



Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.



International stock market risk contagion during the COVID-19 pandemic

Yuntong Liu^a, Yu Wei^{a,*}, Qian Wang^a, Yi Liu^b

^a School of Finance, Yunnan University of Finance and Economics, Kunming, Yunnan, China

^b Faculty of Transportation Engineering, Kunming University of Science and Technology, Kunming, Yunnan, China

ARTICLE INFO

JEL classification:

G01
G15
G23
F02
F36
F42

Keywords:

Risk contagion
COVID-19 pandemic
Spillover
International stock markets

ABSTRACT

This paper examines the risk contagion among international stock markets during the COVID-19 pandemic by using the realized volatility information from sixteen major stock markets in the world. The empirical evidence based on the connectedness methods of Diebold and Yilmaz (2012) and Baruník and Krehlík (2018) shows that the COVID-19 epidemic significantly increases the risk contagion effects in international stock markets. Besides, the risk spillovers from stock markets in European and American regions increase rapidly but those in Asian markets decrease obviously after the outbreak of COVID-19 pandemic. Finally, the risk contagion among international stock markets caused by the pandemic can last for about 6 to 8 months. These results provide important implications regarding to financial risk management and macroprudential design.

1. Introduction

The COVID-19 pandemic deeply affects global economy activities (Janiak et al., 2021; Tisdell, 2020; Yang et al., 2021). Governments have released many precautionary measures (such as city lockdown, flight ban and work suspension) to prevent the further spread of the COVID-19 epidemic, which result in heavy global economy recession and huge fluctuations in international stock markets (Contessi and De Pace, 2021; Frezza et al., 2021), as well as stronger market risk contagion (spillover effects) among them (Davidovic, 2021; Wei et al., 2019).

Recent studies about the impacts of the COVID-19 epidemic on financial contagion have been very popular (Bai et al., 2020, 2021; Goodell, 2020; Liang et al., 2021, 2020a). Several researchers (Akhtaruzzaman et al., 2021; Bouri et al., 2021; Corbet et al., 2020; Gharib et al., 2021; Le et al., 2021) find that the correlations among various financial markets increase significantly during the COVID-19 pandemic. For example, Guo et al. (2021) indicate that the COVID-19 epidemic enlarges contagion channels in the international financial system. Li et al. (2021b) use the causal forest and complex network methods to analyze the characteristics of industry risk contagion before and after the pandemic. Contessi and De Pace (2021) find the evidence of instable transmission from the Chinese stock market to other stock markets. Sharif et al. (2020) employ wavelet method and unveil the unprecedented impact of COVID-19 on the geopolitical risk, economic policy uncertainty and stock market volatility over the low frequency bands. Davidovic (2021) indicates international financial markets are more integrated and risk contagion increases during the pandemic. Fassas (2020)

* Corresponding author at: 237 Longquan Road, Kunming, Yunnan, China.
E-mail address: weiyusy@126.com (Y. Wei).

investigates the dynamic connectedness of variance risk premium among developed and emerging stock markets and calculates the total investors' risk aversion connectedness.

Investigating the international risk contagion is of great importance for international investors to allocate their portfolios and for policy makers to propose relevant policies (Bai et al., 2019; Coroneo et al., 2020; Daly et al., 2019; Gkillas et al., 2019; Li and Wei, 2018; Li et al., 2021a; Park and Shin, 2020; Wang et al., 2021). However, there are few researches focusing on the risk contagion effects among international stock markets during the COVID-19 epidemic by using the realized volatility (RV) information in these markets.

For highly liquid stocks, using RV as market risk measurement has clear advantages. First of all, RV is a nonparametric estimator of intraday price fluctuations (Nielsen and Shephard, 2002), and it is very easy to calculate and free from functional form assumptions. Secondly, the distribution of daily logarithm RV appears to be very close to normal distribution, which means that it meets most of assumptions in risk analyzing models (e.g., GARCH-type or HAR-type volatility models). Thirdly, RV measurement ignores the overnight variations in stock price and sometimes the variations in the first few minutes of the trading day when recorded prices may contain large errors (Liang et al., 2020b, 2019; Ma et al., 2018; Wei et al., 2020, 2021). Thus, based on the connectedness methods of Diebold and Yilmaz (2012) and Baruník and Křehlík (2018), this paper aims to explore the risk contagion effects across international stock markets by utilizing the RV measurements released by Oxford-Man Institute of Quantitative Finance, and provide some implications relative to financial risk management.

2. Methodology

2.1. Spillover analysis in time domain

To analyze the risk spillover effect among different stock markets, this paper firstly employs the connectedness method proposed by Diebold and Yilmaz (2012), hereafter labelled as DY method. This approach is based on a forecast generalized variance decomposition (FGVD) process in vector auto-regression (VAR) models, and it can not only measure the spillover index in time domain but also identify the risk contagion direction of this spillover index. The method starts from a covariance stationary N -variate generalized VAR framework with lag p :

$$Y_t = \phi_1 Y_{t-1} + \phi_2 Y_{t-2} + \dots + \phi_p Y_{t-p} + \varepsilon_t, \tag{1}$$

where $Y_t = (Y_{1t}, Y_{2t}, \dots, Y_{Nt})$ represent volatilities in various stock markets $1, 2, \dots, N$. ϕ_i is the i th coefficient matrix, $\varepsilon_t \sim N(0, \Sigma_\varepsilon)$ is white noise with possibly non-diagonal covariance matrix Σ_ε . Assuming that Y_t is a covariance stationary process, which means that the roots of $|\phi_i|, i = 1, 2, \dots, p$ are outside the unit circle. This VAR(p) can be organized as the following vector moving average representation:

$$Y_t = \varepsilon_t + M_1 \varepsilon_{t-1} + M_2 \varepsilon_{t-2} + \dots + M_\infty \varepsilon_{t-\infty}, \tag{2}$$

where $M_h = \phi_1 M_{h-1} + \phi_2 M_{h-2} + \dots + \phi_p M_{h-p}, i = 1, 2, \dots, \infty$ is in a recursive form. I is N -dimensional unit matrix. Eq. (2) can measure contribution of market y_k to the forecast error variance of y_j at $h = 1, 2, \dots, H$ horizons.

DY method decomposing the forecast error variance of Eq. (2) is based on the researches of Koop et al. (1996); Pesaran and Shin (1998), which are invariant to variable ordering. The proportion of the forecast error variance in forecasting y_j due to shocks from market y_k at H -horizon is $(\Theta_H)_{j,k}$. When $j \neq k$, $(\Theta_H)_{j,k}$ denotes the pairwise directional spillover from market k to j , and it can be computed as

$$(\Theta_H)_{j,k} = \frac{\sigma_{kk}^{-1} \sum_{h=0}^{H-1} ((M_h \Sigma_\varepsilon)_{j,k})^2}{\sum_{h=0}^{H-1} (M_h \Sigma_\varepsilon M_h')_{j,j}}, \tag{3}$$

where $\sigma_{kk} = (\Sigma)_{kk}$ is the standard error of the k th equation in VAR framework, M_h is an $N \times N$ matrix of moving average coefficients with lag h . Σ_ε is the non-diagonal covariance matrix of VAR error term ε_t . Based on $(\Theta_H)_{j,k}$, the standardized pairwise spillover from market k to j is

$$(\Theta'_H)_{j,k} = (\Theta_H)_{j,k} / \sum_k (\Theta_H)_{j,k}. \tag{4}$$

Furthermore, the total volatility spillover index is constructed as

$$S_H = 100 \frac{\sum_{j \neq k} (\Theta'_H)_{j,k}}{\sum (\Theta_H)_{j,k}} = 100 \left(1 - \frac{Tr\{\Theta'_H\}}{N} \right), \tag{5}$$

where $Tr\{\bullet\}$ indicates the trace operator. The total spillover index measures the contribution of spillovers of volatility shocks across all markets to the total forecast error variance. Additionally, the directional spillover received by market j from all other markets k is defined as

$$S_{H,j \leftarrow \bullet} = 100 \frac{\sum_{k,k \neq j} (\Theta'_H)_{j,k}}{\sum (\Theta_H)_{j,k}} = 100 \frac{\sum_{k,k \neq j} (\Theta'_H)_{j,k}}{N}. \tag{6}$$

Table 1
Stock markets and corresponding stock indexes.

| Continent | Region | RegionSymbol | Exchange Name | IndexSymbol | Index Name |
|-----------|---------------|--------------|------------------------------------|-------------|-----------------------------------|
| Europe | England | UK | LSE Group | FTSE | FTSE 100 |
| | Eurozone | EURO | Euronext | STOXX50E | EURO STOXX 50 |
| | Norway | NOR | Euronext Oslo | OSEAX | Oslo Exchange All Share Index |
| | Germany | DEU | Deutsche Boerse AG | GDAXI | DAX |
| | Spain | ESP | BME Spanish Exchanges | IBEX | IBEX 35 Index |
| | Swiss | CHE | SIX Swiss Exchange | SSMI | Swiss Stock Market Index |
| Asia | Australia | AUS | ASX Australian Securities Exchange | AORD | All Ordinaries |
| | China | CHN | Shanghai Stock Exchange | SSEC | Shanghai Composite Index |
| | Hong Kong | HK | Hong Kong Exchanges and Clearing | HSI | HANG SENG Index |
| | India | IND | National Stock Exchange of India | NSEI | NIFTY 50 |
| | Korea | KOR | Korea Exchange | KS11 | Korea Composite Stock Price Index |
| | Japan | JPN | Japan Exchange Group | N225 | Nikkei 225 |
| America | Brazil | BRA | Brasil Bolsa Balcão | BVSP | BVSP BOVESPA Index |
| | Canada | CAN | TMX Group | GSPTSE | S&P/TSX Composite Index |
| | United States | US | New York Stock Exchange | SPX | S&P 500 |
| | Mexico | MEX | Bolsa Mexicana de Valores | MXX | IPC Mexico |

Notes: According to the World Federation of Exchange market capitalization, the summation capitalization of these sixteen stock markets accounts for almost 70% global stock market capitalization.

Similarly, the directional spillover transmitted by market j to all other markets k is

$$S_{H,\bullet \leftarrow j} = 100 \frac{\sum_{k,k \neq j} (\Theta'_H)_{k,j}}{\sum (\Theta_H)_{k,j}} = 100 \frac{\sum_{k,k \neq j} (\Theta'_H)_{k,j}}{N} \tag{7}$$

In addition, to measure the net directional spillover of market j , we can simply calculate the difference between Eq. (6) and Eq. (7) as

$$S_{H,j} = S_{H,\bullet \leftarrow j} - S_{H,j \leftarrow \bullet} \tag{8}$$

2.2. Spillover analysis in frequency domain

In order to analyze the risk spillovers in different time horizons, Baruník and Křehlík (2018) further develop a frequency response function based on DY method (hereafter labelled as BK method). By applying Fourier transformation on the impulse response M_i , we can get $(f(\omega))_{j,k}$, which is the ratio of the spectrum of j th market at frequency ω ($\omega \in (-\pi, \pi)$) due to shocks in k th market, and the equation is shown as follows:

$$(f(\omega))_{j,k} \equiv \frac{\sigma_{kk}^{-1} |(M(e^{-i\omega})\Sigma)_{j,k}|^2}{(M(e^{-i\omega})\Sigma M'(e^{+i\omega}))_{j,j}} \tag{9}$$

In order to apply the forecast error variance decomposition for different frequencies, $(f(\omega))_{j,k}$ needs to be weighted by the frequency share of variance of the j th market. The weighting function is defined as

$$\Gamma_j(\omega) = \frac{(M(e^{-i\omega})\Sigma M'(e^{+i\omega}))_{j,j}}{\frac{1}{2\pi} \int_{-\pi}^{\pi} (M(e^{-i\lambda})\Sigma M'(e^{+i\lambda}))_{j,j} d\lambda} \tag{10}$$

which indicates the power of j th market at a given frequency over the sum through frequencies in the frequency band $(-\pi, \pi)$. Therefore, the FEVD on the frequency band $h = (a, b)$, $a, b \in (-\pi, \pi)$ and $a < b$ is

$$(\Theta_h)_{j,k} = \frac{1}{2\pi} \int_h \Gamma_j(\omega) (f(\omega))_{j,k} d\omega \tag{11}$$

When $h \rightarrow \infty$, $(\Theta_\infty)_{j,k}$ is equal to $(\Theta_h)_{j,k}$ in time domain, Eq. (11) can be transformed as

$$(\Theta_\infty)_{j,k} = \frac{1}{2\pi} \int_{-\pi}^{\pi} \Gamma_j(\omega) (f(\omega))_{j,k} d\omega \tag{12}$$

So the GFEVD on the frequency band $h = (a, b)$, $a, b \in (-\pi, \pi)$ and $a < b$ can be further standardized as

$$\left(\tilde{\Theta}_h \right)_{j,k} = (\Theta_h)_{j,k} / \sum_k (\Theta_\infty)_{j,k} \tag{13}$$

$(\tilde{\Theta}_h)_{j,k}$ measures the spillover from market k to market j in frequency band h . Then, the frequency spillover effect on the frequency band

Table 2
Descriptive Statistics.

| Region | Market | Mean | Std. Dev. | Skewness | Kurtosis | Jarque-Bera | ADF | Q(5) | Q(10) | Q(20) |
|---------|-----------|----------|-----------|----------|----------|----------------|------------|-----------|------------|-------------|
| Europe | England | 1.64E-04 | 4.81E-04 | 9.39 | 113.491 | 170,095.45*** | -11.833*** | 293.23*** | 397.85*** | 425.072*** |
| | Eurozone | 1.59E-04 | 3.87E-04 | 6.324 | 48.983 | 30,798.549*** | -7.752*** | 585.17*** | 757.50*** | 781.755*** |
| | Norway | 2.01E-04 | 1.14E-03 | 15.674 | 266.102 | 950,701.314*** | -16.23*** | 42.20*** | 53.11*** | 54.419*** |
| | Germany | 1.16E-04 | 2.29E-04 | 5.470 | 37.124 | 17,388.94*** | -6.374*** | 767.33*** | 1002.06*** | 1033.941*** |
| | Spain | 1.50E-04 | 3.35E-04 | 8.546 | 93.877 | 115,791.278*** | -6.728*** | 416.56*** | 482.50*** | 487.059*** |
| | Swiss | 1.20E-04 | 4.32E-04 | 8.693 | 92.762 | 113,202.074*** | -10.62*** | 390.62*** | 482.46*** | 493.388*** |
| Asia | Australia | 1.08E-04 | 3.28E-04 | 8.67 | 100.972 | 134,050.596*** | -9.406*** | 400.51*** | 544.55*** | 560.272*** |
| | China | 7.70E-05 | 8.72E-05 | 3.469 | 18.976 | 4108.360*** | -9.481*** | 260.57*** | 340.28*** | 376.466*** |
| | Hong Kong | 7.03E-05 | 1.43E-04 | 13.427 | 211.115 | 596,276.977*** | -13.846*** | 75.94*** | 79.46*** | 80.874*** |
| | India | 1.36E-04 | 5.81E-04 | 13.007 | 197.692 | 522,461.149*** | -13.23*** | 145.51*** | 166.81*** | 169.225*** |
| | Korea | 9.02E-05 | 2.01E-04 | 8.873 | 96.466 | 122,563.015*** | -10.655*** | 387.17*** | 423.40*** | 426.621*** |
| | Japan | 7.79E-05 | 2.46E-04 | 11.72 | 172.191 | 395,079.245*** | -11.515*** | 224.48*** | 289.76*** | 297.167*** |
| America | Brazil | 1.64E-04 | 4.10E-04 | 6.451 | 51.048 | 33,516.874*** | -6.663*** | 568.33*** | 749.57*** | 818.095*** |
| | Canada | 7.92E-05 | 2.77E-04 | 8.645 | 97.608 | 125,256.361*** | -9.933*** | 460.26*** | 589.49*** | 601.777*** |
| | America | 1.32E-04 | 3.88E-04 | 6.466 | 52.373 | 35,275.144*** | -7.486*** | 585.60*** | 787.64*** | 805.063*** |
| | Mexico | 7.90E-05 | 9.53E-05 | 5.957 | 58.792 | 44,073.449*** | -12.091*** | 272.71*** | 473.82*** | 603.242*** |

Notes: *, ** and *** denote rejections of the null hypothesis at the 10%, 5% and 1% significance levels, respectively. The Jarque-Bera statistic is used to test the null hypothesis of the normal distribution. Q(5), Q(10) and Q(20) are the Ljung-Box Q statistics with lag order of 5, 10 and 20, respectively. ADF refers to the statistics from the augmented Dickey-Fuller unit root tests. This table calculated based on the entire sample period span from 24 January 2019 to 30 December 2020.

Table 3
International stock market spillovers estimated by DY method.

| Overall spillover | REGION | Before pandemic 64.7 | | | After pandemic 88.2 | | |
|-------------------|--------|-------------------------|-------------|--------------|------------------------|-------------|--------------|
| | | FROM | TO | NET | FROM | TO | NET |
| Europe | UK | 3.99 | 4.36 | 0.367 | 5.42 | 6.36 | 0.945 |
| | EURO | 4.79 | 8.21 | 3.42 | 5.45 | 10.3 | 4.82 |
| | NOR | 4.06 | 2.51 | -1.55 | 5.11 | 4.99 | -0.122 |
| | DEU | <u>4.89</u> | 5.65 | 0.752 | 5.49 | 9.33 | 3.84 |
| | ESP | 4.21 | 2.73 | -1.48 | 5.52 | 7.95 | 2.43 |
| Asia | CHE | 4.85 | 6.61 | 1.76 | 5.44 | 8.17 | 2.73 |
| | AUS | 4.76 | 1.62 | <u>-3.15</u> | 5.74 | 6.22 | 0.481 |
| | CHN | 2.91 | 2.06 | -0.855 | 3.98 | 0.171 | -3.81 |
| | HK | 4.06 | 3.57 | -0.482 | 6.15 | 0.373 | -5.78 |
| | IND | 2.56 | 1.37 | -1.19 | <u>6.22</u> | 0.095 | <u>-6.12</u> |
| America | KOR | 3.99 | 4.39 | 0.400 | 5.94 | 0.712 | -5.22 |
| | JPN | 4.11 | 2.87 | -1.24 | 6.02 | 2.79 | -3.23 |
| | BRA | 2.91 | 1.10 | -1.81 | 5.61 | 5.89 | 0.285 |
| | CAN | 4.52 | 7.53 | 3.01 | 5.49 | 9.93 | 4.44 |
| | US | 4.69 | 6.78 | 2.10 | 5.47 | 9.79 | 4.32 |
| | MEX | 3.44 | 3.39 | -0.050 | 5.14 | 5.14 | -0.002 |

Notes: This table reports both on the pre- and post- COVID-19 sub-samples stock markets' risk spillover based on DY method. The 'FROM' column provides directional spillover from all others to market j. The 'TO' column provides directional spillover to all others from market k. The 'Overall spillover' is the sum of directional spillover. The bold figure highlights the biggest risk contributor or transmitter, and underlined figure indicate the biggest risk receiver.

h can be defined as

$$C_h^f = 100 \left(\frac{\sum_{j \neq k} \left(\tilde{\Theta}_h \right)_{j,k} - Tr \left(\tilde{\Theta}_h \right)}{\left(\tilde{\Theta}_h \right)_{j,k}} \right) = 100 \left(1 - \frac{Tr \left(\tilde{\Theta}_h \right)}{N} \right). \tag{14}$$

In a similar way, we can calculate the directional spillover and net spillover in the same way indicated in Eqs. (6)-(8).

3. Data

The 5-min realized volatilities (RV5) data in our analysis are obtained from Oxford-Man Institute of Quantitative Finance, which are also commonly used in recent researches (Liang et al., 2020b, 2019; Ma et al., 2018; Wei et al., 2020, 2021). The dataset spans from 24th January 2019 to 30th December 2020, with a total 326 daily observations. The dataset is divided equally into two parts by the date of 13th January 2020, when the first cross-border coronavirus transmission of infection was reported by the World Health Organization, and both pre- and post-epidemic sub-datasets have 163 observations. Table 1 exhibits some representative regions (classified by continents) with their respective stock exchanges and indices labels. The summation of market capitalization of these regions accounts for almost 70% global stock market value, and the chosen regions incorporates both developed and developing stock markets across the three continents.

Table 2 presents the descriptive statistics of RV5 for all the stock indices. The results show that all the stock RV5 series are stationary, right-skewed, leptokurtic and non-normally distributed. The Q-statistics suggest significant autocorrelation within 5-, 10- and 20-day lags in these time series.

4. Empirical results

In this section, we present estimation results from the DY and BK methods, based on both pre- and post-COVID-19 epidemic sub-samples, with a focus on the risk spillover in international stock markets and its changes in different time horizons during the COVID-19 pandemic.

4.1. International spillover effects in time domain

According to Akaike information criterion (Chen et al., 2020; Tao et al., 2018; Wei et al., 2010), we choose lag of 2 for pre-pandemic sub-sample and lag of 1 for post-pandemic sub-sample in the VAR estimations. Table 3 reports the results from the DY method.

Table 3 presents several interesting results. Firstly, the overall stock markets' risk spillover effect leaps from 64.7% to 88.2% after the outbreak of COVID-19 pandemic. This significant increase indicates that international stock markets is more integrated and risk contagion is easier to transfer among different markets. Secondly, from the 'TO' column, we find that the outbreak of COVID-19 enhances the risk spillover of European and American regions but reduces those of most Asian regions. Before the COVID-19

Table 4
Short term stock markets spillover (Weekly).

| Overall spillover | REGION | Before epidemic | | | After epidemic | | |
|-------------------|--------|-----------------|-------------|--------------|----------------|-------------|--------------|
| | | FROM | TO | NET | FROM | TO | NET |
| | | 27.6 | | | 39.3 | | |
| Europe | UK | 1.27 | 0.66 | -0.62 | 1.63 | 3.84 | 2.21 |
| | EURO | 1.25 | 7.20 | 5.95 | 1.08 | 3.73 | 2.65 |
| | NOR | 2.04 | 0.77 | -1.27 | 2.94 | 7.77 | 4.83 |
| | DEU | 1.35 | 3.41 | 2.06 | 2.14 | 1.85 | -0.290 |
| | ESP | 2.72 | 0.45 | -2.27 | 2.57 | 0.426 | -2.14 |
| | CHE | 1.08 | 2.87 | 1.79 | 1.04 | 10.2 | 9.21 |
| Asia | AUS | <u>4.07</u> | 0.901 | <u>-3.17</u> | 3.05 | 0.140 | -2.91 |
| | CHN | <u>0.787</u> | 0.699 | -0.088 | 2.49 | 0.032 | -2.46 |
| | HK | 1.77 | 2.00 | 0.236 | <u>3.81</u> | 0.143 | <u>-3.68</u> |
| | IND | 1.31 | 0.185 | -1.12 | 3.32 | 0.060 | -3.26 |
| | KOR | 2.25 | 1.57 | -0.675 | 3.63 | 0.380 | -3.25 |
| | JPN | 2.24 | 0.962 | -1.28 | 2.90 | 0.270 | -2.63 |
| America | BRA | 1.31 | 0.850 | -0.461 | 1.99 | 1.36 | -0.631 |
| | CAN | 1.59 | 2.97 | 1.38 | 1.92 | 6.33 | 4.41 |
| | US | 1.30 | 1.33 | 0.032 | 1.99 | 2.38 | 0.389 |
| | MEX | 1.28 | 0.781 | -0.498 | 2.75 | 0.314 | -2.44 |

Notes: This table reports both on pre- and post- epidemic sub-samples stock markets' risk connectedness based on BK method. The 'FROM' column provides directional connectedness or spillover from all others markets to markets j. The 'TO' column provides directional spillover to all others markets from market k. The overall spillover is the sum of directional spillover. The bold figures highlight the biggest risk contributor or transmitter, and underlined figures indicate the biggest risk receiver.

Table 5
Medium term stock markets spillover (Monthly).

| Overall spillover | REGION | Before epidemic | | | After epidemic | | |
|-------------------|--------|-----------------|-------------|---------------|----------------|-------------|--------------|
| | | FROM | TO | NET | FROM | TO | NET |
| | | 11.4 | | | 22.7 | | |
| Europe | UK | 0.748 | 0.317 | -0.432 | 0.972 | 5.94 | 4.97 |
| | EURO | 0.770 | 1.19 | 0.424 | 1.70 | 2.27 | 0.569 |
| | NOR | 0.974 | 0.083 | -0.892 | 1.02 | 1.19 | 0.169 |
| | DEU | 0.850 | 0.917 | 0.067 | 1.71 | 0.901 | -0.808 |
| | ESP | 0.553 | 0.146 | -0.407 | <u>1.88</u> | 0.137 | <u>-1.75</u> |
| | CHE | 0.685 | 1.77 | 1.08 | 0.931 | 5.52 | 4.59 |
| Asia | AUS | 0.731 | 0.197 | -0.534 | 1.45 | 0.155 | -1.29 |
| | CHN | 0.649 | 0.533 | -0.116 | 1.43 | 0.075 | -1.36 |
| | HK | 0.420 | 0.696 | 0.276 | 1.43 | 0.117 | -1.31 |
| | IND | 0.375 | 0.080 | -0.295 | 1.46 | 0.049 | -1.41 |
| | KOR | 0.905 | 1.40 | 0.490 | 1.10 | 0.577 | -0.523 |
| | JPN | 0.692 | 0.678 | -0.014 | 1.55 | 0.173 | -1.38 |
| America | BRA | <u>1.04</u> | 0.372 | <u>-0.666</u> | 1.58 | 1.86 | 0.283 |
| | CAN | <u>0.724</u> | 1.94 | 1.22 | 1.55 | 1.83 | 0.280 |
| | US | 0.863 | 0.614 | -0.249 | 1.65 | 1.69 | 0.040 |
| | MEX | 0.410 | 0.459 | 0.048 | 1.29 | 0.211 | -1.07 |

Notes: This table reports both on pre- and post- epidemic sub-samples stock markets' risk connectedness based on BK method. The 'FROM' column provides directional connectedness or spillover from all others markets to markets j. The 'TO' column provides directional spillover to all others markets from market k. The overall spillover is the sum of directional spillover. The bold figures highlight the biggest risk contributor or transmitter, and underlined figures indicate the biggest risk receiver.

pandemic, the Eurozone, US, Canada, Swiss and Germany, are major contributors of risk spillover with almost 34.8% share (sum of the 'TO' column values in these regions). After the pandemic, the contribution share of these regions increases to 47.5%. On the contrary, the total spillover share of all Asian regions except for Australia decreases from 15.9% before pandemic to 10.4% after that. In terms of risk spillover received from others (the 'FROM' column results), the situations are similar among the regions. All the stock markets receive more risk spillovers from others comparing to the cases before the pandemic. In specific, India is the most affected country as it receives the largest proportion of spillover among all regions. Thirdly, the 'NET' column of Table 3 exhibits that Eurozone is the biggest net risk transmitter in both pre- and post- pandemic periods with transmission shares of 3.42% and 4.82%, respectively. While, Asian regions, especially India and Hong Kong, are major net risk receivers. The biggest net risk receiver changes from Australia with 3.15% to India and Hong Kong with 6.12% and 5.78%, respectively after the pandemic. Other Asian countries, such as China and Korea, also receive more risk spillover shares than before.

Table 6
Long-term stock markets spillover (Longer than one month).

| Overall spillover | REGION | Before epidemic | | | After epidemic | | |
|-------------------|--------|-----------------|-------------|---------------|----------------|-------------|--------------|
| | | FROM | TO | NET | FROM | TO | NET |
| | | 7.09 | | | 23.2 | | |
| Europe | UK | 0.434 | 0.215 | -0.219 | 1.14 | 7.42 | 6.29 |
| | EURO | 0.532 | 0.505 | -0.027 | <u>2.12</u> | 1.87 | -0.246 |
| | NOR | 0.637 | 0.026 | <u>-0.611</u> | 0.713 | 0.928 | 0.215 |
| | DEU | 0.595 | 0.365 | -0.230 | 2.02 | 1.07 | -0.946 |
| | ESP | 0.327 | 0.071 | -0.257 | 1.62 | 0.083 | <u>-1.54</u> |
| | CHE | 0.475 | 1.22 | 0.748 | 1.12 | 5.66 | 4.55 |
| Asia | AUS | 0.282 | 0.102 | -0.180 | 1.56 | 0.193 | -1.36 |
| | CHN | 0.673 | 0.538 | -0.134 | 0.771 | 0.095 | -0.675 |
| | HK | 0.237 | 0.619 | 0.382 | 0.913 | 0.069 | -0.844 |
| | IND | 0.226 | 0.058 | -0.168 | 1.42 | 0.053 | -1.37 |
| | KOR | 0.450 | 1.09 | 0.644 | 1.21 | 0.688 | -0.523 |
| | JPN | 0.395 | 0.341 | -0.054 | 1.64 | 0.181 | -1.46 |
| America | BRA | <u>0.676</u> | 0.192 | -0.484 | 1.86 | 2.20 | 0.340 |
| | CAN | <u>0.412</u> | 1.25 | 0.843 | 1.97 | 0.675 | -1.29 |
| | US | 0.544 | 0.258 | -0.286 | 1.94 | 1.82 | -0.121 |
| | MEX | 0.197 | 0.232 | 0.035 | 1.17 | 0.154 | -1.02 |

Notes: This table reports both on pre- and post- epidemic sub-samples stock markets' risk connectedness based on BK method. The 'FROM' column provides directional connectedness or spillover from all others markets to markets j. The 'TO' column provides directional spillover to all others markets from market k. The overall spillover is the sum of directional spillover. The bold figures highlight the biggest risk contributor or transmitter, and underlined figures indicate the biggest risk receiver.

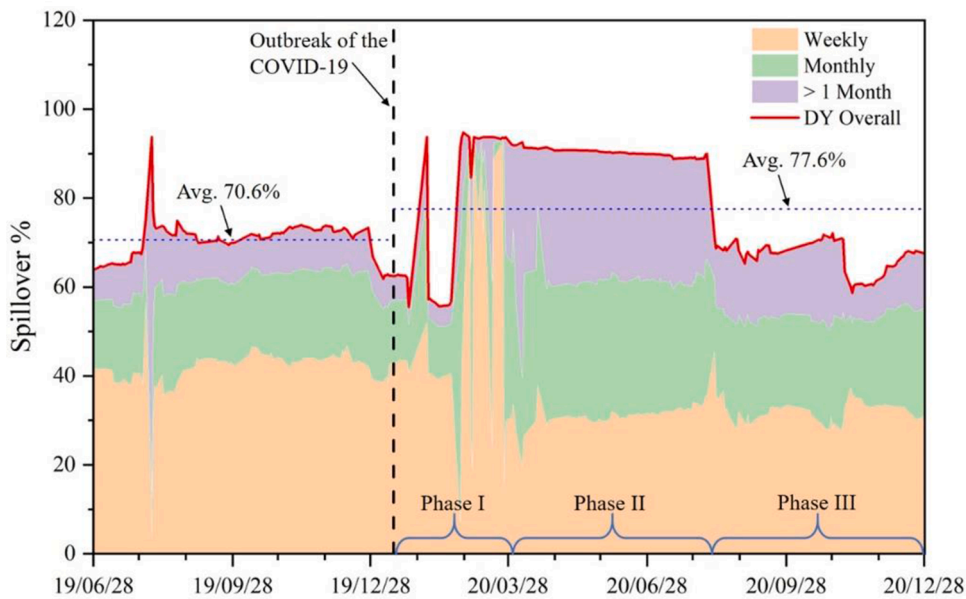


Fig. 1. Dynamic overall spillover based on rolling-window size of 70 days.

4.2. International spillover effects in frequency domain

For policy makers, international investors and speculators, they are more likely interested in the risk contagion effects in different time horizons (Liu et al., 2020; Zhang et al., 2019). To investigate the spillover changes in different time frequencies, we extend our analysis further by using BK method. Tables 4, 5, 6 exhibit risk spillover estimates in a framework of frequency domains.

We find that the results from BK method are consistent with those from DY method. On the one hand, the overall spillover effects among international stock markets increase significantly for all time frequencies after the pandemic. The total spillover effects increase sharply from 27.6% to 39.2% in short-term, 11.4% to 22.7% in medium-term and 7.09% to 23.2% in long-term. These results reveal that the COVID-19 pandemic has deep impacts on stock markets worldwide, and these influences of the pandemic may last for months or even years. On the other hand, similar to the DY results, we also find that the total spillover share from Asian countries falls quickly after the COVID-19 pandemic in all time frequencies.

At short term frequency, Swiss and Norway replace the Eurozone and become the top two risk contributors in the post-COVID-19

period with a spillover shares of 10.2% and 7.77%, respectively. While the major risk receivers are still in Asian regions, such as Hong Kong and Korea. However, the situation has changed in the medium- and long-term cases. At medium- and long-term frequencies, Canada is the dominant risk contributor and Brazil is the biggest risk receiver before the COVID-19 pandemic. After the pandemic, UK turns to the largest risk contributor, and the Eurozone, Germany, Canada and the US become the major four risk receivers. Moreover, the ‘NET’ results show that the largest net risk transmitter is Swiss with 9.21% spillover share after the pandemic at short-term frequency. While UK becomes the biggest net risk transmitter over the medium-term and long-term horizons, which is in line with the finding of ‘TO’ results of Tables 4, 5, 6. Asian countries are still the main net risk receivers for all time frequencies, further confirming the results from DY method in Section 4.1. In addition, the change of regions’ transmission direction is irregular for these regions (signs of ‘NET’ column values are not fixed), indicating that the net risk spillover transmitters and receivers are unexpected, and the impacts of the COVID-19 pandemic on risk spillovers in international stock markets change rapidly.

4.3. Dynamic spillover effects in time and frequency domains

The analyses on pre- and post-pandemic sub-samples in Section 4.1 and 4.2 only offer us the static pictures for risk spillovers in international stock market. In this section, we further investigate the dynamic spillover effects by using a rolling-window estimation method (Li et al., 2020; Liu et al., 2020; Wei et al., 2017). We choose several different window sizes and expand the pre-pandemic sub-sample in the estimation processes for robustness check, and find that these results are similar to those reported in previous examinations. To save place, we present the results of robustness checks in the Appendices. Fig. 1 only reports the dynamic results of the overall spillovers with a rolling-window size of 70 days in both time and frequency domains across all the sixteen markets.

In terms of time domain results by DY method, Fig. 1 indicates that the average overall spillover index measured rises from 70.6% before the pandemic to 77.6% after that, indicating the enhancement in risk contagion among the international stock markets. With regarding to frequency domain outcomes by BK approach, we can see that the risk spillover after the pandemic may be roughly divided into three phases: I) Between 13th January and the end of March 2020, weekly and monthly risk spillovers occupy a large proportion of the DY overall spillover index, implying that the COVID-19 impacts are primarily responded in the short- and mid-term stock market spillovers. II) From April to July 2020, the long-term spillover index increases more sharply than others. However, the mid-term spillover comes the second, and the short-term spillover falls. III) After July 2020, both the DY overall spillover and the BK spillovers in different frequencies almost drop back to pre-pandemic level. These findings reflect the time-varying fluctuations in the risk spillover across international stock markets, and the impacts induced by the pandemic on international stock markets may last for about 6 to 8 months. For international investors and speculators, they should realize how their portfolio’s risk is altered and timely manage their portfolio risk. Policy makers can also improve regulation decisions in preventing larger risk contagion and maintaining financial market stability according to these dynamic spillovers.

5. Conclusions

This paper investigates risk contagion among sixteen major stock markets across three continents, and compares the spillover effects before and after the outbreak of COVID-19 pandemic in both time and frequency domains. The major empirical results show that, firstly, after the burst of COVID-19 pandemic at the beginning of 2020, the integration of international stock markets enhances greatly and the market risk contagion among them also increases significantly. Therefore, in order to maintain international stock markets stability, policy makers should focus on the risk spillovers directions and make timely policies to prevent the spread of risks across borders. Secondly, the pandemic-induced shocks in international stock markets may last for 6–8 months and come through three phases. In severe phases I) and II) of the epidemic, stock market regulators should strengthen supervision measures, and improve market accountability and transparency. In phase III), the epidemic-induced risks would be incorporated in stock prices, therefore, market supervisors can gradually relax the epidemic response restrictions. Additionally, the results indicate that the epidemic strengthens the spillover contributions of European and American markets but reduces those in most Asian markets. For international investors and portfolio managers, their portfolio risks may be heavily influenced by the pandemic. Thus, they are suggested to hedge the portfolio risks by increasing the investment weights in Asian stock markets and actively managing their portfolios during the pandemic.

Declaration of interest statement

Yuntong Liu, Yu Wei, Qian Wang, and Yi Liu declare no conflicts of interest in this manuscript.

Acknowledgements

The authors are grateful for the financial support from the National Natural Science Foundation of China (71671145, 71971191), Humanities and social science fund of ministry of education of China (17YJA790015, 17XJA790002, 18YJC790132, 18XJA790002), Science and Technology Innovation Team of Yunnan Provincial Universities (2019014) and Yunnan Fundamental Research Projects (202001AS070018).

Appendix

Fig. A1, A2, A3

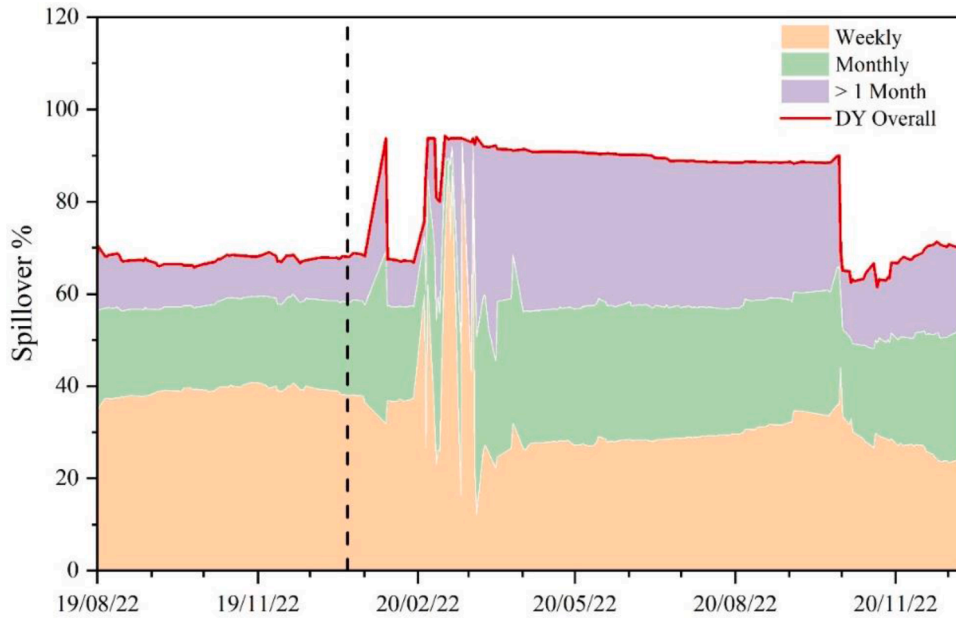


Fig. A1. Dynamic overall spillover based on rolling-window size of 100 days.

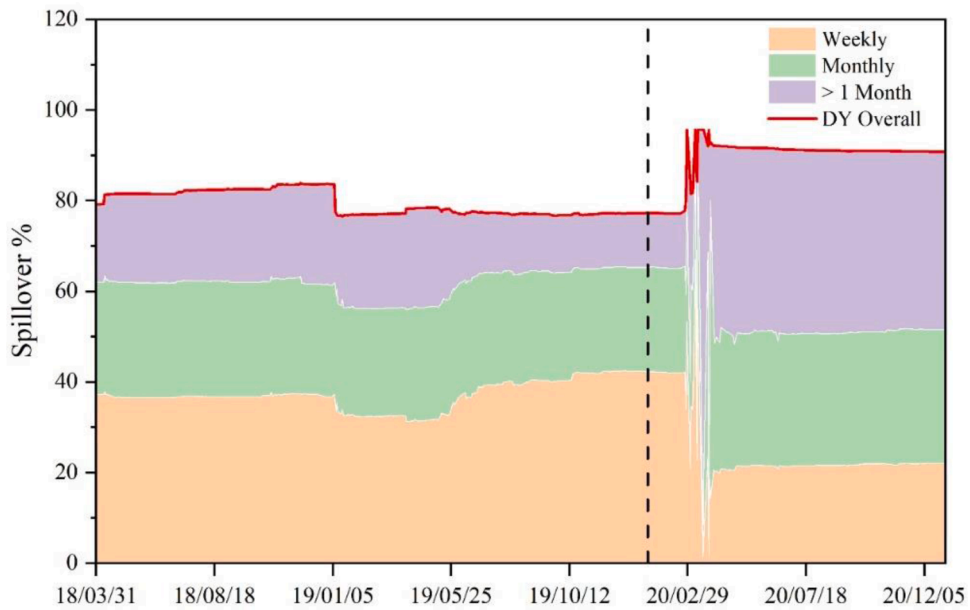


Fig. A2. Dynamic overall spillover based on rolling-window size of 130 days.

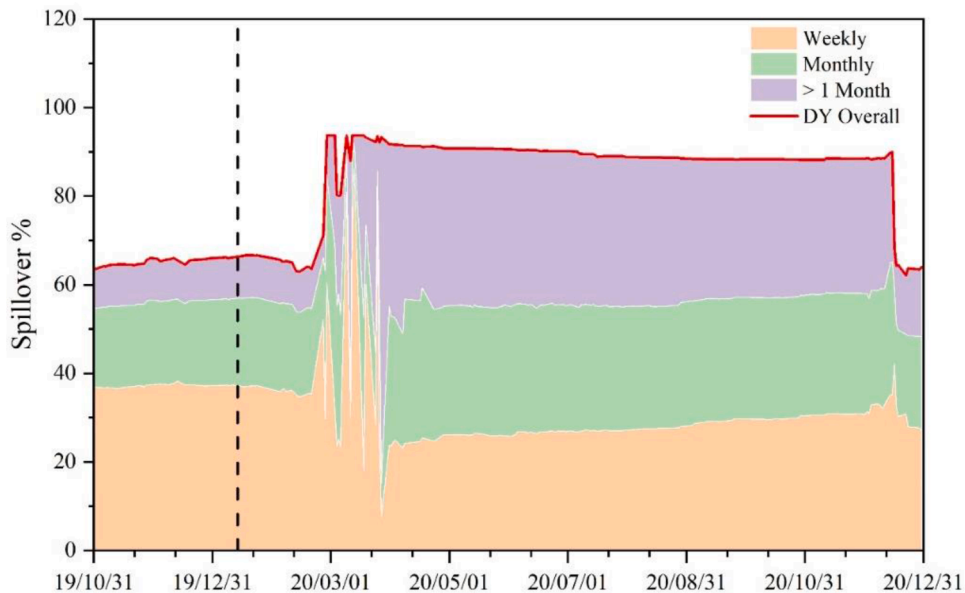


Fig. A3. Dynamic overall spillover based on rolling-window size of 550 days.

References

- Alkhtaruzzaman, M., Boubaker, S., Sensory, A., 2021. Financial contagion during COVID-19 crisis. *Finance Res. Lett.* 38, 101604.
- Bai, L., Li, X.F., Wei, Y., Wei, G.W., 2020. Does crude oil futures price really help to predict spot oil price? New evidence from density forecasting. *Int. J. Finance Econ.* 2345.
- Bai, L., Wei, Y., Wei, G.W., Li, X., Zhang, S.Q., 2021. Infectious disease pandemic and permanent volatility of international stock markets: a long-term perspective. *Finance Res. Lett.* 40, 101709.
- Bai, L., Zhang, X., Liu, Y., Wang, Q., 2019. Economic risk contagion among major economies: new evidence from EPU spillover analysis in time and frequency domains. *Physica A* 535, 122431.
- Barunfk, J., Krehlik, T., 2018. Measuring the frequency dynamics of financial connectedness and systemic risk. *J. Financ. Econom.* 16, 271–296.
- Bouri, E., Cepni, O., Gabauer, D., Gupta, R., 2021. Return connectedness across asset classes around the COVID-19 outbreak. *Int. Rev. Financ. Anal.* 73, 101646.
- Chen, W., Ma, F., Wei, Y., Liu, J., 2020. Forecasting oil price volatility using high-frequency data: new evidence. *Int. Rev. Econ.* 66, 1–12.
- Contessi, S., De Pace, P., 2021. The international spread of COVID-19 stock market collapses. *Finance Res. Lett.*, 101894. In Press.
- Corbet, S., Larkin, C., Lucey, B., 2020. The contagion effects of the COVID-19 pandemic: evidence from gold and cryptocurrencies. *Finance Res. Lett.* 35, 101554.
- Coroneo, L., Jackson, L.E., Owyang, M.T., 2020. International stock comovements with endogenous clusters. *J. Econ. Dyn. Control* 116, 103904.
- Daly, K., Batten, J.A., Mishra, A.V., Choudhury, T., 2019. Contagion risk in global banking sector. *J. Int. Financ. Mark. Inst. Money* 63, 101136.
- Davidovic, M., 2021. From pandemic to financial contagion: high-frequency risk metrics and bayesian volatility analysis. *Finance Res. Lett.*, 101913. In Press.
- Diebold, F.X., Yilmaz, K., 2012. Better to give than to receive: predictive directional measurement of volatility spillovers. *Int. J. Forecast.* 28, 57–66.
- Fassas, A.P., 2020. Risk aversion connectedness in developed and emerging equity markets before and after the COVID-19 pandemic. *Heliyon* 6, e05715.
- Frezza, M., Bianchi, S., Pianese, A., 2021. Fractal analysis of market (in)efficiency during the COVID-19. *Finance Res. Lett.* 38, 101851.
- Gharib, C., Mefteh-Wali, S., Jabeur, S.B., 2021. The bubble contagion effect of COVID-19 outbreak: evidence from crude oil and gold markets. *Finance Res. Lett.* 38, 101703.
- Gkillas, K., Tsagkanos, A., Vortelinos, D.I., 2019. Integration and risk contagion in financial crises: evidence from international stock markets. *J. Bus. Res.* 104, 350–365.
- Goodell, J.W., 2020. COVID-19 and finance: agendas for future research. *Finance Res. Lett.* 35, 101512.
- Guo, Y., Li, P., Li, A., 2021. Tail risk contagion between international financial markets during COVID-19 pandemic. *Int. Rev. Financ. Anal.* 73, 101649.
- Janiak, A., Machado, C., Turen, J., 2021. Covid-19 contagion, economic activity and business reopening protocols. *J. Econ. Behav. Organ.* 182, 264–284.
- Koop, G., Pesaran, H.H., Potter, S.M., 1996. Impulse response analysis in nonlinear multivariate models. *J. Econom.* 74, 119–147.
- Le, T.H., Do, H.X., Nguyen, D.K., Sensory, A., 2021. Covid-19 pandemic and tail-dependency networks of financial assets. *Finance Res. Lett.* 38, 101800.
- Li, X., Wei, Y., 2018. The dependence and risk spillover between crude oil market and China stock market: new evidence from a variational mode decomposition-based copula method. *Energy Econ.* 74, 565–581.
- Li, Y., Zhuang, X., Wang, J., 2021a. Analysis of the Cross-Region Risk Contagion Effect in Stock Market Based on Volatility Spillover Networks: evidence from China. *North Am. J. Econ. Finance* 56, 101359.
- Li, Z., Zhou, Q., Chen, M., Liu, Q., 2021b. The impact of COVID-19 on industry-related characteristics and risk contagion. *Finance Res. Lett.* 39, 101931.
- Li, Z.X., Wei, G.W., Wang, R., Wu, J., Wei, C., Wei, Y., 2020. Edas method for multiple attribute group decision making under q-rung orthopair fuzzy environment. *Technol. Econ. Dev. Econ.* 26, 86–102.
- Liang, C., Li, Y., Ma, F., Wei, Y., 2021. Global equity market volatilities forecasting: a comparison of leverage effects, jumps, and overnight information. *Int. Rev. Financ. Anal.* 75, 101750.
- Liang, C., Tang, L., Li, Y., Wei, Y., 2020a. Which sentiment index is more informative to forecast stock market volatility? Evidence from China. *Int. Rev. Financ. Anal.* 71, 101552.
- Liang, C., Wei, Y., Lei, L., Ma, F., 2020b. Global equity market volatility forecasting: new evidence. *Int. J. Finance Econ.*
- Liang, C., Wei, Y., Li, X., Zhang, X., Zhang, Y., 2019. Uncertainty and crude oil market volatility: new evidence. *Appl Econ* 52, 2945–2959.
- Liu, Y., Wei, Y., Liu, Y., Li, W., 2020. Forecasting oil price by hierarchical shrinkage in dynamic parameter models. *Discrete Dyn. Nat. Soc.*, 6640180
- Ma, F., Wei, Y., Liu, L., Huang, D., 2018. Forecasting realized volatility of oil futures market: a new insight. *J. Forecast.* 37, 419–436.
- Nielsen, O.E.B., Shephard, N., 2002. Econometric analysis of realized volatility and its use in estimating stochastic volatility models. *J. R. Stat. Soc.* 64, 253–280.
- Park, C.-Y., Shin, K., 2020. Contagion through national and regional exposures to foreign banks during the global financial crisis. *J. Financ. Stab.* 46, 100721.
- Pesaran, H.H., Shin, Y., 1998. Generalized impulse response analysis in linear multivariate models. *Econ. Lett.* 58, 17–29.

- Sharif, A., Aloui, C., Yarovaya, L., 2020. COVID-19 pandemic, oil prices, stock market, geopolitical risk and policy uncertainty nexus in the US economy: fresh evidence from the wavelet-based approach. *Int. Rev. Financ. Anal.* 70, 101496.
- Tao, Q.Z., Wei, Y., Liu, J.P., Zhang, T., 2018. Modeling and forecasting multifractal volatility established upon the heterogeneous market hypothesis. *Int. Rev. Econ. Finance* 54, 143–153.
- Tisdell, C.A., 2020. Economic, social and political issues raised by the COVID-19 pandemic. *Econ. Anal. Policy* 68, 17–28.
- Wang, H., Yuan, Y., Li, Y., Wang, X., 2021. Financial contagion and contagion channels in the forex market: a new approach via the dynamic mixture copula-extreme value theory. *Econ. Model.* 94, 401–414.
- Wei, Y., Bai, L., Yang, K., Wei, G., 2020. Are industry-level indicators more helpful to forecast industrial stock volatility? Evidence from Chinese manufacturing purchasing managers index. *J. Forecast.* 40, 17–39.
- Wei, Y., Liang, C., Li, Y., Zhang, X., Wei, G., 2021. Can CBOE gold and silver implied volatility help to forecast gold futures volatility in China? Evidence based on HAR and Ridge regression models. *Finance Res. Lett.* 35, 101287.
- Wei, Y., Liu, J., Lai, X., Hu, Y., 2017. Which determinant is the most informative in forecasting crude oil market volatility: fundamental, speculation, or uncertainty? *Energy Econ.* 68, 141–150.
- Wei, Y., Qin, S., Li, X., Zhu, S., Wei, G., 2019. Oil price fluctuation, stock market and macroeconomic fundamentals: evidence from China before and after the financial crisis. *Finance Res. Lett.* 30, 23–29.
- Wei, Y., Wang, Y., Huang, D., 2010. Forecasting crude oil market volatility: further evidence using GARCH-class models. *Energy Econ.* 32, 1477–1484.
- Yang, K., Wei, Y., Li, S., Liu, L., Wang, L., 2021. Global financial uncertainties and China's crude oil futures market: evidence from interday and intraday price dynamics. *Energy Econ.* 96, 105149.
- Zhang, Y., Wei, Y., Zhang, Y., Daxiang, J., 2019. Forecasting oil price volatility: forecast combination versus shrinkage method. *Energy Econ.* 80, 423–433.