & Kong (2014) used VAR and MA(1)-GARCH(1,1) models to find that the leading effect of the NDF market on the spot exchange rate diminishes after the establishment of the CNH market. Ding, Tse & Williams (2014) studied the linkage mechanism between the renminbi offshore and onshore markets using a VAR model and pointed out that there is a mutual guidance relationship between CNH and CNY. By using the VECM model, Cheung & Rime (2014) concluded that there is a dynamic correlation between the renminbi offshore spot rate and the onshore spot rate, and that the former has a progressively stronger influence on the latter. Owyong, Wong & Horowitz (2015) studied the cointegration and lead-lag effects between offshore and onshore spot and forward markets and found a stronger causal relationship from the spot onshore rate to the spot offshore rate than vice versa. Du (2018) investigated the interaction between CNH, CNY and NDF based on a VAR model and Granger causality test and showed that there is a significant unidirectional guidance effect of both CNY and NDF on CNH. Ho, Shi & Zhang (2018) found that the NDF markets impact the future fluctuations of the spot market, but the spot market does not have predictive power for the volatility of the NDF markets. Wei, Ning & Li (2020) found that after the "811" exchange rate reform, there is a reciprocal lead-lag relationship between the renminbi onshore and offshore markets, that is, a bidirectional payoff spillover relationship. Xu, Hamori & Kinkyo (2021) concluded that after the 2015 reform, the CNH tends to lead the CNY across almost all frequencies, except at the lowest frequency where the CNY leads the CNH.

(iii) The attribution of pricing power to the renminbi exchange rate

Based on the hypothesis that the renminbi onshore market is the center of information in the renminbi offshore market, Deng (2010) found that in the short-term the onshore renminbi market has strong pricing power over the onshore market, but in the long-term the NDF has more of a price guidance advantage. Shi & Sun (2017) concluded that after the "8.11" exchange rate reform, the onshore CNY market has gradually lost its position as the pricing center of the renminbi exchange rate, which may all to the offshore market as the influence of the offshore CNH and NDF on CNY has increased. By using VAR model and DCC-MVGARCH model, Li, Wu & Zhao (2017) found that the renminbi pricing power was owned by CNY market before the exchange rate reform, while it showed phase characteristics after the reform. Li, Liang, & Bu (2017) showed that the offshore market is gradually taking control of spot pricing power since March 2016 based on rolling cointegration traces, and there is a risk that pricing power of onshore spot exchange rate will fall by the wayside. Weng, Ning & Li (2020) showed that after the "8.11" exchange rate reform, pricing power in the offshore market is increasing but not completely lost in the onshore market. Zhong & Deng (2020) suggested that after the countercyclical factor was enabled, the volatility spillover effect of the renminbi onshore market on the offshore market rose, and the influence of the onshore market on the pricing of the renminbi exchange rate rose again.

(iv) Impact of exchange rate reform on the relationship between the renminbi onshore and offshore markets

Based on the DCC-MVGARCH-BEKK model, Ma & Zhang (2018) found that the "8.11" exchange rate reform has increased the volatility spillover effect of the onshore market on the offshore market and weakened that of the latter on the former. Ho, Shi & Zhang (2018) suggested that exchange rate reform and public information flows have a significantly positive impact on the renminbi spot-forward conditional correlations. Li, Liang, & Bu (2017) showed that the recent renminbi market reforms all increase the volatility of the pricing differential between the renminbi onshore and offshore markets. Wan, Yan & Zeng (2020) concluded that the shift in the renminbi exchange rate regime from a pegged exchange rate regime to a managed floating exchange rate regime and the expansion of the floating band strengthen inter-market correlations and spillovers from the offshore market to the onshore market. Ruan et al. (2019) suggested that after the "8.11" reform, the persistent cross-correlation of CNH and CNY markets is stronger in the short-term but weaker in the long-term. Zhong & Deng (2020) showed that the spillover effect of the renminbi onshore market on the offshore market has gradually weakened, while that of the latter on the former has increased after the "8.11" reform. Xu, Hamori & Kinkyo (2021) found that the interdependence between the CNY and CNH has increased significantly following the 2015 reform. Li et al. (2021) compared return and volatility spillover effects between the two markets before and after the "8.11" reform and highlighted that remarkable change has occurred in both the return and volatility spillovers.

(v) Application of wavelet transform to volatility spillover among financial markets

Wavelet analysis can mine financial time series at different trading frequencies without losing information from the time domain dimension (Grinsted et al., 2004; Xu, Hamori & Kinkyo, 2021). It mainly includes four tools: wavelet correlation coefficients, wavelet cross-correlation, cross-wavelet power spectrum, and wavelet coherence spectrum. Wavelet correlation coefficient helps to explain the interrelationship between different financial markets. Jalal & Gopinathan (2023) concluded that exchange rate and geopolitical risks exhibit a stronger relationship than energy prices and economic policy uncertainty at both low and high frequencies of different magnitudes during COVID-19 to the new normal. Gozgor, Khalfaoui & Yarovaya (2023) confirmed that climate uncertainty and supply chain pressure negatively affect commodity markets. Wei et al. (2023) found a positive correlation between supply-driven and demand-driven oil shocks and bond markets at most quantitative levels. The wavelet cross-correlation and wavelet coherence spectrum can reveal the lead-lag relationship between two financial markets. Redin et al. (2018) demonstrated that oil price shocks lead economic activity at low frequencies (long run) in all G-7 countries by using the wavelet coherence spectrum. Tweneboah (2019) stated that in the post-2008 global financial crisis era, zinc emerged as a potential market leader in all small wave scales except the lowest scale. Hong & Li (2020) revealed that the housing market leads the stock market in the long run by using the cross-wavelet power spectrum, supporting the credit price effect. Liu et al. (2023) showed that correlation and the lead-lag relationships between EPU and the macro-financial variables are frequency-dependent and time-varying. The cross-wavelet power spectrum can reveal the co-movement between financial markets in different time-frequency domains. Shahzad, Aloui & Jammazi (2020) provided evidence of a clear heterogeneity in the relationships between credit, stock and volatility markets across various sectors and trading frequencies. Xu, Hamori & Kinkyo (2021) highlighted that the co-movement of CNY and CNH exchange rates increases significantly after the 2015 reform and shows that CNH tends to lead the CNY across almost all frequencies. Cagli & Mandaci (2023) provided the evidence of a low level of uncertainty linkage between cryptocurrencies and other markets. Almaskati (2023) found a significant and strong relationship between oil and GCC forward markets at low frequencies during periods of low oil prices, with the help of wavelet cross wavelets.

To summarize, first, the existing studies have explored the impact of the COVID-19 on the stock markets, oil markets, bond markets, and cryptocurrency markets, few have studied the influence of the COVID-19 on the foreign exchange markets. As mentioned earlier, the COVID-19, as a major public event, can have an impact on the linkages between international financial markets through investor sentiment, cross-market contagion, and real economy feedback. However, as one of the important international financial markets, the renminbi foreign exchange market is also be affected by the COVID-19. For example, the COVID-19 outbreak will trigger market turmoil and investor panic, which leads to a loss of confidence in economic development prospects (Sun, Bao & Lu, 2021). Influenced by this negative sentiment, international capital shorted the renminbi in the short-term, thus exacerbating the correlation between renminbi onshore and offshore markets. Second, the existing studies have examined the linkage between the renminbi onshore and offshore markets from the perspectives of lead-lag relationship, the attribution of exchange rate pricing power, and the impact of exchange rate reform, which has laid the foundation for further understanding the relationship of the two markets, but there are still the following areas to be explored and improved. (i) In Chinese renminbi onshore and offshore markets, investors are operating at various time horizons based on their diverse beliefs, preferences, and objectives as well as heterogeneous expectations and risk tolerance, as suggested by the fractal market hypothesis (Sun, Xiang & Marquez, 2019; Xu, Hamori & Kinkyo, 2021)[1]. That is, the renminbi exchange rate contains different transaction frequency information at the same point and has both time-frequency domain characteristics. However, previous studies have mostly analyzed the dynamic correlations among exchange rates from the time domain perspective, ignoring the rich information and behavioral characteristics on different timescales (frequency domain), which has certain limitations. (ii) Previous studies on the correlation among renminbi exchange rates have mostly used VAR models, Granger causality tests, and GARCH-type volatility models. These methods are limited to describing the linear behavior of financial markets, ignoring the dual characteristics of financial time series in both time and frequency domains, and are not able to fully portray and explain the complexity and highly non-linear characteristics of the renminbi exchange market. However, wavelet analysis is a method that can capture time-frequency domain features of financial time series, considering multi-resolution and time-frequency analysis. It is now widely used to study the volatility spillover among financial markets at different times and frequencies (Grinsted et al., 2004; Xu, Hamori & Kinkyo, 2021; Gozgor, Khalfaoui & Yarovaya, 2023). Furthermore, it can successfully handle non-stationary time series (Xu, Hamori & Kinkyo, 2021). Therefore, we intend to explore the time-frequency volatility spillovers between the renminbi onshore and offshore markets during the COVID-19 crisis by employing wavelet analysis.

The contributions of this article are as follows. First, we find that the volatility spillovers between the renminbi onshore and offshore markets have increased significantly after the COVID-19 outbreak. The prior studies have explored the impact of the COVID-19 on the stock markets, oil markets, bond markets, and cryptocurrency markets, few have studied the influence of the COVID-19 on the renminbi markets. Furthermore, few studies have given empirical evidence of the relationship between the renminbi onshore and offshore markets under significant negative external shocks. Our study takes the COVID-19 pandemic as an external shock to directly test the volatility spillovers between the renminbi onshore and offshore markets during the pandemic, which enriches the relevant literature in this field (Ashraf, 2020; Xu, Hamori & Kinkyo, 2021). Second, focusing on the lead-lag relationship between the two markets, we find that the onshore market has the dominant position on price discovery and leads the offshore market during the COVID-19 crisis, due largely to local information advantages and the central bank's interventions in the renminbi onshore market. The results have meaningful implications for investors, policy makers and other participants in renminbi market. Third, our study provides strong evidence that the significant volatility spillovers of the two markets are decomposed into many sub-spillovers on different timescales (frequencies), most possibly precipitated by heterogeneous behaviors across various investment horizons. The results try to account for non-linear and complex fluctuation characteristics of the two markets from the theory of investor behavior heterogeneity, which provides a new empirical basis for the fractal market hypothesis.

The rest of this paper is organized as follows. "Methodology and data" section discusses methodology and data. "Results" discusses the empirical results. "Conclusions" section concludes the paper.

## Methodology and data

**Methodology**.

(1) Discrete wavelet transform

The father wavelets $\omega(t)$ and mother wavelets $\phi(t)$ make up the basic wavelets. Given a time series $f(t) \in L^2(R)$, the discrete wavelet transforms are

$$a_{J,k}(t) = \int \omega_{J,k}(t) f(t) dt \quad (1)$$

$$d_{j,k}(t) = \int \phi_{J,k}(t) f(t) dt \quad (2)$$

Here, $k$ is a translation parameter and $j = 1, 2, \ldots J$ are the scaling parameters in a $J$-level decomposition. After discrete wavelet decposition, $f(t)$ can be

$$f(t) = A_J + D_J(t) + D_{J-1}(t) + \ldots + D_1(t) \quad (3)$$

where $A_j$ represents a smooth component, and $D_{J,k}, D_{J-1,k}, \ldots, D_{1,k}$ indicate detailed parts.

The wavelet cross-correlation between two time series $X_t$ and $Y_t$ with lag $k$ is

$$R_{X_t,Y_t,v_j}(\pm k) = \frac{\widehat{cov}(X_t, Y_{t\pm k})}{\{var(X_t) var(Y_t)\}^{1/2}} \quad (4)$$

Here, $v_j$ is wavelet scale, and $\widehat{cov}(X_t, Y_{t\pm k})$ denotes the covariance with $k$-lag. $var(X_t)$ and $var(Y_t)$ are the variance of $X_t$ an $Y_t$, respectively.

(2) Continuous wavelet transform[2]

Consider a time series $f(t) \in L^2(R)$, whose continuous wavelet transform (CWT) is

$$W_{f(t)}(u,s) = \int f(t) \frac{1}{\sqrt{s}} \phi^*\left(\frac{t-u}{s}\right) dt \quad (5)$$

Here, $u$ denotes the position, *. is the complex conjugate form, and $s$ represents the scale.

The CWT can be used to analyze power spectrum while preserving the characteristics of time series, and the variance (power) is

$$\|f(t)^2\| = \frac{1}{C_\phi} \int_0^\infty \left[ \int_{-\infty}^{+\infty} \left| W_{f(t)}(u,s) \right|^2 du \right] \frac{ds}{s^2} \quad (6)$$

Following Torrence & Compo (1998), the cross-wavelet transform between $X_t$ and $Y_t$ is

$$W_{X_t,Y_t}(u,s) = W_{X_t}(u,s) W^*_{Y_t}(u,s) \quad (7)$$

Further, the cross-wavelet power (wavelet coherence) is

$$R^2(u,s) = \frac{\left| S\left(s^{-1} W_{X_t,Y_t}(u,s)\right) \right|^2}{\left| S\left(s^{-1} W_{X_t}(u,s)\right) \right|^2 \left| S\left(s^{-1} W_{Y_t}(u,s)\right) \right|^2} \quad (8)$$

**Table 1 Descriptive statistics of the CNY and NDF logarithmic returns.**

| | CNY | NDF |
|---|---|---|
| Observation | 2061 | 2061 |
| Mean | 0.000013 | 0.000022 |
| Median | 0.000000 | 0.000000 |
| Standard deviation | 0.002171 | 0.00278 |
| Minimum | −0.01436 | −0.01847 |
| Maximum | 0.018197 | 0.036527 |
| Sum | 0.025922 | 0.045538 |
| Skewness | 0.391450 | 1.264385 |
| kurtosis | 12.508410 | 24.57706 |
| Jarque-Bera statistic | 7816.588*** | 40,529.92*** |
| ADF unit-root test | −44.747210*** | −33.511450*** |
| Pearson correlation coefficient | 0.7927840*** | |

*** indicates the 1% significance level.

where $R^2(u, s)$ is a squared correlation located in time and frequency.

Following Bloomfield et al. (2004), the phase difference[3] is defined as

$$\tau_{X_t,Y_t}(u,s) = tan^{-1}\left( \frac{I\left\{ S\left(s^{-1} W_{X_t,Y_t}(u,s)\right) \right\}}{R\left\{ S\left(s^{-1} W_{X_t,Y_t}(u,s)\right) \right\}} \right) \quad (9)$$

where $I$ and $R$ are the imaginary and real parts, respectively. The relationships of $\tau_{X_t,Y_t}$, $X_t$ and $Y_t$ are as follows: (i) $\tau_{X_t,Y_t} = 0$, $X_t$ and $Y_t$ move in-phase; $\tau_{X_t,Y_t} = \pi$ or $-\pi$, $X_t$ and $Y_t$ have anti-phase relationship; (ii) $\tau_{X_t,Y_t} \in \left\{\frac{\pi}{2}, \pi\right\}$ or $\tau_{X_t,Y_t} \in \left\{-\frac{\pi}{2}, 0\right\}$. $Y_t$ leads $X_t$ (iii) $\tau_{X_t,Y_t} \in \left\{0, \frac{\pi}{2}\right\}$ or $\tau_{X_t,Y_t} \in \left\{-\pi, -\frac{\pi}{2}\right\}$, $X_t$ leads $Y_t$.

**Data**. We select the renminbi against the dr spot exchange rate (denoted as CNY) to represent the Chinese renminbi onshore market. Following Li, Liu & Li (2021) and Jia et al. (2021), we use the closing price of one-year offshore renminon-liverable forward (NDF) to characterize the renminbi offshore market.[4] All data are derived from the Wind database (http://www.wind.com.cn) and the sample period is from May 1, 2012, to April 30, 2021. After some data filtering, logarithmic return series of CNY and NDF with the length of 2061 are both obtained by using the formula $R_{i,t} = \ln P_{i,t} - \ln P_{i-1,t}$.

Descriptive statistics are reported in Table 1. Both return series are skewed with excess kurtosis. The Jarque-Bera statistics indicate that the distributions of the two series are asymmetric and leptokurtic, that is, their distribution is non-normal. The Augmented Dickey-Fuller (ADF) unit-root test results show that the return series are stationary. The Pearson correlation coefficient is 0.7927840 and statistically significant, suggesting a significant positive correlation between the two series.

## Results

**Multi-resolution analysis of volatility spillovers between renminbi onshore and offshore markets based on discrete wavelet transform**. This study employs the maximal overlap discrete wavelet transform (MODWT) to decompose CNY and NDF with Daubechies filter of length 8 (Hong & Li, 2020), as illustrated by Figs. 2 and 3.[5] $S$ represents the original logarithmic return series. $A6$ denotes smooth signals and their trend. $Di$ ($i = 1, 2, 3, 4, 5, 6$) are detailed components, corresponding to timescales (frequencies) of $2^i$ to$2^{i+1}$ days. To explore the impact of the COVID-19 on the volatility spillovers between two markets, we divide our sample period into two sub-periods: the

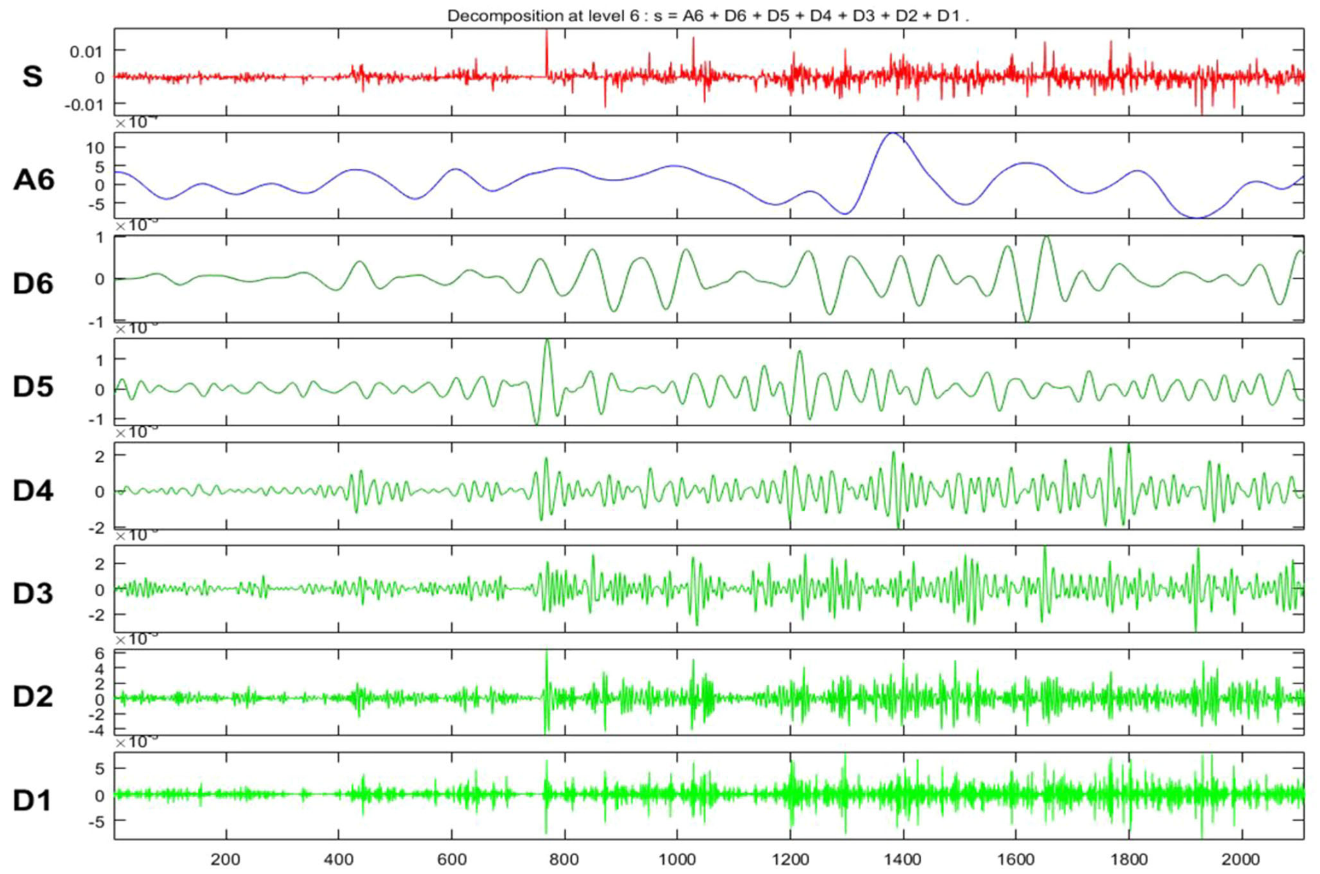


**Fig. 2** Wavelet decomposition of CNY.

pre-COVID-19 period (May 1, 2012–January 22, 2020) and the post-COVID-19 period (January 23, 2020–April 30, 2021).[6]

*The volatility spillovers before the COVID-19 outbreak*. Figures 4 and 5 illustrates the wavelet correlation coefficients and wavelet cross-correlation for the pre-COVID-19 period, respectively. In Fig. 4, the coefficient starts at around 0.68817 in the timescale *D*1 (2–4 days) and increases, and nearly touches 0.93291 at the longest timescale *D*6 (64–128 days). This suggests that as the timescale increases, the volatility spillovers between renminbi onshore and offshore markets are gradually significant. That is, the linkages between the two markets increase as the investment horizon (timescale) is prolonged. Therefore, we infer that, the benefits of portfolio diversification appear to be greater in the short-term horizon but diminish in the higher or long-term horizon. Meanwhile, in the short-term, market specific or idiosyncratic factors are important for investors in renminbi onshore and offshore markets (Jena, Tiwari & Roubaud, 2018).

In Fig. 5, on the timescales *D*1, *D*2, *D*3, the absolute values of the wavelet cross-correlation with greater lag days are closing to zero, suggesting that there are no clear volatility spillovers between CNY and NDF. On the timescale *D*4, there are relatively significant spillovers. On the timescales *D*5, *D*6, the coefficients are all greater than 0.5 within lag days ±5, signifying the strong volatility spillovers between CNY and NDF. Therefore, we conclude that as the timescale increases, the renminbi onshore and offshore markets gradually show bidirectional volatility spillovers. This may be that with a series of market-oriented reforms of renminbi exchange rate formation mechanism, such as "8.11" exchange reform in 2015, the capital liquidity and market maturity of renminbi onshore market have been improved, and the speed of information flow between the two markets has been accelerated (Peng & Kang, 2020), thus making the bidirectional spillover effect between CNY and NDF more apparent in the long run. Our results support the viewpoints of Li, Liu & Li (2021) that there is a bidirectional spillover relationship between the renminbi onshore and offshore market after the "811" exchange rate reform.

Furthermore, from Fig. 5, on the timescales *D*1, *D*2, *D*3, *D*4, *D*5, there exists no obvious lead-lag relationship between CNY and NDF, illustrated by the symmetric characteristic of the curves. On the timescale *D*6 (64–128 days), the curve gravitates toward the right, signifying CNY has higher contributions to price discovery and then leads NDF. The results basically support the viewpoints of Owyong, Wong & Horowitz (2015) there is a stronger causal relationship from the renminbi spot onshore rate to the renminbi offshore rate than vice versa. However, those are different from the conclusion of Ho, Shi & Zhang (2018) that the renminbi spot market does not have predictive power for the volatility of the NDF markets and different from the viewpoints of Shi & Sun (2017) that the onshore CNY market has gradually lost its position as the pricing center of the renminbi exchange rate, which may all to the offshore market as the influence of the offshore NDF on CNY has increased. A possible reason for the difference with the arguments of Ho, Shi & Zhang (2018) and Shi & Sun (2017) is that they only explore the relationship between the onshore and offshore markets in the time domain, while our study considers both the time-frequency domain characteristics of the renminbi exchange rate.

*The volatility spillovers after the COVID-19 outbreak*. Figures 6 and 7 represent the wavelet correlation coefficients and wavelet cross-correlation for the post-COVID-19 period, respectively. In Fig. 6, wavelet correlation coefficients are high at all timescales. It starts with a correlation coefficient of 0.87347 in the timescale *D*1

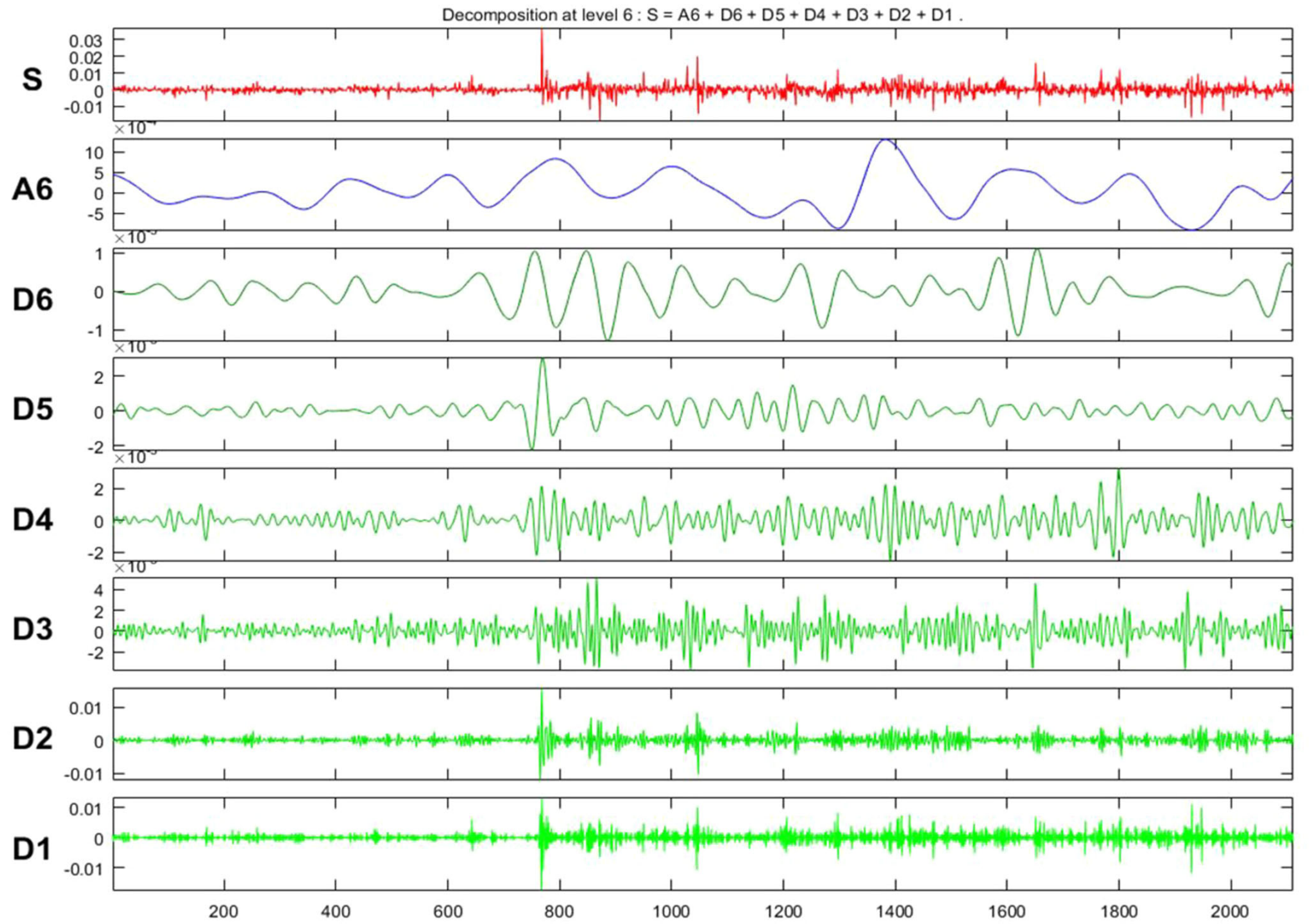


**Fig. 3** Wavelet decomposition of NDF.

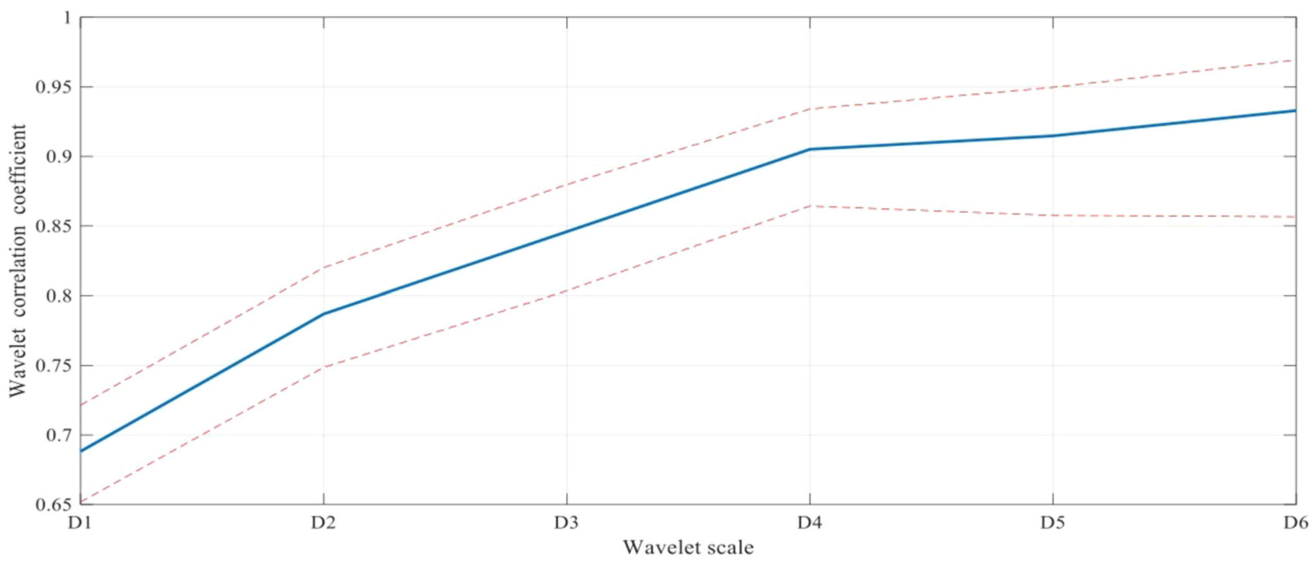


**Fig. 4 Wavelet correlation coefficients between CNY and NDF (01/05/2012–22/01/2020).** Notes: The dotted red lines designated the lower and upper bounds at a 95% confidence interval. The same as Fig. 6 below.

(2–4 days) and increases to 0.94164 at the longest timescale $D6$ (64–128 days). Thus, the trend of increasing correlation coefficients with an increasing timescale after the COVID-19 outbreak is consistent with that before the outbreak, but the coefficient values of the former are significantly larger than those of the latter. Thus, we conclude that the COVID-19 outbreak increases the volatility spillovers between renminbi onshore and offshore markets. The possible reasons are as follows. First, the COVID-19 outbreak triggered market turmoil and investor panic, which leads to a loss of confidence in economic development prospects

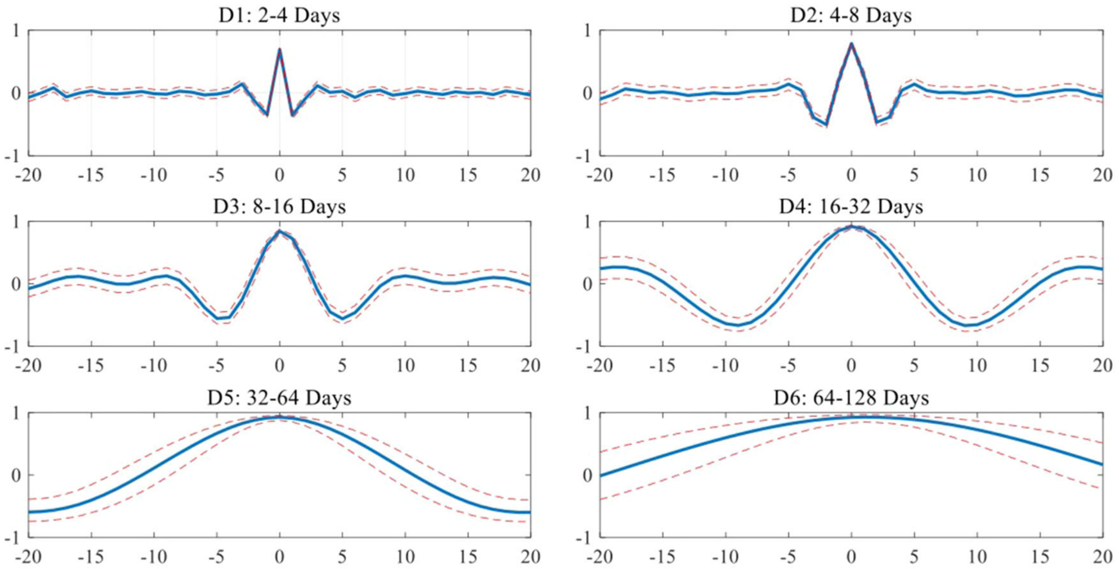


**Fig. 5 Wavelet cross-correlation between CNY and NDF at different lag days and timescales (01/05/2012–22/01/2020).** Among them $R(-k)$ (or $R(k)$) represent the influence degree of the $k$-day lag of NDF (or CNY) on CNY (or NDF). The lower and upper bounds of the 95% confidence interval are indicated by the dotted red lines. The same as Fig. 7 below.

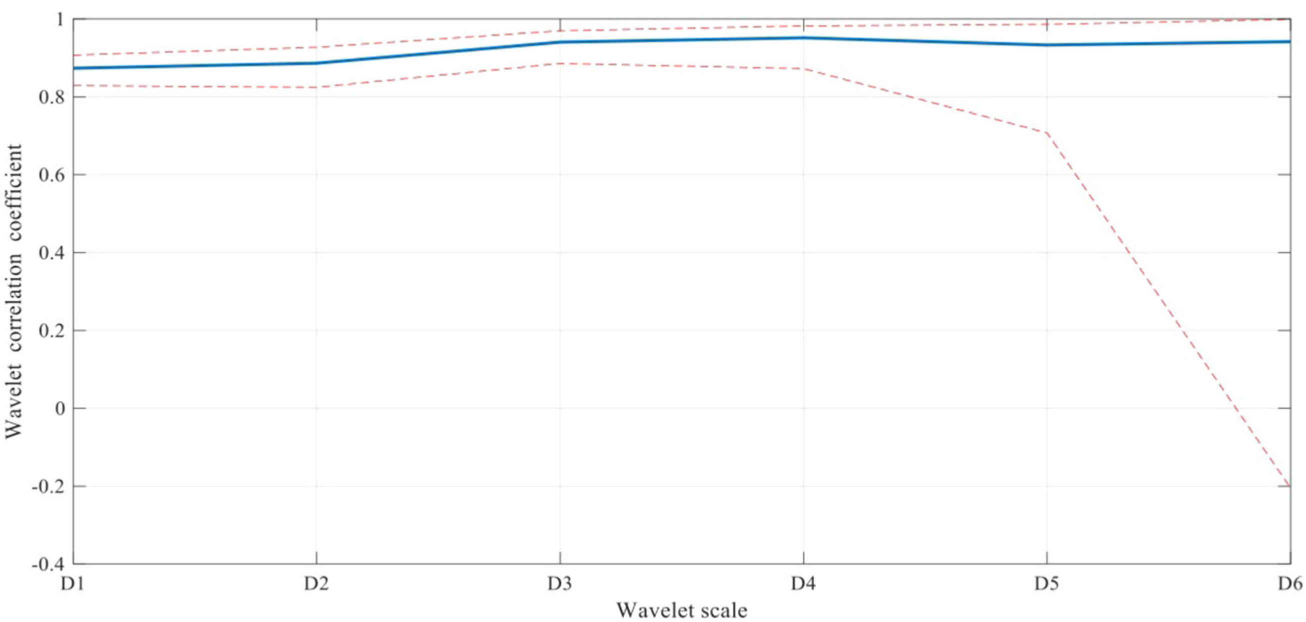


**Fig. 6** Wavelet correlation coefficients between CNY and NDF (23/01/2020–30/04/2021).

(Sun, Bao & Lu, 2021). Influenced by this negative sentiment, international capital shorted the renminbi in the short-term, thus exacerbating the correlation between renminbi onshore and offshore markets. Second, with the aggravation of the COVID-19, the motive of foreign exchange investors to hedge the risk of exchange rate fluctuations becomes more obvious. Thus, they may take cross-market arbitrage behavior, position adjustment, hedging, and other strategies, which further accelerate the transmission of information volatility between the offshore and onshore markets, making the two markets show more significant volatility spillovers (Liu et al., 2021). Third, the COVID-19 epidemic will impact the real economy from both the supply side and the demand side, leading to a reduction in corporate labor, consumer income, purchasing power, etc. And these will have an impact on various aspects of the balance of payments, which in turn will affect the expectations of exchange rate appreciation and depreciation. However, these will lead to an increase in the risk of volatility in the renminbi exchange rate and an increase in demand from investors in the renminbi market for hedging and speculation, thus increasing the volatility spillover between the renminbi onshore and offshore markets.

From Fig. 7, we find that as the timescale increases from $D1$ to $D6$, the value of wavelet cross-correlation within lag days ±5 increases significantly, reflecting the bidirectional nature of the volatility spillovers between renminbi onshore and offshore markets, similar to the pre-COVID-19 period. However, on the timescale $D5$ (32–64 days), the amplitudes are greater on the right side of the curves, demonstrating that CNY guides NDF, which is different from the pre-COVID-19 period. Therefore, we argue that during the COVID-19 crisis, the renminbi onshore market has the potential to

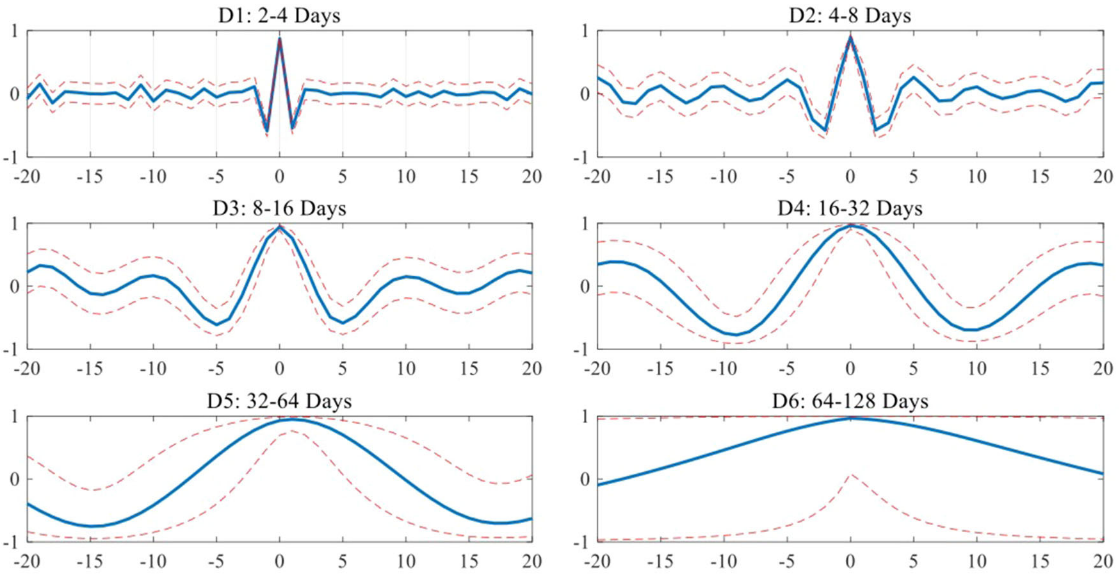


**Fig. 7** Wavelet cross-correlation between CNY and NDF at different lag days and timescales (23/01/2020–30/04/2021).

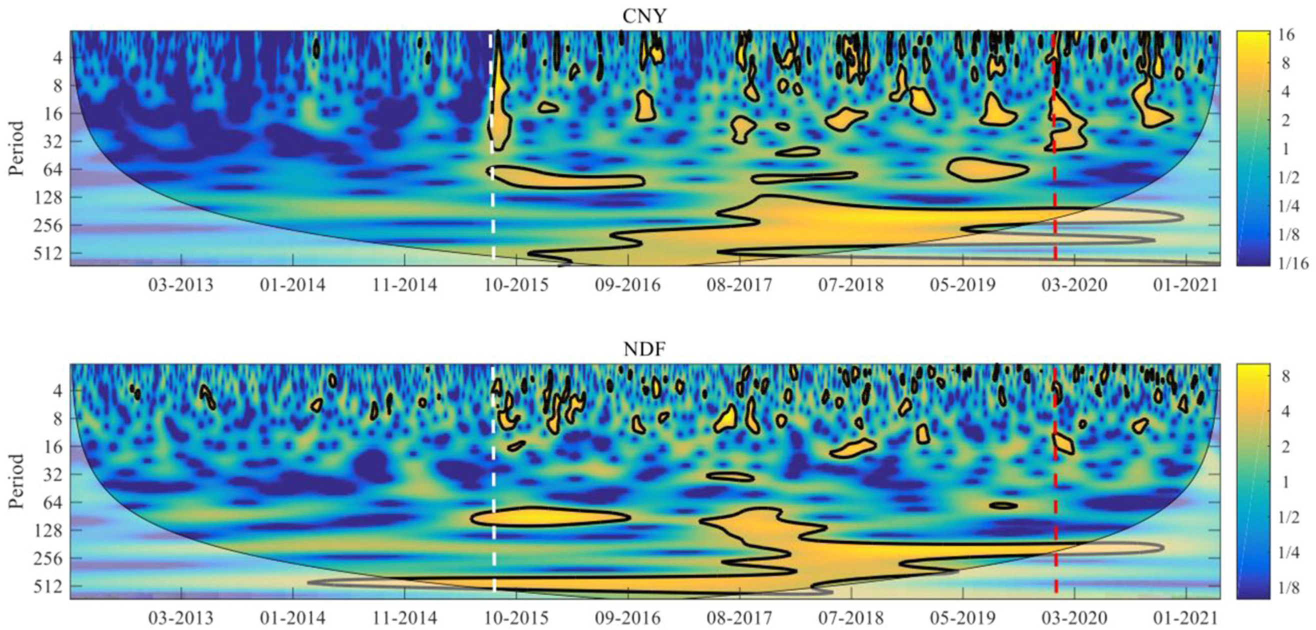


**Fig. 8 Wavelet power spectrum of CNY and NDF.** Notes: The vertical axis indicated represents the timescale (frequency), and the horizontal axis represents the time period. The thin black curve refers to the cone of influence (COI), suggesting that the area is influenced by edge effects. The color bar on the right of the spectrum changes from deep blue to deep yellow, implying that the power goes from low to high. The vertical white line indicated August 11, 2015, as the dividing line for China's "8.11" exchange reform. The vertical red line is a reference for the start of the COVID-19 outbreak.

serve as a leader for price discovery on the timescale of 32–64 days. This suggests that during the COVID-19 crisis, short- to medium-term investors should pay more attention to the onshore market information, as this market plays the advantage of local information and leads the offshore market at this time.

**Time-frequency analysis of volatility spillovers between renminbi onshore and offshore markets based on continuous wavelet transform**. Figure 8 depicts the wavelet power spectrum of CNY and NDF. In Fig. 8, CNY shows significantly high power on the timescale of 2–48 days and 64–128 days after China's "8.11" exchange reform[7], indicating short- and medium-term investors dominate in the renminbi onshore market. This is because that the Chinese central bank announced a surprise devaluation of the renminbi by 1.86% on August 11, 2015 (referred to as "8.11"). This exchange rate reform is a beneficial attempt to change the renminbi into a free-floating exchange rate, and attracts a wider range of short-term investors. Furthermore, significant high power is also observed on a timescale of 16–48 days after the COVID-19 outbreak, suggesting that the renminbi onshore market is flooded with short-term investors. This is possibly because that the COVID-19 outbreak exacerbated market panic, causing

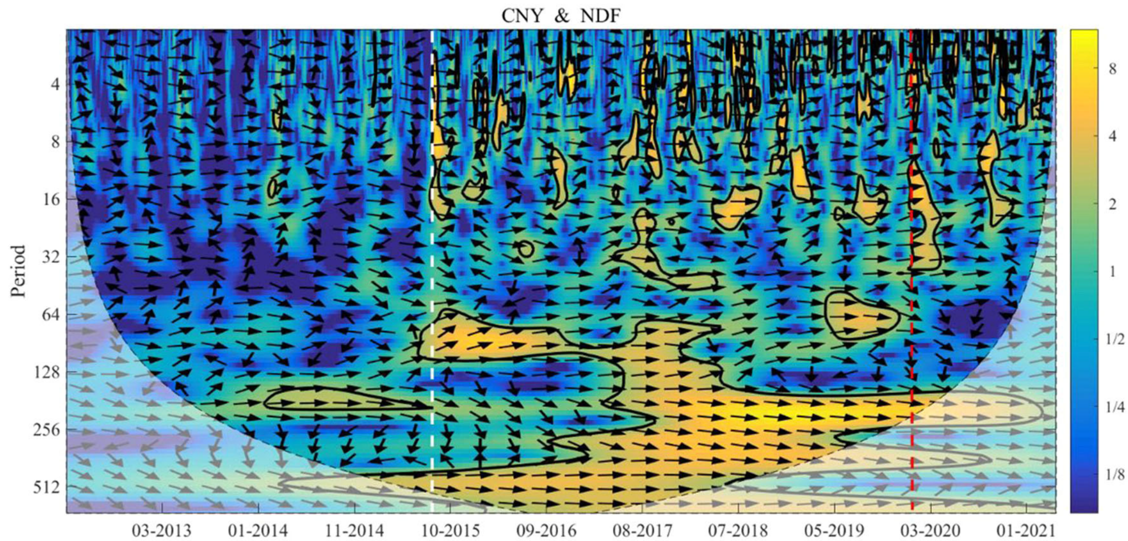


**Fig. 9 Cross-wavelet power spectrum between CNY and NDF.** Notes: The thick black contour (marking the yellow areas in the figure) represents the 5% significance level estimated by the Monte Carlo simulations, suggesting significant co-movements between CNY and NDF. The vertical white line indicates August 11, 2015, as the dividing line for China's "8.11" exchange reform. The vertical red line is a reference for the start of the COVID-19 outbreak. The remaining annotations are the same as Fig. 8.

more short-term investors to hedge exchange rate risks in the renminbi onshore market.

In Fig. 8, the wavelet power spectrum of NDF shows that there exist massive high-power areas distributed over different time-scales, demonstrating a clear separation among short-term, medium-term, and long-term investors in the renminbi offshore market (Hong & Li, 2020). From May 2015 to September 30, 2016, we find massive high-power areas on a timescale of 64–128 days, but it narrows significantly after September 21, 2016, suggesting the decline of the medium-term or long-term investors' enthusiasm (Hong & Li, 2020). Furthermore, high-power areas are also observed on a timescale of 12–24 days after the COVID-19 outbreak, indicating short-term investors are dominant in the renminbi offshore market during the COVID-19 crisis. This may be due to the fact that the COVID-19 outbreak increased the risk of exchange rate volatility, thus triggering more short-term investors in the renminbi offshore market to hedge against risks.

Figure 9 depicts the cross-wavelet power spectrum between CNY and NDF. In Fig. 9, there are many yellow areas marked by thick black contour, indicating that the significant volatility spillovers between renminbi onshore and offshore markets are decomposed into many sub-spillovers on different timescales (frequencies) and time periods. This is possibly because that there are a large number of investors with operating at various time horizons ranging from seconds to several years in renminbi onshore and offshore markets. Therefore, mostly due to the heterogeneity of the multiple investors interacting in these markets, the volatility spillovers between CNY and NDF may vary across over time and frequency. In Fig. 9, the yellow areas are more pronounced after August 11, 2015[8], suggesting the volatility spillovers between renminbi onshore and offshore markets have increased significantly after "8.11" exchange reform. The above result supports the arguments of Li, Liu & Li (2021) that China's "8.11" exchange reform strengthens cross-market correlations and information flows between renminbi onshore and offshore markets. The possible reasons are as follows. First, after the "8.11" exchange reform, the Chinese central bank has relaxed its direct management of the renminbi exchange rate, while the exchange rate formation mechanism has become more transparent and in line with market expectations, and the pricing function of the renminbi onshore market has become increasingly visible (Li, Wu & Zhao, 2017). Thus, this can increase the volatility spillover from the onshore market to the offshore market. Second, after the "8.11" exchange rate reform, due to the lack of sufficient communication between the central bank and the market, it failed to stabilize market expectations in a timely manner, resulting in uncertainty and even panic among the public, and frequent international capital flows in the Hong Kong renminbi offshore market, leading to increased volatility spillover between the onshore and offshore markets (Zhong & Deng, 2020).

In Fig. 9, on a timescale of 0–32 days, the cross-wavelet power spectrum of CNY and NDF is filled with blue color during September 2019-December 2019, i.e., before the COVID-19 outbreak, indicating that the volatility spillovers between the two markets are not significant at this time. However, multiple yellow areas can be observed after the COVID-19 outbreak. This suggests that volatility spillovers between the renminbi onshore and offshore markets have increased significantly after the COVID-19 outbreak, which is consistent with these in Fig. 6 and also reflects the robustness of the results. Specifically, three significant high-degree co-movements (yellow areas) between CNY and NDF across various time periods and frequencies can be identified.

- For the January 2020 and March 2020 periods across the 8–32 days timescale.
- An 8–16 days timescale between October 2020 and December 2020.
- For December 2020 to February 2021 period across the 0–8 days timescale.

Figure 10 presents the wavelet coherence spectrum between CNY and NDF. In Fig. 10, from August 11, 2015, to August 2017, the arrows are mostly ↗ and occasionally ↖ or ↘ on a timescale of 0–32 days (high frequency), prevalently ↗ on a timescale of 32–128 days (medium-frequency), and mostly ↘ on a timescale of 128–256 days (low frequency). This suggests that after the "8.11" exchange reform, the two markets are staggering to guide each other in the short-term (high frequency). And the renminbi

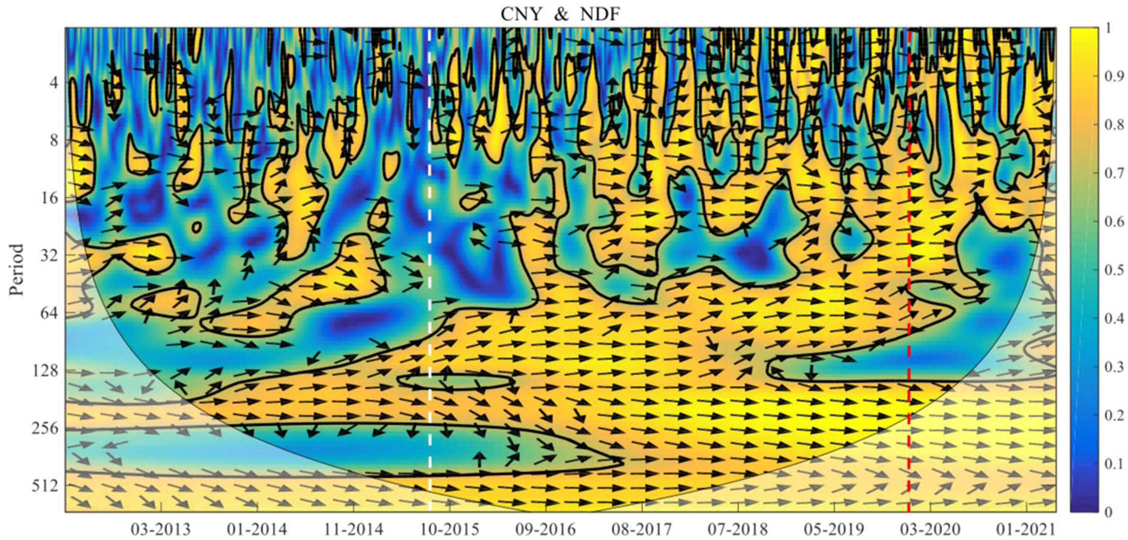


**Fig. 10 Wavelet coherence spectrum between CNY and NDF.** Notes: The arrows indicate the phase difference between CNY and NDF. (ii) The arrow points to the right (left), indicating that the two exchange rates exhibit and in-phase (anti-phase) relationship. The arrow points to the right (left), indicating that the two exchange rates exhibit and in-phase (anti-phase) relationship. The arrow pointing to the upper right (↗) or the lower left (↙) provides evidence that CNY guides NDF, while the arrow pointing to the lower right (↘) or the upper left (↖) means that NDF leads CNY. The vertical white line indicates August 11, 2015, as the dividing line for China's "8.11" exchange reform. The vertical red line is a reference for the start of the COVID-19 outbreak. The remaining annotations are the same as Fig. 8.

onshore market leads the offshore market in the medium-term, while the latter guides the former in the long-term (low frequency). However, between January 2014 and August 2015, the arrows in Fig. 10 dominate ↘ on a timescale of 32–64 days, indicating that NDF leads CNY in the medium-term before the "8.11" exchange reform. Therefore, combining the above, we argue that the "8.11" reform has improved the short- and medium-term price discovery capabilities of the renminbi onshore market. The possible reasons are as follows. After the "8.11" exchange reform, the capital liquidity and market maturity of the renminbi onshore market have been improved (Li, Wu & Zhao, 2017). Hence, the onshore market may reflect more market information than before and thus can lead the offshore market in the short- and medium-term. However, the renminbi offshore market is relatively more market-oriented and less regulated, and thus more sensitive to domestic and international economic factors and can better reflect long-term market performances. Therefore, it has higher contributions to price discovery and leads the onshore market in the long-term. The above results are consistent with the viewpoints of Li, Liu & Li (2021) that "8.11" reform increase the relative importance of the renminbi onshore market, but different from the conclusions of Xu, Hamori & Kinkyo (2021) that the renminbi offshore market tends to lead the onshore market across almost all frequencies after the "8.11" exchange reform.

In Fig. 10, before the COVID-19 outbreak, for example, from August 2017 to January 2020, the arrows mostly point to →, indicating an in-phase relationship between CNY and NDF. It may be that CNY and NDF are more susceptible to common endogenous or exogenous factors, such as China's macroeconomic fundamentals and the interest rate hike of the Federal Reserve. However, after the COVID-19 outbreak, the arrows mostly point ↗, especially on timescales of 4–64 days, indicating that the renminbi onshore market has the dominant position on price discovery and leads the offshore market, which is following the conclusion from Fig. 7 and also reflects the robustness of the results. The possible reasons are as follows. The trading scale of the renminbi onshore market is larger than that of the offshore market, and the former has a comparative advantage in reflecting the fundamental and local information of the renminbi. Meanwhile, after the "8.11" exchange reform in 2015, the liquidity and pricing power of the renminbi onshore market has been continuously improved. However, during the COVID-19 crisis, the market was flooded with panic and investment incentives. Thus, the renminbi onshore market, with its local information advantage and the central bank's interventions, acts as an "anchor" to the offshore market. Therefore, the renminbi onshore market has the potential to serve as a leader for price discovery during the COVID-19 crisis.

In Fig. 10, as the timescale increases from 0 to 256 days, the color of wavelet coherence spectrum gradually varies from blue-yellow interlace to all-yellow. This provides strong evidence that with the increase of the timescales, the volatility spillovers between the two exchange rates are gradually significant, which is consistent with the conclusion from Fig. 3. This also reflects the robustness of the results in this paper.

## Conclusions

This paper investigates the time-frequency volatility spillovers between Chinese renminbi onshore and offshore markets during the COVID-19 crisis. The study reveals that: (i) Regardless of whether it is in the COVID-19 crisis or not, the volatility spillovers between renminbi onshore and offshore markets are gradually significant and bidirectional as the timescale increases. These suggest that the benefits of portfolio diversification appear to be greater in the short-term horizon but diminish in the higher or long-term horizon. (ii) The significant volatility spillovers of the two markets are decomposed into many sub-spillovers on different timescales, mostly due to the heterogeneity of the multiple investors' behaviors across various investment horizons. (iii) The volatility spillovers between the two markets have increased significantly after China's "8.11" exchange rate reform and the COVID-19 outbreak. Possible reasons for this are as follows. First, the "8.11" exchange rate reform may strengthen cross-market correlations and information flows (Li, Liu & Li, 2021). Second, the COVID-19 outbreak may affect the volatility spillovers between the renminbi onshore and offshore markets through investor sentiment, cross-market contagion, and real economy feedback. (iv) After the "8.11" exchange reform, the renminbi onshore and offshore markets are staggering to guide each other in the short-term. And the renminbi onshore market leads the offshore market in the medium-term, while the latter guides the former in the long-term. Furthermore, the "8.11" reform has improved the short- and medium-term price discovery capabilities of the renminbi onshore market. The result is consistent with the viewpoints of Li, Liu & Li (2021) that "8.11" reform increase the relative importance of the renminbi onshore market, but different from the conclusions of Xu, Hamori & Kinkyo (2021) that the renminbi offshore market tends to lead the onshore market across almost all frequencies after the "8.11" exchange reform. (v) During the COVID-19 crisis, the renminbi onshore market has higher contributions to price discovery and guides the offshore market, due largely to local information advantages and the central bank's interventions in the renminbi onshore market.

Our findings have meaningful implications, as follows. First, the wavelet correlations appear to increase with timescale, so there are more potential gains of portfolio diversification for investors at short-term timescales. Second, the renminbi onshore and offshore markets have different lead-lag relationships over different trading cycles. Therefore, for investors and hedgers, instead of determining the lead-lag relationship of prices based on the original sample, they should focus on the analysis of the spillover pattern on the trading cycle of their own preferences in order to make sound decisions. Third, as the renminbi onshore market leads the offshore market during the COVID-19 crisis, investors should pay more attention to the information changes in the onshore market. Fourth, although the "8.11" reform has improved the short- and medium-term price discovery capabilities of the renminbi onshore market, the renminbi onshore exchange rate formation mechanism still needs further market-oriented reforms to improve its long-term price discovery abilities. Fifth, for the regulators, they should formulate corresponding trading rules according to the decision-making tendencies and preferences of trading subjects to ensure the normal and stable operation of the renminbi market. For example, investors should be cultivated to think rationally about investment and increase the holding period for the purpose of preserving and increasing value, reduce the short-term trading caused by speculative factors, and increase the cultivation of institutional investors.

There are some deficiencies in this paper, which can be solved in the future study. In this paper, we use only the renminbi against the US dollar spot exchange rate (denoted as CNY) and the one-year offshore renminbi non-deliverable forward (NDF) to measure the Chinese renminbi onshore and offshore markets, respectively, and explore the volatility spillover effects between these two markets accordingly. However, the renminbi offshore exchange rate also includes other products such as the offshore spot exchange rate and the offshore deliverable forward exchange rate. Due to the substitution effect, there is also a price interaction between these offshore products, but these factors are not considered in this paper. Thus, future research may combine these factors to investigate the relationship between renminbi onshore and offshore markets. Additionally, in order to promote renminbi internationalization, it is also worth further studying the linkage between the renminbi foreign exchange markets and other international financial markets.

## Data availability

The data supporting the findings from this study are available at https://doi.org/10.7910/DVN/W3TO3B.

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## Notes

1 For example, some investors (such as money market funds) focus on short-term investments (hours, days) while the others (such as pension funds) prefer to making medium-term or long-term investments (from several months to yearly horizon) (Sun, Xiang & Marquez, 2019).
2 This study uses the MatLab software wavelet package developed by Grinsted, Moore & Jevrejeva (2004) to perform the cross-wavelet transform and wavelet coherence (http://www.pol.ac.uk/home/research/waveletcoherence/).
3 The phase difference can reflect the lead-lag relationship between time series, namely which one is dominant in the price discovery process.
4 There are two reasons for this practice. First, since the NDF market is highly market-based and not under the direct jurisdiction of local monetary authorities, the NDF exchange rate can reflect rational expectations of renminbi exchange rate fluctuations in international financial markets (Li, Liu & Li, 2021, Jia et al., 2021). Second, although the Hong Kong offshore (CNH) market has traded offshore deliverable forwards (DF) products in recent years, the NDF product has been a dominant vehicle in the offshore market for a long time. And it has experienced different renminbi exchange rate regimes and major events, which is an experience that CNH derivatives do not have.
5 Figs. 2 and 3 show the wavelet decomposition under the full sample, just to help understand smooth signals and detailed components. To save space, four wavelet decomposition plots under subsamples are not shown in this paper.
6 FollowingNammouri, Chlibi & Labidi (2021), we choose the start date of the COVID-19 outbreak as the date of the first confirmed case reported by the WHO.
7 On August 11, 2015, the People's Bank of China (PBoC) declared a devaluation of the central parity rate of renminbi by 1.86%, which is referred to as China's "8.11" exchange reform.
8 For example, the timescale of 4-16 days between August 11, 2015, and September 15, 2015, the timescale of 64–128 days observed between August 11, 2015, and July 2018, and so on.

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## Author contributions
LW: Conceptualization, design of suitable methodology, investigation, data analysis, reviewing and revising it critically for important intellectual content, and final approval of the version to be published. YX and QC: validation, methodology, editing, supervision, and writing-original draft. All authors substantially contributed to the article and approved the submitted version.

## Competing interests
The authors declare no competing interests.

## Ethical approval
Not applicable as this study did not involve human participants.

## Informed consent
This article does not contain any studies with human participants performed by any of the authors.

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