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Systemic Risk in Global Volatility Spillover Networks: Evidence from Option-implied Volatility Indices

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Abstract

With option-implied volatility indices, we identify networks of global volatility spillovers and examine time-varying systemic risk across global financial markets. The US stock market is the center of the network and plays a dominant role in the spread of volatility spillover to other markets. The global systemic risks have intensified since the Federal Reserve exited from quantitative easing, hiked interest rate， and shrank its balance sheet. We further show that the US monetary tightening is an important catalyst for the intensifying global systemic risk. Our findings highlight the pernicious effects of monetary tightening after an era of cheap money.

Key Words: Network; Option-implied Volatility; Spillover; Systemic risk

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1. Introduction

The 2008 global financial crisis not only underscores the importance of global risk spillovers, but also leads to recent growth in the study of financial networks.[1] Recent studies have linked systemic risk to financial networks, such as Acemoglu et al. (2012, 2015) and Elliott et al. (2014). A financial network describes a collection of nodes (financial markets or institutions) and the links between them (Allen and Babus, 2009). With the assistance of financial networks, we can investigate risk spillovers systematically, measure the direction and intensity of spillovers at the micro-level, understand the systemic risk which arises through the structure and dynamics of network linkages, and so on.

In order to ease the cascade effects of the 2008 crisis, the US Federal Reserve and other central banks have decreased interest rates to zeros and engaged in quantitative easing in the previous decade. As the economy recovered, the Federal Reserve had exited from quantitative easing in October 2014, raised interest rates since December 2015, and shrank its balance sheet from October 2017. These monetary tightening policies coincided with some bouts of market turbulence.[2] The coincidence of timing led many to blame the US turbulence and the associated spillovers on the tightening.

To systematically investigate the global influence of monetary tightening, we identify networks of global volatility spillovers with daily option-implied volatility indices. Volatility is a representative measure of risk for asset valuation and thus volatility spillover is essentially risk spillover. In contrast to ex-post physical volatility measures, implied volatility is better for

[1] Financial Stability Board (2009) argues that systemic risk can arise through interlinkages between the components of the financial system so that individual failure or malfunction has repercussions around the financial system.
[2] For example, The S&P 500 index fell by 14% in the last quarter of 2018 and the yield on 10-year US Treasuries fell by 0.7%. This coincided with the Fed's rate hike in September 2018 and shrinking balance sheet by a faster pace of $50 billion a month from October 2018.

studying volatility spillover because it contains ex-ante risk-neutral expectation of future volatility and is readily available at daily or even intraday frequency. Moreover, we link global volatility spillovers to the systemic risk across the global financial markets and examine the source of global systemic risk. Our study extends the literature and makes contributions to the following aspects.

First, we extend the network modeling and construct time-varying global systemic risk measures. Yang and Zhou (2013) use a structural VAR approach to uncover the network of contemporaneous causal relations. Diebold and Yilmaz (2014) use generalized forecast error variance decompositions of a VAR model to form time-varying weighted and directed networks by estimating how much the innovation of a market contributes to the variance of the forecast error for another market. However, the elements of variance decomposition matrix are not additive and comparable directly because variation of different variables may be quite different. To deal with the problem of additivity and comparability, we construct spillover networks with a more considerate weighting scheme which takes the historical variation of spillover receivers' VIX changes into account.

Second, we find that the structure and dynamics of implied volatility spillover network are quite asymmetric. Although asymmetric correlation (Solnik and Watewai, 2016) and asymmetric volatility transmission (Koutmos and Booth, 1995) have been documented in previous studies, they do not look at asymmetry in a network setting. In an asymmetric network, the linkage structure is dominated by a small number of hubs affecting many different markets so that shocks from an individual market might not cancel out through diversification but instead propagate throughout the network and generate strong spillovers (Carvalho, 2014). In our study, the US stock market is the center of the global volatility spillover network and thus shocks from the US generate intensifying volatility spillovers across markets, supporting the role of the US market as a leader among global financial markets (Bessler and Yang, 2003). Although there is no surprise to see the asymmetric structure of the global volatility spillover network given the size of the US economy and financial markets, we find that the global systemic risk has intensified since the Federal Reserve exited from quantitative easing, raised interest rates, and shrank its balance sheet. This evidence suggests that the US plays an increasingly dominant role as a volatility supplier to markets globally.

More importantly, we find that the US monetary tightening is an important catalyst for the intensifying global systemic risks as well as volatility spillovers from the US stock market to the rest of the world. In addition, the inclusion of additional controls, such as the business cycle and macroeconomic climate, does not diminish the important role of monetary tightening in driving global systemic risk and volatility spillovers from the US. The US short interest rates have increased substantially since quantitative easing came to an end and thus are used to proxy for monetary condition and future policy stance (Hamilton and Jorda, 2002; Fama, 2013). Our findings extend the recent literature which links conventional and unconventional monetary policies to systemic risk. Allen and Carletti (2013) argue that systemic risk is endogenous and is related to central bank policies. Jimenez et al. (2014) and Yang and Zhou (2017) show that low interest rates and quantitative easing are potential sources of systemic risk. We further document that the global systemic risk is intensifying with monetary tightening after an era of cheap money. Our findings suggest that global investors and regulators should take a systemic perspective in understanding the impact of US monetary tightening around the world.

The rest of this paper is organized as follows: Section 2 describes the data; Section 3 discusses the methodology; Section 4 presents empirical findings and, Section 5 concludes.

2. Data

We identify networks of volatility spillovers of 9 stock markets using implied equity volatility indices collected from Bloomberg. First, there are 8 developed stock markets' implied volatility indices, including US VIX (the Chicago Board Option Exchange's S&P500 volatility index), VDAX (Deutsche Borse's DAX-30 volatility index), VFTSE (Euronext's FTSE100 volatility index), VSMI (SWX Swiss Exchange's SMI volatility index), VCAC (Euronext-Paris' CAC-40 volatility index), VXJ (Nikkei 225 volatility index), VKOSPI (Korea's KOSPI200 volatility index) and VHSI (Hong Kong Hang Seng volatility index). Second, we include an emerging markets volatility index (CBOE's Emerging market ETF volatility Index) which become available in recent years. All these 9 implied volatility indices are model-free measures for the market's expectation of a 30-day volatility.

In addition to equity volatility indices, we included the Bank of America Merill Lynch's Treasury Option Volatility Estimate Index (MOVE).[3] It has been widely cited among practitioners that MOVE in the US government bond market is equivalent to VIX in the stock market. Moreover, MOVE is included by the IMF in its Global Financial Stability Report along with US VIX. However, it is important to note that MOVE is not a model-free measure but is based on Black's (1976) model. More specifically, it is a weighted average of the normalized implied yield volatility estimated from at-the-money one-month options for 2, 5, 10, and 30-year US Treasury bonds with weights based on the estimates of option trading volumes in each maturity of Treasury bonds. Zhou (2014) studies the joint dynamic of MOVE altogether with US VIX. Yang and Zhou (2017) examine the spillover network of MOVE with various VIX indices.

Our sample runs from March 2011, when the CBOE emerging market VIX index became

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[3] We do not include implied volatility indices of other debt markets because they are not readily available.

available, to the end of 2018 for a total of 2047 trading days. During the time period, the resonance of the implied volatility indices is strengthening. All VIX indices increased sharply when the US lost its AAA credit rating in August 2011, and when there were big selloffs in August 2015 and February 2018, as shown in Figure 1. The fact that all volatility indices fluctuate in a similar pattern indicates that there is a strong spillover effect between them. However, at first glance at Figure 1 does not reveal the structure and dynamics of volatility spillover, which will be explored further below.

[Figure 1 here]

To address nonsynchronous trading issues, we compute volatility changes of the implied volatility indices as two-day rolling-average changes following Forbes and Rigobon (2002).[4] Table 1 summarizes the statistics for volatility changes of the 10 volatility indices. The mean of volatility changes is quite small and the standard deviation ranges from 2.68% for MOVE to 5.30% for US VIX. Although the skewnesses and kurtosises of all volatility changes are positive, the magnitudes of their fat tails are much greater than those of their long tail counterparts. Jarque-Bera tests indicate that all volatility changes are not normally distributed. AR1 tests suggest strong serial autocorrelations for most volatility changes. Additionally, ADF tests show that all volatility changes are stationary.

[4] Compared with using weekly differences of volatility indices, the benefit of two-day averaging is to keep as many observations as possible for subsequent structural VAR analysis. Although two-day averaging obscures some lead/lag effects, most lead/lag relations are still captured by lags in VAR analysis.

[Table 1 here]

We also collect some economic and financial variables that can influence the risk spillover intensity across markets estimated with the above series of volatility changes. First, to investigate the impact of the US monetary tightening since QE tapering in December 2013, we use the US short-term interest rates, which are represented by six-month government bond yields, as proxy for the monetary condition since bond rates reflect the market's expectation of the Fed's future monetary policy stance (Hamilton and Jorda, 2002; Fama, 2013). Thus, the various short-term government bond yields are also obtained from Datastream. Although the US short rates were essentially zeros in the era of quantitative easing, they have increased substantially since the QE came to the end.

Second, we control the level of US VIX and change of US dollar exchange rates. King and Wadhwani (1990) and King et al. (1994) argue that the linkage strength of international stock markets depends mainly on volatility. Yang and Zhou (2017) show that volatility spillover intensity increases with the level of VIX, following the Lehman Brothers' collapse and the global financial crisis in 2008. Meanwhile, the demand for the US dollar has intensified due to investors flocking to safety whenever there is a crisis, or merely an outbreak of uncertainty in financial markets (Habib and Stracca, 2012; Chan et al., 2018). Therefore, conditions in the US financial markets can be transmitted rapidly to others through the change of the US dollar exchange rates. In this paper, we calculate US dollar exchange rates change using the trade-weighted US dollar spot index obtained from the St. Louis Fed's Federal Reserve Economic Data (FRED) database. The dollar index measures the value of the US dollar against the currencies of a broad group of major US trading partners. Higher values of the index indicate a stronger US dollar.

Third, we further control business cycle and liquidity condition. Among daily business cycle variables commonly used in the literature, the term spread is defined as the difference between the ten-year and three-month Treasury yields, and reflects shorter-term business conditions. Ferson and Harvey (1991) show that an inverted yield curve predicts recession frequently. The default spread is measured as the difference between Moody BAA-rated corporate bond and 10-year Treasury bond yields, which is a proxy for longer-term business conditions (Fama and French, 1989). The TED spread is the difference between the three-month LIBOR based on US dollars and the three-month Treasury yield, which measures funding liquidity in particular and market liquidity in general (Brunnermeier and Pedersen, 2009). In addition to these financial variables that can predict the business cycle, we use a daily business condition index developed by Aruoba et al. (2009) to track US real business conditions.[5] Allen et al. (2012) show that increases (decreases) of this index indicate improving (deteriorating) macroeconomic conditions. The above variables are obtained from the Federal Reserve Bank of Philadelphia, and the St. Louis Fed's Federal Reserve Economic Data (FRED) database.

3. Empirical Methodology

With 10 series of volatility changes, we identify global volatility spillover networks and construct time-varying systemic risk across global financial markets. Then, we exam the underlying economic forces of the global systemic risk and test several hypotheses.

3.1. Generalized Forecast Error Variance

We first run a vector autoregressive (VAR) model on the vector of volatility changes, $\Delta\boldsymbol{IV_t}$

$$\Delta\boldsymbol{IV}_t = \sum_{i=1}^{I} \boldsymbol{\Phi}_i \Delta\boldsymbol{IV}_{t-i} + \boldsymbol{\varepsilon}_t \tag{1}$$

[5] This index uses weekly initial jobless claims, monthly payroll employment, industrial production, personal income less transfer payments, manufacturing and trade sales, and quarterly real gross domestic product.

where $\Delta \boldsymbol{IV_t}$ is a 10×1 vector of jointly determined dependent variables, $\{\boldsymbol{\Phi}_i, i = 1,2,\cdots, I\}$ are 10×10 coefficient matrix, I is lag order and $\boldsymbol{\varepsilon}_t$ is the error term which satisfying $E(\boldsymbol{\varepsilon}_t) = \mathbf{0}$, $E(\boldsymbol{\varepsilon}_t \boldsymbol{\varepsilon}_t') = \mathbf{\Sigma}$ and $E\left(\boldsymbol{\varepsilon}_t \boldsymbol{\varepsilon}_{t'}'\right) = \mathbf{0}$ for all $t = t'$. [6]

The VAR model is typically used with the Cholesky decomposition by assuming a recursive contemporaneous causal structure or imposing some causal orderings based on economic theories. However, the Cholesky decomposition is often restrictive and unrealistic, while theory-based orderings are often subjective or even arbitrary. To overcome this problem, we adopt the ordering-free generalized forecast error variance decomposition proposed by Pesaran and Shin (1998) to quantify volatility spillover intensities. Under the above model specification, Eq. (1) can be further written as an infinite moving average process,

$$\Delta \boldsymbol{IV}_t = \sum_{l=0}^{\infty} \boldsymbol{A}_l \boldsymbol{\varepsilon}_{t-l} + \boldsymbol{\varepsilon}_t, t = 1, 2, \dots, T. \tag{2}$$

With Eq. (2), the *ij*-th element of the generalized forecast error variance decompositions is shown in the Eq. (3),

$$\theta_{i\leftarrow j}^{H} = \frac{\sigma_{ii}^{-1} \sum_{l=0}^{H} (e_i' A_l \Sigma e_j)^2}{\sum_{l=0}^{H} e_i' A_l \Sigma A_l' e_j}, \tag{3}$$

$$S_{i\leftarrow j}^{H} = \frac{\theta_{i\leftarrow j}^{H}}{\sum_{j=1}^{N} \theta_{i\leftarrow j}^{H}}, \tag{4}$$

where $\Sigma = \{\sigma_{ij}, i, j = 1,2,\cdots,10\}$ is the variance–covariance matrix of the error term in Eq. (1), A_l is the coefficient matrix in Eq. (2), and $\boldsymbol{e}_i$ is an 10×1 selection vector with unity as its *i*-th element and zeros elsewhere. We further normalized $\theta_{i\leftarrow j}^{H}$ using Eq. (4) following Pesaran and Shin (1998). $S_{i\leftarrow j}^{H}$ measures the proportion of the total H-step ahead forecast error variance of the *i*-th variable which is attributed to the innovations of the *j*-th variable in the VAR model.

[6] $\mathbf{\Sigma} = \{\sigma_{ij}, i, j = 1,2, \dots,10\}$ is an 10×10 positive definite matrix.

The resulting forecast error variance decompositions can be used to define weighted, directed, and time-varying networks (Diebold and Yilmaz, 2014). First, the entries in the variance decomposition matrix are variance shares ranging from 0% to 100%, measuring how much the innovation of a variable contributes to the variance of the total H-step-ahead forecast error for another variable in $\Delta \boldsymbol{IV}_t$, and thus are the capacity of a variable in explaining the variation of another variable. Second, the variance decomposition matrix is generally asymmetric, thereby suggesting that links are directed. For example, if the variance share of the ij link (the *i*-th variable's variation explained by the *j*-th variable's innovation) is greater than that of the ji link, we can argue that there is a directional net spillover effect from the *j*-th variable to the *i*-th variable. Third, the network dynamics can be traced by studying variance decomposition matrices at different points of time. We will discuss these in detail below.

3.2. Structure and Dynamics of Volatility Spillover Networks

Although the variance decompositions can be used to define weighted, directed spillover networks, different elements of the variance decompositions in the Eq. (4), such as $S^H_{UK\leftarrow US}$ and $S^H_{JP\leftarrow US}$, are not additive and comparable directly because the variations of the receivers' volatility changes (such as UK VIX and JP VIX) can be quite different. [7] To deal with the problem of additivity and comparability, we construct volatility spillover network by extending Diebold and Yilmaz (2014)'s method with a weighting scheme that takes the historical variations of receivers' volatility changes into account, as shown in Eq. (5),

	ΔIV_1	ΔIV_2	$\dots$	ΔIV_N	
ΔIV_1	$w_1 S^H_{i\leftarrow 1}$	$w_1 S^H_{i\leftarrow 2}$	$\dots$	$w_1 S^H_{i\leftarrow N}$	(5)
ΔIV_2	$w_2 S^H_{2\leftarrow 1}$	$w_2 S^H_{2\leftarrow 2}$	$\dots$	$w_2 S^H_{2\leftarrow N}$	

[7] $S^H_{UK\leftarrow US}$ and $S^H_{JP\leftarrow US}$ are the proportions of the H-step ahead forecast error variance of the UK VIX and Japanese VIX changes which are explained by the innovations in US VIX respectively.

$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
ΔIV_N	$w_N S^H_{N\leftarrow 1}$	$w_N S^H_{N\leftarrow 2}$	$\cdots$	$w_N S^H_{N\leftarrow N}$

where w_i is standard deviation of the i-th receiver's volatility change. We also check the robustness of the weight by replacing the standard deviation by variance of the i-th receiver's volatility change. Considering the historical variation of the i-th market, $w_i S^H_{i\leftarrow j}$ measures the spillover effect of the *j*-th market on the *i*-th market.

To proceed, we calculate outward and inward spillover for each market by taking the average on each column and row of the off-diagonal elements of the spillover network respectively. Specifically, the outward spillover effect from the *j*-th variable to others is shown in Eq. (6),

$$OUT^H_j = \frac{\sum_{i\neq j} w_i S^H_{i\leftarrow j}}{(N-1)}, \text{ for } i,j \in \Omega_{ALL},^{8} \tag{6}$$

and the inward spillover effect from others to the *i*-th variable is shown in Eq. (7),

$$IN^H_i = \frac{\sum_{j\neq i} w_i S^H_{i\leftarrow j}}{(N-1)}, \text{ for } i,j \in \Omega_{ALL}, \tag{7}$$

where N is the number of markets in Ω_{ALL} and weight w_i is the historical standard deviation of the *i*-th receiver's volatility change.

Furthermore, we calculate the net spillover effect of a market as the difference between its outward spillover effect and inward spillover effect, as shown in the Eq. (8).

$$NET^H_i = OUT^H_j - IN^H_i, \text{for } i = j \in \Omega_{ALL} \tag{8}$$

We also calculate eigenvector centrality for each market, which is defined as the principal eigenvector of the spillover matrix. Intuitively, a market is considered more central if it is connected to other markets that are central themselves (Ahern and Harford 2014).

[8] $\Omega_{ALL} = \{US, DE, GB, CH, FR, JP, KR, HK, EM, MO\}$.

Finally, we construct a global systemic risk index ($GSYS^H$) by averaging up the weighted shares of all the off-diagonal entries in the spillover network, according to Eq. (9),

$$GSYS^H = \frac{\sum_{j\neq i}\sum_{i\neq j} w_i s_{i\leftarrow j}^H}{N\times(N-1)}, for\ i,j\ \in \Omega_{ALL}. \tag{9}$$

$GSYS^H$ measures global systemic risk, which "can arise through interlinkages between the components of the financial system so that individual failure or malfunction has repercussions around the financial system" (Financial Stability Board, 2009).

To track the dynamics of market-wide and system-wide spillovers defined in Eq. (6) to (9), we estimate the spillover matrix with a rolling window by using only the most recent 250-day sample. We also explore the robustness of the window length by using the most recent 200-day sample.

3.3. Determinants of Systemic Risk Volatility Spillover Indices

To study the underlying force of the global systemic risk, we regress the global systemic risk index, which estimated using rolling samples, on the lagged interest rate, US VIX and exchange rate change, as well as control variables using Eq. (10),

$$GSYS_t^H = \beta_0 + \beta_1 INT_{t-1} + controls_{t-1} + \varepsilon_t, \text{for } H = 1, 3 \text{ or } 12, \tag{10}$$

where $GSYS^H$ is global systemic risk of the volatility spillover network for the H horizons defined in Eq. (9). *INT* is the proxy of US short term interest rate.

Our hypothesis is that β_1 should be positive, suggesting that systemic risk increase with the US interest rate. In the era of monetary tightening, the increase in interest rate drives up both risk aversion and uncertainty, which is expected to increase risk-neutral volatility in the US and spills over to other markets.

In addition, we investigate volatility spillovers from the US stock market to other markets with the following regression:

$$w_i S_{i\leftarrow US}^{H=12} = \beta_0 + \beta_1 INT_{t-1} + controls_{t-1} + \varepsilon_t, \text{for } i \in \Omega_{ALL}/\{US, MO\} \quad (11)$$

where $w_i S_{i\leftarrow US}^{H=12}$ is the spillover effect of US stock market on other markets defined in Eq. (5). Our hypothesis is that volatility spillover intensity of the US market to other markets grows with the US interest rate, regardless of developed and emerging market markets.

4. Empirical Results

The results are organized as follows. First, we present the static result of the spillover network. Next, we discuss the dynamics of spillover networks around the date when the US Fed announced the end of quantitative easing. Third, we reveal the result of market-wide and system-wide volatility spillover dynamics and locate the underlying forces of the intensifying global systemic risk.

4.1. Results on Statics Analysis

We first run a VAR model as shown in Eq. (1) with volatility changes for the 10 implied volatility indices under consideration using the full sample. The optimal lag number is 10, 4, and 4 according to Akaike information criterion (AIC), Schwarz criterion (SC), and Bayesian information criterion (BIC). Parsimoniously, we select 4 lags as suggested by SC and BIC.

Table 2 presents the full sample spillover network based on 12-day ahead generalized forecast error variance decompositions along with corresponding indices. Note that different horizons of spillover network allow for time-lagged dynamic causal linkages. We report results for the 12-day ahead spillover network because they stabilize from this horizon ahead and beyond. Some highlights are as follows.

First, the US stock market is an extensive and significant volatility supplier to other markets since US VIX shock explains substantial portions of variation in Emerging market VIX (23.60%), Japanese VIX (17.57%), Korean VIX (17.08%), Swiss VIX (16.27%), HK VIX (15.31%), French VIX (14.99%), UK VIX (14.72%) and German VIX (14.42%). Taking into consideration of historical standard deviation of receiver's VIX index for the full sample as shown in Table 1, the weighed spillover effect of the US market are 100.13 basis points for emerging market VIX, 78.12 basis points for UK VIX, 75.62 basis points for Japanese VIX, 71.27 basis points for French VIX, 68.75 basis points for Swiss VIX, 66.10 basis points for Korean VIX, 61.85 basis points for German VIX, and 59.52 basis points for HK VIX.[9] Thus, the outward spillover effect of the US stock market is 68.34 basis points on average, much higher than other market counterparts. Also, eigenvector centrality for the VIX is the highest, confirming that the US stock market is at the most central position of global volatility spillover network.

Second, the US stock market is the biggest net sender, suggesting that the US stock market play a dominate role in spreading volatility to other stock markets. In addition to the US stock market, the emerging stock market, German and French stock markets are also net senders with nontrivial net spillovers of 21.73 basis points, 9.32 basis points, and 6.00 basis points, respectively. In contrast, other markets are net receivers of volatility spillovers, ranging from -24.39 basis points for the Japanese stock market to -18.22 basis points for the Hong Kong stock market. Three major Asian stock markets, those in the Japan, Korea, and Hong Kong, are the ones that are most vulnerable to volatility spillovers.

Thirdly, there are significant asymmetries in the roles of the US stock market in spreading out and receiving volatility spillover. The system-wide spillover intensity, which is 34.29 basis points, is far below the US VIX's outward spillover intensity of 68.34 basis points but is only

[9] The historical standard deviation is 4.62% for US, 4.29% for German, 5.31% for UK, 4.23% for Switzerland, 4.76% for France, 4.30% for Japan, 3.87% for Korea, 3.89% for Hong Kong, 4.24% for Emerging market. The spillover effect is product of variance decomposition and historical standard deviation as has been shown in Eq. (5). To present the spillover network proper scale, all the values are multiplied by 10000 and reported in basis points.

slightly below its inward spillover intensity of 35.86 basis points. This signifies that the US stock market bears the main responsibility in spreading risk, while it is relatively robust to riots in the global financial market.

Table 2. Spillover Matrix for the Full Sample

Table 2 reports the full sample spillover network among volatilities of global financial markets from March 18, 2011 to December 31, 2018. "US", "DE", "GB", "CH", "FR", "JP", "KR" "HK", "EM" and "MO" stand for the volatilities changes of US VIX, German VIX, UK VIX, Swiss VIX, French VIX, Japanese VIX, Korean VIX， Hong Kong VIX, emerging market VIX, and MOVE respectively. Column variables are the origin of spillovers while row variables are the spillover receivers. The *ij*-th entry of the matrix is the pairwise spillover intensity from the *j*-th marekt to the *i*-th market in Eq. (5). To facilitate the analysis, we attach the corresponding indices to the network. The row labeled "OUT" summarizes the market-wide's outward spillover as defined in Eq. (6). The column labeled "IN" summarizes the market-wide's inward spillover as defined in Eq. (7). The row labeled "NET" is the market-wide's net spillover effect as defined in Eq. (8). The bottom-right element is the system-wide global systemic risk as defined in Eq. (9). The row labeled "Centrality" is eigenvector centrality for each market. Eigenvector centrality is defined as the principal eigenvector of the spillover matrix. Intuitively, a market is considered more central if it is connected to other markets are themselves central (Ahern and Harford 2014).

	US	DE	GB	CH	FR	JP	KR	HK	EM	MO	IN
US	207.34	47.91	45.11	42.84	47.18	9.03	10.68	11.64	102.48	5.85	35.86
DE	61.85	90.94	62.27	61.82	76.47	7.28	8.00	8.78	48.08	3.56	37.57
GB	78.12	72.59	149.20	60.84	75.91	8.64	9.24	12.39	59.57	4.26	42.39
CH	68.75	67.12	58.06	84.35	64.40	8.72	9.36	10.09	47.95	3.73	37.58
FR	71.27	79.67	68.92	61.76	112.67	7.47	8.23	9.81	52.09	3.67	40.32
JP	75.62	34.66	33.43	32.97	34.16	114.95	25.41	23.67	50.19	5.36	35.05
KR	66.10	31.26	29.87	29.51	28.55	24.55	91.29	31.31	50.57	4.05	32.86
HK	59.52	30.22	32.83	28.85	30.41	19.16	28.66	98.49	56.96	3.63	32.25
EM	100.13	41.58	43.32	35.28	40.59	7.21	11.14	16.40	122.67	5.98	33.51
MO	33.69	16.96	18.43	13.45	19.16	3.96	2.81	2.16	29.28	127.65	15.55
OUT	68.34	46.89	43.58	40.81	46.32	10.67	12.62	14.03	55.24	4.45	34.29
NET	32.48	9.32	1.19	3.24	6.00	-24.39	-20.25	-18.22	21.73	-11.09	
Centrality	0.43	0.37	0.38	0.35	0.38	0.20	0.19	0.20	0.38	0.09	

To quantify the structural change of the spillover network due to the end of quantitative easing, we divided the full sample before and after the end of quantitative easing into two subsamples, with one subsample from March 18, 2011 and ending on October 30, 2014, with the other subsample from October 31, 2014 and ending December 31, 2018. The optimal lag number are 8, 2, and 2 for the first subsample and 10, 2, and 2 for the second subsample, according to AIC, SC, and BIC respectively. Parsimoniously, we select 2 lags for the two subsamples.

Panel A of Table 3 reveal the spillover matrix for the first subsample. The outward spillover effect for US VIX is 59.19 basis points by the end of quantitative easing. Panel B of Table 3 displays the spillover matrix for the second subsample. After the end of quantitative easing, the outward spillover effect of US VIX increased to 72.69 basis points, because the global stock markets have become much more volatile since then.[10] Meanwhile, the global systemic risk is 32.15 basis points and 36.66 basis points with 18.41% and 19.83% contributions by the US stock market respectively, before and after October 2014. It suggests that the US has made greater contribution to exacerbating global systemic risk in the post-QE era. While various spillover effects of US market increased sharply from Panel A to Panel B, the spillovers of other markets do not change much. Moreover, the eigenvector centrality for the US stock market increased from 0.41 to 0.43, indicating that US gain further systemic importance in global volatility spillover network. Moreover, the eigenvector centrality for MOVE also increased substantially from 0.07 to 0.11 which is further evidence of the growing impact of the US over the globe.

[10] The standard deviations of volatility changes increased from 4.62% to 5.83% for US VIX, from 4.06% to 4.49% for German VIX, from 4.88% to 5.66% for UK VIX, from 3.85% to 4.53% for Swiss VIX, from 4.38% to 5.06% for French VIX, from 3.96% to 4.58% for Japanese VIX, from 3.46% to 4.20% for Korean VIX, from 3.71% to 4.03% for Hong Kong VIX, from 4.12% to 4.35% for emerging market VIX.

[Table 3]

4.2. Results on Global Systemic Risks

To explore the dynamics of volatility spillovers, we estimate spillover networks each day with a 250-days rolling subsample and 2 lags. We also check the robustness by estimating the rolling models using one lag, which is the optimal lag for the rolling samples suggested by SC and BIC.

Figure 2 displays the global systemic risk indices at various horizons estimated using Eq. (9) with a 250-day rolling window. There is a clear upward trend in the global systemic risk around the world since the QE tapering. In particular, global systemic risk fell sharply when the US Fed warranted exceptionally low levels for the federal funds rate in June 2013 and when Federal Reserve Bank of New York president William C. Dudley made a dove speech in August 2016. On the contrary, global systemic risk intensified substantially when the Federal Reserve announced the end of quantitative easing in late 2013 and the hikes of federal fund rate, and especially when the global stock markets sold off in August 2015 and February 2018.

Figure 2. Global Systemic Risk

Figure 2 plots the global systemic risk index of the spillover networks, which is defined in Eq. (9), for 1-day, 6-day and 12-day ahead horizons. Several important events are annotated on the tick marks.

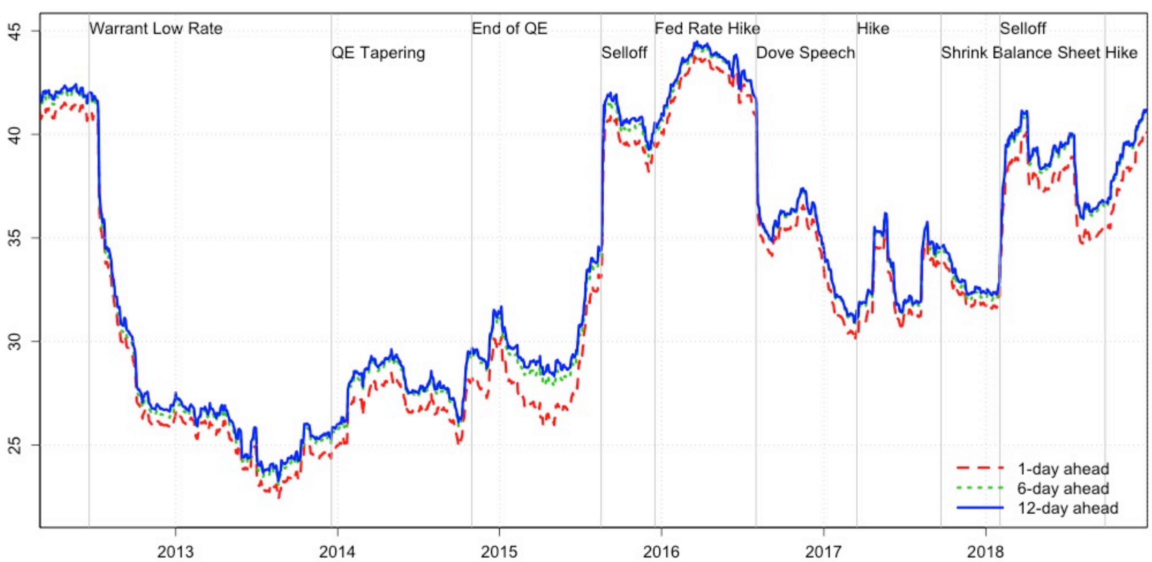
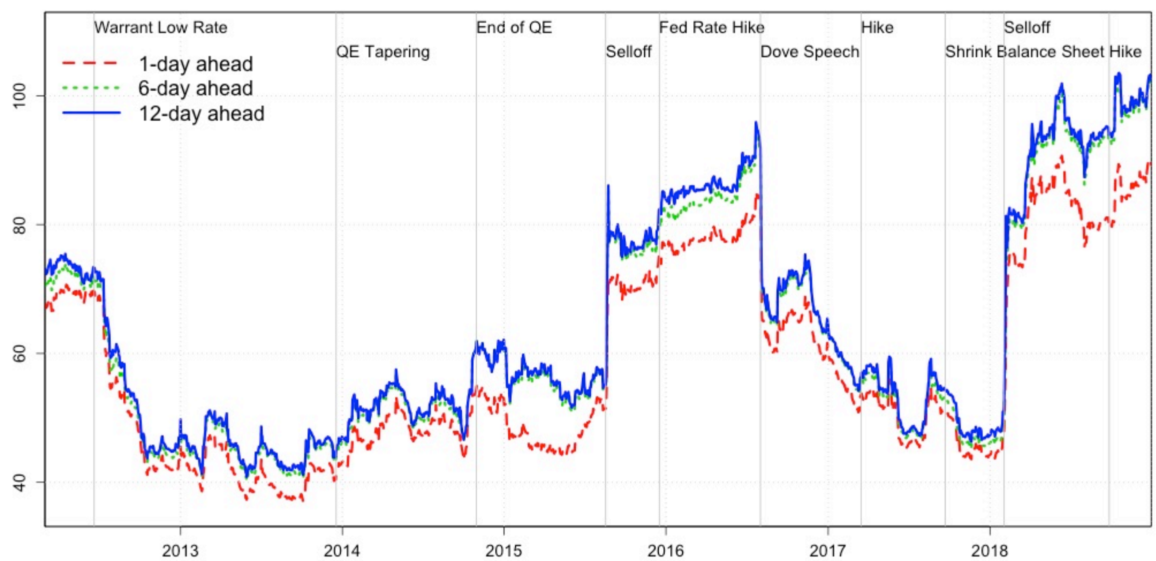


Figure 3 presents the dynamics of the outward spillover of the US stock market estimated using Eq. (6). We observe similar patterns as in Figure 2, namely, the US stock market plays as a dominant volatility supplier to other markets. The global volatility spillover network is increasingly asymmetric since the US stock market alone took account of 17% of the global systemic risk in 2012 and climbed steadily until 2016. When the US stock market crashed in 2018 February, the US stock market contributes around 25% of the global systemic risk with an abrupt increase which accompanied by the decline of other markets. This striking difference tells a tale of two worlds wherein the US plays an increasingly dominant role in the global financial network while the role of the rest of the world diminishes.

Figure 3. Outwards Spillover Effect from the US Stock Market

Figure 3 plots the dynamic of outwards spillover effect from the US stock market, which is defined in Eq. (6), for 1-day, 6-day and 12-day ahead horizons. Several important events are annotated on the tick marks.



4.3. Results on the Underlying Force of Global Systemic Risk

We go further to investigate the underlying factor of the intensified systemic risk. Panel A of Table 4 presents summary statistics for all the variables form March 1, 2012 to December 30, 2018 in daily frequency. Similar to Table 2, the daily average of global systemic risk as defined in

Eq. (9) is 33.46 basis points with the standard deviation of 6 basis points. The US interest rate represented by 6-month US Treasury bond yield has mean of 0.5% and standard deviation of 0.69%. *VIX* is 15.13% on average with a fat and positive-skewed tail. The average change of US dollar index is positive, suggesting the trend of US dollar appreciation during the sample period.

Panel B of Table 4 presents correlation matrix of the above variables. The index of global systemic risk is highly positively correlated with the interest rate, VIX index and TED spread, suggesting that global systemic risk increase with short term financing costs, US stock market volatility and tight liquidity. In contrast, the global systemic risk is negatively correlated with business cycle variables, term spread and default spreads. Besides, short term interest rate is negatively correlated with term spread but positively correlated with default spread and TED spread.

Table 4. Summary Statistics and Correlation Matrix for Regression Analysis

Panel A of the table presents summary statistics for regression analysis. All the variables start form March 1, 2012 to December 30, 2018 in daily frequency. G*SYS* is systemic risk of global volatility spillover network for the 12-day horizons defined in Eq. (9). *INT* is US interest rate represented by yields of 6-month US government treasury bond rates. *TERM* is term spread which is represented by difference between the 10-year and three-month Treasury yields. *DEF* is default spread. *TED* is TED spread. *ΔADS* and *ΔDXY* is change of business condition index and US dollar index respectively. Panel B presents correlation matrix of the above variables.

Panel A Summary Statistics

Abbr.	Mean	Std. dev	Min	Max	Skew	Kurt	JB test	Nobs
GSYS	33.46	6.02	23.27	44.48	0.21	1.74	0.13***	1796
INT	0.50	0.69	-0.01	2.44	1.44	3.75	0.66***	1782
VIX	15.13	3.94	9.14	40.74	1.51	6.56	1.63***	1796
ΔDXY	0.01	0.42	-2.40	2.03	-0.09	4.86	0.26***	1782
TERM	1.77	0.58	0.33	2.97	0.03	2.15	0.05***	1782
DEF	-2.36	1.07	-3.62	3.19	3.33	15.56	15.02***	1782
TED	0.30	0.10	0.11	0.68	0.99	3.29	0.29***	1782
ΔADS	-0.02	0.75	-16.05	13.26	-5.09	265	5158.5***	1796

Panel B Correlation Matrix

	GSYS	*INT*	*VIX*	*ΔDXY*	*TERM*	*DEF*	*TED*
INT	0.38***						
VIX	0.38***	-0.01					
ΔDXY	0.01	-0.01	0.02				
TERM	-0.56***	-0.78***	-0.07**	0.03			
DEF	-0.08***	0.31***	-0.15***	0.00	-0.12***		
TED	0.60***	0.21***	0.12***	0.00	-0.41***	-0.02	
ΔADS	0.01	0.03	0.01	0.00	-0.03	0.00	-0.01

More importantly, Table 5 summarizes the daily regression results of the underlying forces of the intensifying global systemic risk. In Model 1, the 6-month US government bond rate alone explains a big portion of the global systemic risk index, suggesting that the short-term interest rate is a driving force of the global systemic risk. Moreover, the coefficients of the 6-month government bond rate are all positive and significant at the 1% level, which supports our hypothesis that global systemic risk increases with the US monetary tightening.

In Model 2, the addition of the US VIX index explains about 32% of the global systemic risk. The incremental explanatory power is about 14% in terms of Adjusted R^2. Both AIC and BIC statistics decline, which also indicates better fitness of the model. The coefficients of US VIX index are significantly positive at 1% level which complies with the intuition that shock from the US stock market increase systemic risk. Meanwhile, the coefficients of the 6-month government bond rate remain significantly positive at the 1% level.

We further add the change of US dollar in Model 3. Neither improvement of adjusted R^2 nor decrease of both AIC and BIC statistics indicates that US dollar exchange trade isn't the driving force of international volatility contagion. In Model 4, we extend the set of control variables by adding term spread, default spread, TED spread, and changes of US business condition index. The adjusted R^2 increases to about 58% and both AIC and BIC statistics further decline. The findings are consistent with those in former models. The coefficients of 6-month US government bond rate remain significantly positive but with a smaller value.

Among the control variables, the coefficients on both term spread and default spread are negative at the 1% significance level. This suggests that systemic risk increases with lower term spread and default spread, which signal worse business condition in the future. The TED spread is significantly positive associated with systemic risk. A higher TED spread indicates worse funding liquidity, which leads to more intense spillover. Having controlled for this type of spillover due to bad news, interest rate is still significant in explaining global systemic risk.

[Table 5 here]

In sum, the US monetary tightening is an important driver of the intensifying global systemic risk, even after controlling risk and business cycle factors. It offers new evidence that quantitative easing has side effect (Bernanke, 2012) and suggests that global investors and regulators should take a systemic perspective of understanding the impact of US monetary tightening around the world.

We further examine the determinants of US outward spillover on other markets by estimating Eq. (11). Table 6 report the results with the daily 12-day ahead spillover indices of the US stock market on other markets defined in Eq. (5). There is significant variation across markets as shown by the adjusted R^2 value, ranging from 36% for the Emerging stock market to 68% for the Japanese market. Our hypothesis that hiking interest rate is a driving force of volatility spillover is supported by significantly positive coefficients of the US government bond rate for all markets. Specifically, the coefficients for the interest rate are much larger in Asia and Emerging stock markets than those of other developed stock markets. The coefficients are 26.66 for Japan, 16.11 for Korea, 13.52 for Hong Kong, and 15.07 for Emerging stock market. It indicates that the volatility spillover from the US stock market increase by 26.66, 16.11, 13.52, and 15.07 basis points in Japan, Korea, Hong Kong and Emerging market with 1% increase in short term interest rate. In contrast, the influence of US stock market on the German, UK, and Swiss stock markets are smaller with 7.57, 3.08, and 10.30 basis points respectively in response to 1% increase in short term interest rate.

To conduct robustness check, we also estimated Eq. (11) with spillover effect of the US stock market for other horizons (one and three days ahead) and find similar results. In sum, the Asia and Emerging stock markets are more vulnerable to the US abrupt exit from quantitative easing. As we have known, Emerging markets share the pain when America's economy falters.

But they can also suffer when America's economy prospers, because the Federal Reserve will raise interest rates, lessening demand for emerging-market assets.

Table 6. Determinants of Daily Spillovers of the US Stock Market

This table reports results of daily regressions of the following model: $w_i S_{i \leftarrow US}^{H=12} = \beta_0 + \beta_1 INT_{t-1} + controls_{t-1} + \varepsilon_t$, where $w_i S_{i \leftarrow US}^{H=12}$ is the spillover from the US stock market on the i-th stock market which is defined in Eq. (5).

	Daily 12-day ahead spillovers of the US stock market to one of the following markets ($w_i S_{i \leftarrow US}^{H=12}$)							
Receiver	DE	GB	CH	FR	JP	KR	HK	EM
INT	7.57***	3.08***	10.30***	15.20***	26.66***	16.11***	13.52***	15.07***
	(0.44)	(0.75)	(0.61)	(0.55)	(1.06)	(1.03)	(0.73)	(0.77)
VIX	1.01***	1.99***	1.49***	1.37***	2.35***	2.49***	1.52***	1.88***
	(0.05)	(0.08)	(0.07)	(0.06)	(0.12)	(0.11)	(0.08)	(0.09)
ΔDXY	1.14***	1.34*	1.42**	1.24**	1.00	1.67	1.48**	0.44
	(0.44)	(0.75)	(0.61)	(0.56)	(1.07)	(1.04)	(0.74)	(0.78)
TERM	-1.47***	-0.94	-2.16***	-0.26	-5.24***	-6.14***	0.63	10.66***
	(0.57)	(0.98)	(0.79)	(0.72)	(1.38)	(1.35)	(0.95)	(1.01)
DEF	-0.60***	-1.75***	-1.00***	-0.94***	-2.14***	-2.78***	-1.57***	-2.37***
	(0.19)	(0.32)	(0.26)	(0.24)	(0.46)	(0.44)	(0.31)	(0.33)
TED	24.54***	50.33***	51.38***	29.40***	85.61***	110.41***	75.35***	17.21***
	(1.96)	(3.37)	(2.73)	(2.49)	(4.77)	(4.65)	(3.29)	(3.49)
ΔADS	0.08	0.20	0.05	0.25	-0.01	0.08	-0.16	0.22
	(0.25)	(0.43)	(0.35)	(0.32)	(0.61)	(0.59)	(0.42)	(0.44)
Observations	1782	1782	1782	1782	1782	1782	1782	1782
Adjusted R^2	0.54	0.40	0.59	0.65	0.68	0.63	0.58	0.36
F Statistic	303.68***	170.27***	365.70***	476.57***	541.57***	428.27***	349.89***	142.43***
AIC	11.6	12.68	12.26	12.08	13.38	13.33	12.63	12.75
BIC	11.62	12.71	12.29	12.1	13.41	13.35	12.66	12.78

4.3. Robustness Checks

We first estimate Eq. (10) and (11) using monthly data, which are less noisy. As shown in Table 7, the coefficients for US government rate are significantly positive at 1% level. With 1% increase of interest rate, the global systemic risk indices increase by about 6 basis points for various horizons. Still, the coefficients for interest rate are much larger for Asia and Emerging markets which range from 30.11 to 47.96 while the coefficients for other developed stock markets range from 14.58 for German market to 25.13 for French stock market.

[Table 7 here]

We further show that the results are still robust for interest rates with different maturities. The first three columns of Table 8 report result of regressing the global systemic risk on the US government bond yields with 1-month, 3-month, and 1-year maturity. The corresponding coefficients are significantly positive at 5% level or 1% level.

[Table 8 here]

The results are also robust with methods of estimation. The next two columns of Table 8 replace the global systemic risk index by a new one estimated with 200-day rolling window. Another two columns replace the former global systemic risk index by an index weighted by historical variance instead of standard deviation. The following two columns replace the former explained variable by an index estimated without MOVE index. Except for the first column, coefficients for interest rate are significantly positive at 1% level. Consistent with the results in Table 5, there is strong and robust evidence to confirm our hypothesis that raising interest rate explains global systemic risk.

Furthermore, we check the robustness of the lag order of the VAR model as shown in the 10th and 11th columns in Table 8. We replace dependent variables in Eq. (10) with spillover indices estimated using one lag. Compared to the results in Table 7, the replacement doesn't make much difference.

Finally, we remove GARCH effect from the raw data with a GARCH(1,1) model. The last two column of Table 8 shows the results for Eq. (10) in which global system risk indices are estimated with GARCH-free data. There is still strong and robust evidence to confirm our hypothesis that global systemic risk increases with the US monetary tightening.

5. Conclusions

In this study, we use option-implied volatility indices to identify networks of pairwise volatility spillovers across the global financial markets and construct time-varying systemic risk and market-wide spillover measures. There are several key findings as follows. First, the US stock market is the center of the network, playing a dominant role in spreading volatility to other markets.

Second, the global systemic risk has intensified since the Federal Reserve exited from quantitative easing, hiked interest rate, and shrank its balance sheet. More importantly, the US monetary tightening is an important catalyst of the intensifying systemic risk, after controlling risk and business cycle factors. The implication of our findings is that global investors and regulators should take a systemic perspective in understanding the pernicious effects of US monetary tightening around the world after an era of quantitative easing.

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Table 1. Summary of Two Day Rolling Averaged Daily Implied Volatility Changes

This table summarizes the two-day rolling averaged daily implied volatility changes and their information. "US VIX" (hereafter US) is the Chicago Board Option Exchange (CBOE)'s S&P500 volatility index. "German VIX" (hereafter DE) is the Deutsche Borse's DAX-30 volatility index. "UK VIX" (hereafter UK) is the Euronext's FTSE100 volatility index. "Swiss VIX" (hereafter CH) is the SWX Swiss Exchange's SMI volatility index. "French VIX" (hereafter FR) is the Euronext-Paris's CAC-40 volatility index. "Japanese VIX" (hereafter JP) is the Nikkei 225 volatility index. "Korean VIX" (hereafter KR) is the KOSPI200 volatility index. "HK VIX" (hereafter HK) is Hong Kong's Hang Seng volatility index. "Emerging Market VIX" (hereafter EM) is CBOE EM ETF Volatility. "MOVE Index" (hereafter MO) is Merrill Lynch Option Volatility. The first order autocorrelation AR1, the JB test, the Augmented Dickey Fuller (ADF) and Robinson test values are also reported. *, ** and *** denote rejection of the null hypothesis at the 10%, 5% and 1% level, respectively. The null hypothesis for the first order autocorrelation, Jarque–Bera, and the ADF tests is that the first order autocorrelation is zero, that the series is normally distributed, and that the series has a unit root. The sample spans the period March 17, 2011–December 31, 2018. *Nobs* denotes the number of observations.

Index	Underlying index or asset	Abbr.	Mean (‰)	Std.dev (%)	Skew	Kurt	JB test	AR1	ADF	Nobs
US VIX	S&P500	US	-0.021	5.301	1.176	12.59	8316***	0.441***	411.162***	2047
German VIX (V1X)	DAX30	DE	-0.062	4.291	0.393	6.745	1249***	0.466***	388.841***	2047
UK VIX (VFTSE)	FTSE100	GB	-0.034	5.308	0.344	5.55	595***	0.414***	432.263***	2047
Swiss VIX (VSMI)	SMI	CH	0.000	4.225	0.609	6.072	932***	0.504***	368.162***	2047
French VIX (VCAC)	CAC40	FR	-0.061	4.756	0.15	5.363	484***	0.445***	388.523***	2047
Japanese VIX (VNKY)	Nikkei 255	JP	-0.37	4.304	0.861	10.736	5358***	0.449***	427.294***	2047
Korean VIX (VKOSPI)	KOSPI 200	KR	-0.036	3.871	0.964	11.373	6298***	0.479***	386.601***	2047
Hong Kong VIX (VHSI)	Hang Seng Index	HK	-0.017	3.887	1.203	9.345	3927***	0.481***	365.130***	2047
Emerging Market VIX (VXEEM)	CBOE EM ETF	EM	-0.092	4.243	0.582	6.889	1406***	0.455***	423.460***	2047
MOVE Index	US Treasury Bond	MO	-0.222	2.676	0.563	7.479	1819***	0.458***	392.873***	2047

Table 2. Spillover Matrix for the Full Sample

Table 2 reports the full sample spillover network among volatilities of global financial markets from March 18, 2011 to December 31, 2018. "US", "DE", "GB", "CH", "FR", "JP", "KR" "HK", "EM" and "MO" stand for the volatilities changes of US VIX, German VIX, UK VIX, Swiss VIX, French VIX, Japanese VIX, Korean VIX，Hong Kong VIX, emerging market VIX, and MOVE respectively. Column variables are the origin of spillovers while row variables are the spillover receivers. The *ij*-th entry of the matrix is the pairwise spillover intensity from the *j*-th marekt to the *i*-th market in Eq. (5). To facilitate the analysis, we attach the corresponding indices to the network. The row labeled "OUT" summarizes the market-wide's outward spillover as defined in Eq. (6). The column labeled "IN" summarizes the market-wide's inward spillover as defined in Eq. (7). The row labeled "NET" is the market-wide's net spillover effect as defined in Eq. (8). The bottom-right element is the system-wide global systemic risk as defined in Eq. (9). The row labeled "Centrality" is eigenvector centrality for each market. Eigenvector centrality is defined as the principal eigenvector of the spillover matrix. Intuitively, a market is considered more central if it is connected to other markets are themselves central (Ahern and Harford 2014).

	US	DE	GB	CH	FR	JP	KR	HK	EM	MO	IN
US	207.34	47.91	45.11	42.84	47.18	9.03	10.68	11.64	102.48	5.85	35.86
DE	61.85	90.94	62.27	61.82	76.47	7.28	8.00	8.78	48.08	3.56	37.57
GB	78.12	72.59	149.20	60.84	75.91	8.64	9.24	12.39	59.57	4.26	42.39
CH	68.75	67.12	58.06	84.35	64.40	8.72	9.36	10.09	47.95	3.73	37.58
FR	71.27	79.67	68.92	61.76	112.67	7.47	8.23	9.81	52.09	3.67	40.32
JP	75.62	34.66	33.43	32.97	34.16	114.95	25.41	23.67	50.19	5.36	35.05
KR	66.10	31.26	29.87	29.51	28.55	24.55	91.29	31.31	50.57	4.05	32.86
HK	59.52	30.22	32.83	28.85	30.41	19.16	28.66	98.49	56.96	3.63	32.25
EM	100.13	41.58	43.32	35.28	40.59	7.21	11.14	16.40	122.67	5.98	33.51
MO	33.69	16.96	18.43	13.45	19.16	3.96	2.81	2.16	29.28	127.65	15.55
OUT	68.34	46.89	43.58	40.81	46.32	10.67	12.62	14.03	55.24	4.45	34.29
NET	32.48	9.32	1.19	3.24	6.00	-24.39	-20.25	-18.22	21.73	-11.09	
Centrality	0.43	0.37	0.38	0.35	0.38	0.20	0.19	0.20	0.38	0.09	

Table 3. Spillover Matrix for the Subsamples

Table 3 reports the spillover matrixes for the two subsamples divided by the end of quantitative easing. Column variables are the origin of spillovers while row variables are the spillover receivers. The *ij*-th entry of the matrix is the pairwise spillover intensity from the *j*-th marekt to the *i*-th market in Eq. (5). To facilitate the analysis, we attach the corresponding indices to the network. The row labeled "OUT" summarizes the market-wide's outward spillover as defined in Eq. (6). The column labeled "IN" summarizes the market-wide's inward spillover as defined in Eq. (7). The row labeled "NET" is the market-wide's net spillover effect as defined in Eq. (8). The bottom-right element is the system-wide global systemic risk as defined in Eq. (9). The row labeled "Centrality" is eigenvector centrality for each market. Eigenvector centrality is defined as the principal eigenvector of the spillover matrix. Intuitively, a market is considered more central if it is connected to other markets are themselves central (Ahern and Harford 2014).

Panel A: March 18, 2011 to October 30, 2014

	US	DE	GB	CH	FR	JP	KR	HK	EM	MO	IN
US	157.45	48.66	51.33	41.82	47.23	3.50	5.45	10.43	93.37	3.08	33.87
DE	61.47	81.59	66.08	57.95	67.01	3.83	6.33	9.57	49.88	1.82	35.99
GB	74.56	69.67	118.07	60.23	71.81	5.49	8.12	13.70	61.98	3.99	41.06
CH	57.76	61.73	60.67	73.34	57.34	5.93	7.68	11.15	46.97	2.45	34.63
FR	63.62	72.09	73.19	58.12	98.20	3.98	6.55	9.43	50.47	2.06	37.72
JP	50.63	32.16	37.39	33.99	31.50	115.01	21.41	21.98	46.12	6.14	31.26
KR	47.38	30.94	37.53	30.81	28.11	17.59	71.36	31.11	47.26	3.46	30.47
HK	56.99	33.91	39.46	29.46	32.37	14.98	27.19	75.19	57.98	3.81	32.91
EM	96.48	40.43	46.54	34.58	36.49	4.11	7.70	14.97	126.00	4.98	31.81
MO	23.85	10.60	16.22	7.97	10.81	2.64	1.94	4.13	27.85	187.92	11.78
OUT	59.19	44.47	47.60	39.44	42.52	6.90	10.26	14.05	53.54	3.53	32.15
NET	25.32	8.47	6.54	4.80	4.80	-24.36	-20.20	-18.85	21.73	-8.25	
Centrality	0.41	0.38	0.40	0.35	0.38	0.17	0.18	0.21	0.38	0.07	

Panel B: October 31, 2014 to December 31, 2018

	US	DE	GB	CH	FR	JP	KR	HK	EM	MO	IN
US	234.44	49.05	44.31	44.40	51.27	12.69	13.78	13.43	109.28	10.30	38.72
DE	61.46	95.38	59.64	64.08	84.47	11.17	9.58	9.84	47.64	5.54	39.27
GB	80.23	74.67	170.29	62.04	80.23	12.13	10.81	13.58	57.29	4.69	43.96
CH	74.80	71.11	57.38	89.34	71.49	12.01	11.01	11.13	49.14	5.45	40.39
FR	74.79	84.80	65.46	64.07	122.85	11.00	9.88	11.77	55.87	6.00	42.63
JP	88.21	38.94	32.97	34.02	39.18	104.29	28.99	28.85	55.53	7.25	39.33
KR	78.38	32.41	28.05	30.29	31.73	29.57	99.09	32.35	52.35	5.85	35.67
HK	58.95	29.16	29.66	30.50	31.64	24.24	30.28	107.87	56.54	4.59	32.84
EM	101.87	42.42	40.24	35.67	47.16	10.36	12.82	18.12	117.64	8.35	35.22
MO	35.50	21.83	18.00	19.64	28.19	7.44	5.69	3.35	27.79	74.91	18.60
OUT	72.69	49.38	41.74	42.74	51.71	14.51	14.76	15.82	56.82	6.45	36.66
NET	33.96	10.11	-2.22	2.35	9.08	-24.82	-20.91	-17.01	21.60	-12.16	
Centrality	0.43	0.37	0.36	0.35	0.39	0.22	0.20	0.20	0.37	0.11	

Table 4. Summary Statistics and Correlation Matrix for Regression Analysis

Panel A of the table presents summary statistics for regression analysis. All the variables start form March 1, 2012 to December 30, 2018 in daily frequency. G*SYS* is systemic risk of global volatility spillover network for the 12-day horizons defined in Eq. (9). *INT* is US interest rate represented by yields of 6-month US government treasury bond rates. *TERM* is term spread which is represented by difference between the 10-year and three-month Treasury yields. *DEF* is default spread. *TED* is TED spread. *ΔADS* and *ΔDXY* is change of business condition index and US dollar index respectively. Panel B presents correlation matrix of the above variables.

Panel A Summary Statistics

Abbr.	Mean	Std. dev	Min	Max	Skew	Kurt	JB test	Nobs
GSYS	33.46	6.02	23.27	44.48	0.21	1.74	0.13***	1796
INT	0.50	0.69	-0.01	2.44	1.44	3.75	0.66***	1782
VIX	15.13	3.94	9.14	40.74	1.51	6.56	1.63***	1796
ΔDXY	0.01	0.42	-2.40	2.03	-0.09	4.86	0.26***	1782
TERM	1.77	0.58	0.33	2.97	0.03	2.15	0.05***	1782
DEF	-2.36	1.07	-3.62	3.19	3.33	15.56	15.02***	1782
TED	0.30	0.10	0.11	0.68	0.99	3.29	0.29***	1782
ΔADS	-0.02	0.75	-16.05	13.26	-5.09	265	5158.5***	1796

Panel B Correlation Matrix

	GSYS	*INT*	*VIX*	*ΔDXY*	*TERM*	*DEF*	*TED*
INT	0.38***						
VIX	0.38***	-0.01					
ΔDXY	0.01	-0.01	0.02				
TERM	-0.56***	-0.78***	-0.07**	0.03			
DEF	-0.08***	0.31***	-0.15***	0.00	-0.12***		
TED	0.60***	0.21***	0.12***	0.00	-0.41***	-0.02	
ΔADS	0.01	0.03	0.01	0.00	-0.03	0.00	-0.01

Table 5. Determinants of Daily Global Systemic Risk

This table reports results of the daily regressions of the model: $GSYS_t^H = \beta_0 + \beta_1 INT_{t-1} + controls_{t-1} + \varepsilon_t$. *GSYS* is systemic risk of the global volatility spillover network for the *H* horizons defined in Eq. (9). *INT* is the US interest rate represented by yields of 6-month US government treasury bond rates. *VIX* is US VIX index. *ΔDXY* is change US dollar index. *TERM* is term spread which is represented by difference between the 10-year and three-month Treasury yields. *DEF* is default spread. *TED* is TED spread. *ΔADS* is change of business condition.

	Daily 1-day ahead Systemic Risk ($GSYS^{H=1}$)				Daily 3-day ahead Systemic Risk ($GSYS^{H=3}$)				Daily 12-day ahead Systemic Risk ($GSYS^{H=12}$)			
	Model 1	Model 2	Model 3	Model 4	Model 1	Model 2	Model 3	Model 4	Model 1	Model 2	Model 3	Model 4
INT	3.44***	3.44***	3.44***	0.75***	3.47***	3.47***	3.47***	0.97***	3.43***	3.43***	3.43***	0.93***
	(0.18)	(0.16)	(0.16)	(0.22)	(0.18)	(0.16)	(0.16)	(0.22)	(0.18)	(0.16)	(0.16)	(0.22)
VIX		0.57***	0.57***	0.44***		0.57***	0.57***	0.44***		0.58***	0.58***	0.45***
		(0.03)	(0.03)	(0.02)		(0.03)	(0.03)	(0.02)		(0.03)	(0.03)	(0.02)
ΔDXY			0.06	0.16			0.09	0.18			0.09	0.18
			(0.28)	(0.22)			(0.28)	(0.22)			(0.28)	(0.22)
TERM				-3.38***				-3.08***				-3.09***
				(0.29)				(0.28)				(0.28)
DEF				-0.56***				-0.56***				-0.56***
				(0.09)				(0.09)				(0.09)
TED				24.00***				23.93***				23.61***
				(0.99)				(0.98)				(0.98)
ΔADS				0.04				0.04				0.04
				(0.13)				(0.12)				(0.12)
Observations	1782	1782	1782	1782	1782	1782	1782	1782	1782	1782	1782	1782
Adjusted R^2	0.17	0.31	0.31	0.58	0.18	0.32	0.32	0.58	0.18	0.32	0.32	0.58
F Statistic	372.83***	396.32***	264.09***	353.31***	387.90***	415.61***	276.97***	353.49***	380.49***	416.24***	277.39***	350.12***
AIC	10.91	10.73	10.73	10.23	10.89	10.7	10.7	10.22	10.88	10.69	10.69	10.21
BIC	10.91	10.74	10.74	10.25	10.89	10.71	10.71	10.24	10.89	10.7	10.71	10.24

Table 6. Determinants of Daily Spillovers of the US Stock Market

This table reports results of daily regressions of the following model: $w_i S_{i \leftarrow US}^{H=12} = \beta_0 + \beta_1 INT_{t-1} + controls_{t-1} + \varepsilon_t$, where $w_i S_{i \leftarrow US}^{H=12}$ is the spillover from the US stock market on the i-th stock market which is defined in Eq. (5).

	Daily 12-day ahead spillovers of the US stock market to one of the following markets ($w_i S_{i \leftarrow US}^{H=12}$)							
Receiver	DE	GB	CH	FR	JP	KR	HK	EM
INT	7.57***	3.08***	10.30***	15.20***	26.66***	16.11***	13.52***	15.07***
	(0.44)	(0.75)	(0.61)	(0.55)	(1.06)	(1.03)	(0.73)	(0.77)
VIX	1.01***	1.99***	1.49***	1.37***	2.35***	2.49***	1.52***	1.88***
	(0.05)	(0.08)	(0.07)	(0.06)	(0.12)	(0.11)	(0.08)	(0.09)
ΔDXY	1.14***	1.34*	1.42**	1.24**	1.00	1.67	1.48**	0.44
	(0.44)	(0.75)	(0.61)	(0.56)	(1.07)	(1.04)	(0.74)	(0.78)
TERM	-1.47***	-0.94	-2.16***	-0.26	-5.24***	-6.14***	0.63	10.66***
	(0.57)	(0.98)	(0.79)	(0.72)	(1.38)	(1.35)	(0.95)	(1.01)
DEF	-0.60***	-1.75***	-1.00***	-0.94***	-2.14***	-2.78***	-1.57***	-2.37***
	(0.19)	(0.32)	(0.26)	(0.24)	(0.46)	(0.44)	(0.31)	(0.33)
TED	24.54***	50.33***	51.38***	29.40***	85.61***	110.41***	75.35***	17.21***
	(1.96)	(3.37)	(2.73)	(2.49)	(4.77)	(4.65)	(3.29)	(3.49)
ΔADS	0.08	0.20	0.05	0.25	-0.01	0.08	-0.16	0.22
	(0.25)	(0.43)	(0.35)	(0.32)	(0.61)	(0.59)	(0.42)	(0.44)
Observations	1782	1782	1782	1782	1782	1782	1782	1782
Adjusted R^2	0.54	0.40	0.59	0.65	0.68	0.63	0.58	0.36
F Statistic	303.68***	170.27***	365.70***	476.57***	541.57***	428.27***	349.89***	142.43***
AIC	11.6	12.68	12.26	12.08	13.38	13.33	12.63	12.75
BIC	11.62	12.71	12.29	12.1	13.41	13.35	12.66	12.78

Table 7. Determinants of Monthly Systemic Risk and Spillover of the US Stock Market

The first three columns report results of monthly regressions for the following model, $GSYS_t^H = \beta_0 + \beta_1 INT_{t-1} + controls_{t-1} + \varepsilon_t$, where G*SYS* is systemic risk of the global volatility spillover network for the *H* horizons which is defined in Eq. (9). The remaining columns report results of monthly regressions of model: $w_i S_{i \leftarrow US}^{H=12} = \beta_0 + \beta_1 INT_{t-1} + controls_{t-1} + \varepsilon_t$, where $w_i S_{i \leftarrow US}^{H=12}$ is the spillovers from the US market on the i-th stock market which is defined in Eq. (5).

	Monthly systemic risk ($GSYS^{H=1,3,12}$)			Monthly 12-day ahead spillover of US stock market to one of the following markets ($w_i S_{i \leftarrow US}^{H=12}$)							
Horizon/Receiver	1-day	3-day	12-day	DE	GB	CH	FR	JP	KR	HK	EM
INT	5.99***	6.06***	6.03***	14.58***	16.71***	18.71***	25.13***	47.96***	40.76***	30.11***	31.99***
	(1.52)	(1.51)	(1.51)	(2.79)	(5.04)	(4.16)	(3.58)	(7.37)	(6.40)	(4.62)	(4.83)
VIX	0.45***	0.47***	0.48***	1.17***	2.18***	1.81***	1.47***	2.60***	2.59***	1.34**	1.58***
	(0.17)	(0.17)	(0.17)	(0.31)	(0.56)	(0.46)	(0.40)	(0.82)	(0.71)	(0.51)	(0.54)
ΔDXY	-0.34	0.33	0.32	17.80*	24.84	27.90*	21.18*	6.74	30.51	23.66	27.46*
	(5.15)	(5.12)	(5.11)	(9.45)	(17.05)	(14.08)	(12.12)	(24.94)	(21.66)	(15.65)	(16.35)
TERM	0.57	0.77	0.75	3.53	7.69	3.60	6.01	10.63	11.73*	13.04***	20.00***
	(1.54)	(1.53)	(1.52)	(2.82)	(5.08)	(4.20)	(3.61)	(7.44)	(6.46)	(4.67)	(4.87)
DEF	-5.58***	-5.35***	-5.36***	-6.22**	-15.35***	-7.39	-9.96**	-20.40**	-26.81***	-16.93***	-22.39***
	(1.64)	(1.63)	(1.63)	(3.01)	(5.43)	(4.48)	(3.86)	(7.94)	(6.89)	(4.98)	(5.20)
TED	20.53***	20.47***	20.10***	20.85**	32.82**	43.81***	19.80*	72.94***	105.40***	72.05***	-3.22
	(4.74)	(4.71)	(4.70)	(8.70)	(15.69)	(12.95)	(11.15)	(22.94)	(19.93)	(14.39)	(15.04)
ΔADS	0.50	0.34	0.36	2.68	3.76	0.07	4.82	2.45	1.66	-2.86	-0.24
	(3.04)	(3.02)	(3.02)	(5.57)	(10.05)	(8.30)	(7.15)	(14.71)	(12.77)	(9.23)	(9.64)
Observations	81	81	81	81	81	81	81	81	81	81	81
Adjusted R^2	0.60	0.60	0.60	0.63	0.47	0.63	0.72	0.70	0.72	0.67	0.51
F Statistic	18.44***	18.32***	18.23***	20.39***	11.14***	20.17***	30.07***	28.22***	31.03***	23.91***	13.10***
AIC	7.15	7.14	7.14	8.37	9.55	9.17	8.87	10.31	10.03	9.38	9.46
BIC	7.39	7.38	7.38	8.61	9.79	9.4	9.1	10.55	10.26	9.61	9.7

Table 8. Robustness Check of Determinants of Systemic Risk

The table reports results of monthly regressions for the following model, $GSYS_t^H = \beta_0 + \beta_1 INT_{t-1} + controls_{t-1} + \varepsilon_t$, where *GSYS* is systemic risk of the global volatility spillover network for the *H* horizons which is defined in Eq. (9). The first three columns report results of regressing *GSYS* on the US government bond rate with 1-month, 3-month and 1-year maturity. The following every two columns replace *GSYS* by systemic risk index estimated using 200-day rolling window, systemic risk index weighted by historical variance instead of standard deviation, systemic risk index estimated without MOVE index, systemic risk index estimated with 1 lag and systemic risk index estimated with GARCH-free data.

systemic risk	systemic risk ($GSYS^{H=12}$)			estimated with 200-day window		weighted by historical variance		estimated without MOVE index		estimated with one lag		estimated with GARCH-free data	
Maturity/Horizons	1-month	3-month	1-year	3-day	12-day	3-day	12-day	3-day	12-day	3-day	12-day	3-day	12-day
INT	4.23**	4.46***	5.25***	6.24***	6.18***	0.50***	0.50***	7.03***	7.04***	5.65***	5.67***	4.99***	4.95***
	(1.62)	(1.54)	(1.29)	(1.58)	(1.59)	(0.11)	(0.11)	(1.70)	(1.70)	(1.50)	(1.51)	(1.45)	(1.46)
VIX	0.48***	0.47***	0.40**	39.23**	39.74**	0.04***	0.04***	0.58***	0.58***	0.47***	0.47***	0.43***	0.44***
	(0.16)	(0.16)	(0.15)	(17.57)	(17.59)	(0.01)	(0.01)	(0.19)	(0.19)	(0.17)	(0.17)	(0.16)	(0.16)
ΔDXY	-0.70	-0.38	0.41	-4.59	-4.50	0.01	0.01	0.82	0.68	-0.05	-0.03	0.04	0.15
	(4.96)	(4.92)	(4.69)	(5.36)	(5.36)	(0.39)	(0.39)	(5.76)	(5.76)	(5.09)	(5.09)	(4.92)	(4.92)
TERM	-0.86	-0.44	0.60	2.15	2.10	0.09	0.09	0.43	0.44	0.57	0.58	0.24	0.25
	(1.44)	(1.46)	(1.37)	(1.60)	(1.60)	(0.12)	(0.12)	(1.72)	(1.72)	(1.52)	(1.52)	(1.47)	(1.47)
DEF	-3.50**	-3.91**	-4.97***	-4.02**	-3.99**	-0.44***	-0.44***	-7.08***	-7.09***	-5.43***	-5.43***	-4.69***	-4.69***
	(1.56)	(1.58)	(1.47)	(1.71)	(1.71)	(0.12)	(0.12)	(1.83)	(1.83)	(1.62)	(1.62)	(1.57)	(1.57)
TED	18.33***	18.08***	16.12***	16.45***	16.11***	1.28***	1.27***	22.56***	22.31***	19.11***	19.12***	18.16***	17.99***
	(4.60)	(4.55)	(4.32)	(4.93)	(4.93)	(0.36)	(0.36)	(5.30)	(5.30)	(4.68)	(4.69)	(4.53)	(4.53)
ΔADS	-0.44	-0.28	0.13	1.15	1.08	0.01	0.01	0.66	0.69	0.51	0.49	-0.02	-0.02
	(2.93)	(2.90)	(2.77)	(3.16)	(3.16)	(0.23)	(0.23)	(3.40)	(3.40)	(3.00)	(3.00)	(2.90)	(2.90)
Observations	81	81	81	81	81	81	81	81	81	81	81	81	81
Adjusted R^2	0.54	0.55	0.59	0.47	0.47	0.60	0.60	0.64	0.64	0.59	0.59	0.56	0.56
F Statistic	14.23***	14.70***	17.27***	11.26***	11.07***	18.24***	18.13***	21.07***	21.00***	17.28***	17.28***	15.82***	15.65***
AIC	2.79	2.78	2.68	2.94	2.95	-2.32	-2.31	3.09	3.09	2.84	2.84	2.77	2.77
BIC	3.03	3.01	2.91	3.18	3.18	-2.08	-2.07	3.33	3.33	3.08	3.08	3.01	3.01

Figure 1. Movements of Implied Volatilities

This figure plots the 10 implied volatility indices from March 2011 to December 2018. “US VIX” is the Chicago Board Option Exchange (CBOE)’s S&P500 volatility index. “German VIX” is the Deutsche Borse’s DAX-30 volatility index. “UK VIX” is the Euronext’s FTSE100 volatility index. “Swiss VIX” is the SWX Swiss Exchange’s SMI volatility index. “French VIX” is the Euronext-Paris’s CAC-40 volatility index. “Japanese VIX” is the Nikkei 225 volatility index. “Korean VIX” is the KOSPI200 volatility index. “HK VIX” is Hong Kong’s Hang Seng volatility index. “Emerging Market VIX” is CBOE emerging market ETF Volatility. “MOVE Index” is the Bank of America Merrill Lynch’s Treasury Option Volatility Estimate Index. Several important events are annotated on the tick marks. The US Fed warrant low interest rate June 2012 and then officially announced QE tapering on December 18, 2013 and confirmed the end of QE on October 30, 2014. In the following years, The US Fed raised fund rate in December 2015, March 2017 and September 2018. Besides, The US Fed started to shrink balance sheet on October 2017. During the period, president of New York Fed delivered dove speech on August 2016. At last, the stock markets crashed on August 2015 and February 2018.

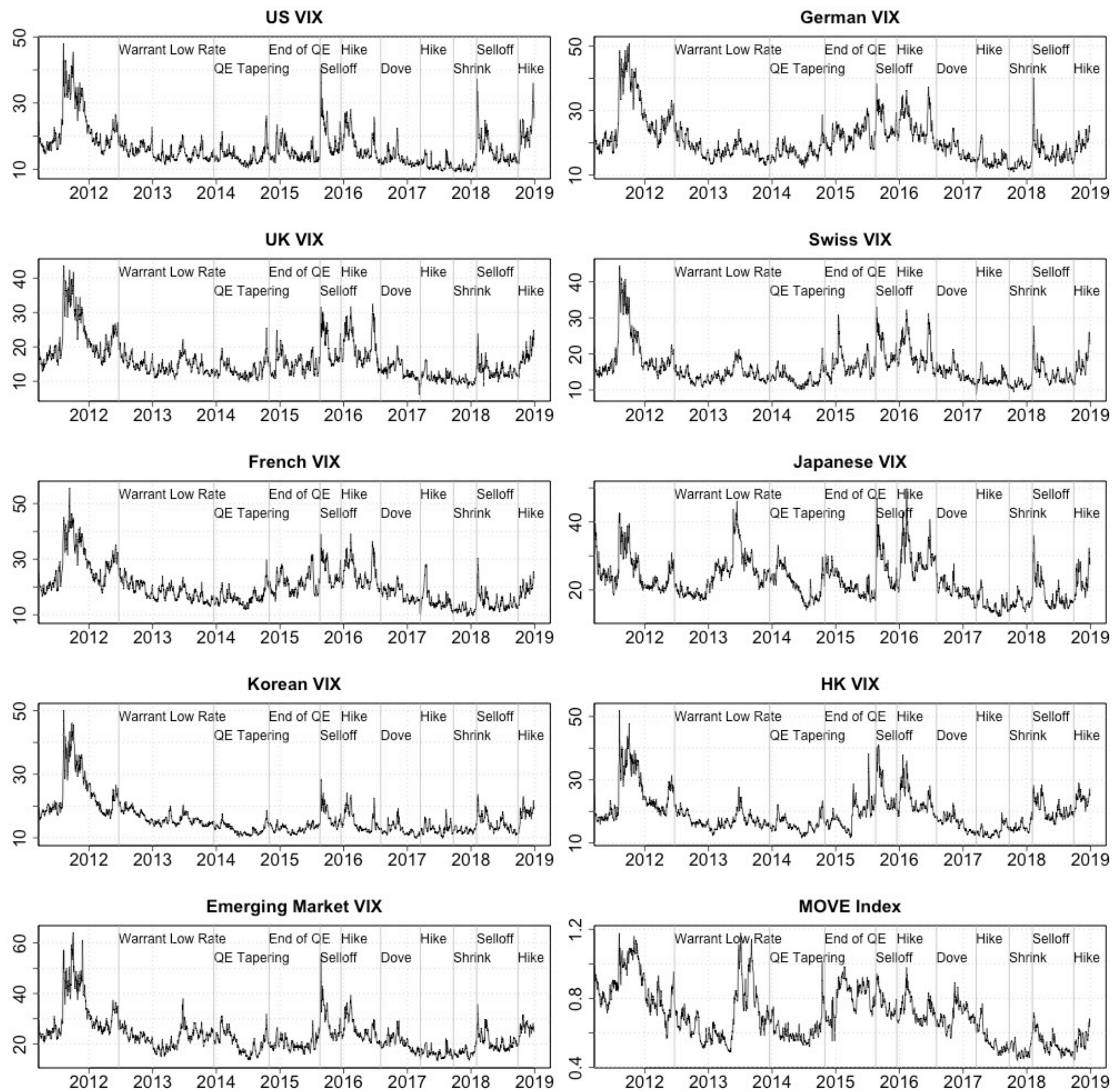

Figure 2. Global Systemic Risk

Figure 2 plots the global systemic risk index of the spillover networks, which is defined in Eq. (9), for 1-day, 6-day and 12-day ahead horizons. Several important events are annotated on the tick marks.

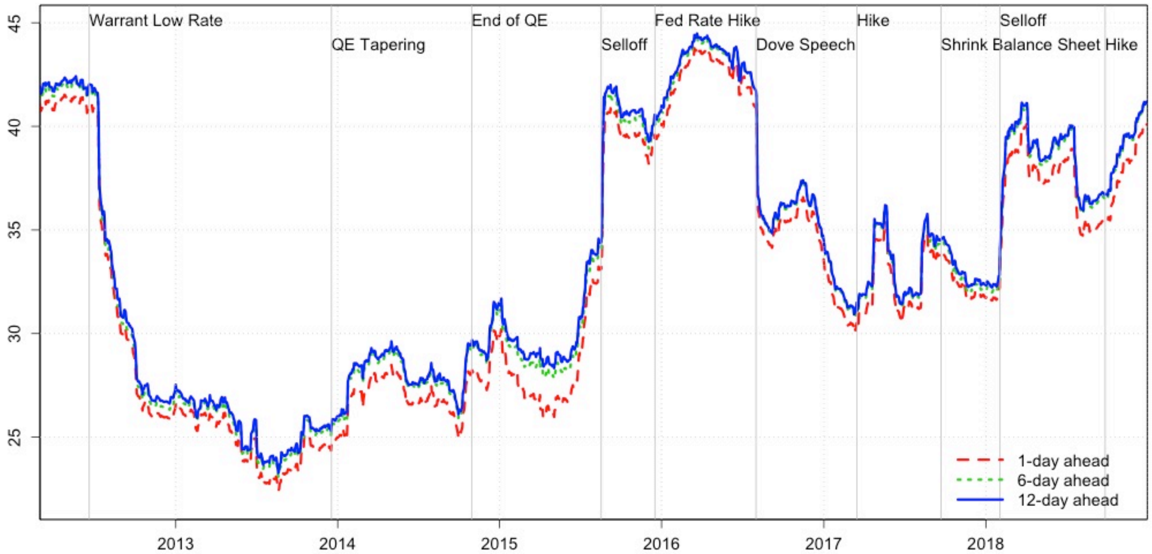

Figure 3. Outwards Spillover Effect from the US Stock Market

Figure 3 plots the dynamic of outwards spillover effect from the US stock market, which is defined in Eq. (6), for 1-day, 6-day and 12-day ahead horizons. Several important events are annotated on the tick marks.