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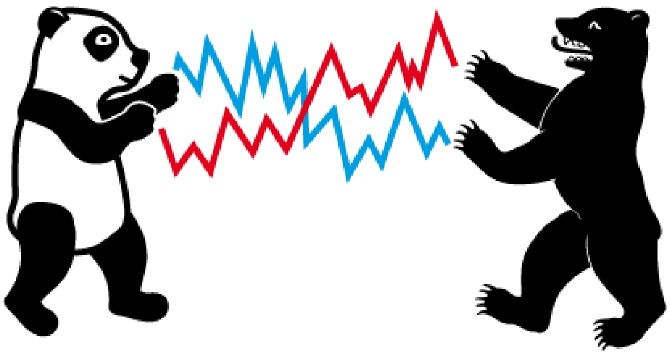

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Systemic Risk in Global Volatility Spillover Networks:
Evidence from Option-implied Volatility Indices

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Abstract

With option-implied volatility indices, we provide a new tool for event studies in a network setting and document systemic risk in the spillover networks across global financial markets. Network linkages are sufficiently asymmetric because the US stock and bond markets play as dominant volatility suppliers to other countries and markets. Shocks from the US generate systemic risk through intensifying volatility spillovers across countries and asset classes. The findings offer new evidence that asymmetric network linkages can lead to sizable aggregate fluctuations and thus potential systemic risk.

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

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1. Introduction

The recent global financial crisis underscores the importance of global risk spillovers. It is also an important driving force of recent growth in the study of financial networks. A financial network describes a collection of nodes (financial markets or institutions) and the links between them (Allen and Babus, 2009). Financial networks give a powerful language for systematic investigation of risk spillovers, including how to measure the direction and intensity of spillovers at micro level, how to understand systemic risk which arises through the structure and dynamics of network linkages,[1] and so on. In this paper, we examine the networks of global implied volatility spillovers across countries and asset classes and draw implications for systemic risk. Our study extends the literature and makes several contributions.

First, we provide a new tool for event studies in a network system. Our approach extends Diebold and Yilmaz (2014) by using recursive forecast error variance decompositions of a structural VAR model to form time-varying weighted directed networks. The outcome of the recursive estimation is a sample of spillover estimates, which uses prior information and currently updated information. Then the difference between recursively estimated spillovers can measure the marginal spillover effect conditional on currently updated information. With such marginal spillover measures defined at pairwise, market-wide, and system-wide levels, we characterize the immediate impact of an announcement or event on the network dynamics of implied volatility spillovers. Essentially, we can see whether network dynamics is stable or subject to structure breaks.

Second, we find that the structure and dynamics of implied volatility spillover network[2]

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[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] Volatility is an important measure of risk and thus volatility spillover is essentially risk spillover. Recent studies, such as Engle et al. (2012), use high-frequency return data to construct daily realized volatility measures,

are quite asymmetric, although asymmetric correlation (Solnik and Watewai, 2016) and asymmetric volatility transmission (Koutmos and Booth, 1995) have been documented in previous studies.[3] 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 volatility spillovers (Carvalho, 2014). Except for the German stock market, non-US markets are net receivers of volatility spillovers, while US stock and Treasury markets are net senders of volatility spillovers, supporting the role of the US market as a leader among global financial markets (Bessler and Yang, 2003). One may argue that there is no surprise to see asymmetric structure of global volatility spillover network given the size of the US economy and financial markets. What is surprising is substantial asymmetry in the dynamics of the global volatility spillover network. Non-US markets transmit less and less volatility to other markets over time. In contrast, volatility spillovers from the US to other markets have intensified steadily (Yang and Zhou, 2017).[4] Moreover, the decrease in spillover from non-US markets exceeds the increased spillover from the US so that net global volatility spillovers have decreased since the 2008 crisis. This provides new evidence for the argument that financial globalization is in retreat.[5] More importantly, it indicates that the US plays an increasingly dominant role as volatility supplier to other countries and markets.

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comparable to direct availability of daily implied volatility. But implied volatility is still better for studying volatility spillover because it contains more *ex ante* information than *ex post* realized volatility measures. For volatility spillover networks in this study, the nodes represent financial markets and the links represent directional volatility spillover intensity from one market to another.

[3] Previous studies do not look at asymmetry in a network setting.

[4] Yang and Zhou (2017) focus on volatility spillover from US stock market to other stock and commodity markets and the role of US quantitative easing. This paper takes a significantly different perspective by studying pairwise, market-wide and system-wide volatility spillovers and exploring network structure and dynamics as well as the immediate impact of an announcement or event on spillover networks.

[5] According to the McKinsey Global Institute (2013), cross-border capital flows have dropped sharply by more than 60% from a peak of $11.8 trillion in 2007.

Third, we show that shocks from the US can lead to significant global volatility spillovers through the asymmetric network linkages described above. When the Federal Reserve launched the first round of quantitative easing (QE1), the linkage structure of global volatility spillovers was dominated by the US Treasury bond and stock markets, and the strength of the propagation mechanism increased dramatically. The same thing happened when the US lost its AAA credit rating. The network of volatility spillovers across financial markets is dominated by US markets and thus shocks from the US cannot be diversified away but instead generate intensifying volatility spillovers across countries and asset classes, which is essentially an important source of systemic risk. In the literature, researchers typically link the causes of systemic risk to network density. For example, Allen and Gale (2000) suggest that a more densely interconnected financial network enhance financial stability. Acemoglu, Ozdaglar, and Tahbaz-Salehi (2015) further argue that the relation between network density and systemic risk exhibits a form of phase transition. Elliott, Golub, and Jackson (2014) distinguish diversification (greater dependence on counterparties) and integration (more counterparties per organization), which have different trade-off effects on financial contagions and can be related to core-periphery and segregation structure of a network. In contrast, Acemoglu, Carvalho, Ozdaglar, and Tahbaz-Salehi (2012) argue that network asymmetry is another potential source of systemic risk because shocks from an individual market can lead to sizable aggregate fluctuations in the system if network linkages are sufficiently asymmetric. Our findings offer new evidence that network asymmetry matter for systemic risk. It is important for investors and policy-makers across the globe to manage the potential systemic risk of an intensifying spillover from the US. Moreover, global regulators and policymakers need to address the issue of network asymmetry by increasing their co-operation and resetting for a healthier and more balanced global financial system.

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

Table 1 summarizes 11 daily implied volatility indices of equity, bond and commodity we collect from Bloomberg and study in this paper. First, there are 8 national stock implied volatility indices, including US VIX (the Chicago Board Option Exchange's S&P500 volatility index), VDAX (Deutsche Borse's DAX-30 volatility index), VCAC (Euronext-Paris' CAC-40 volatility index), VFTSE (Euronext's FTSE100 volatility index), VSMI (SWX Swiss Exchange's SMI volatility index), VXJ (Nikkei 225 volatility index), VKOSPI (Korea's KOSPI200 volatility index) and VHSI (Hong Kong Hang Seng volatility index).[6] Second, commodity markets are commonly considered as an alternative asset class. Conditions in financial markets can be transmitted to commodity markets through portfolio flows including the so-called carry trade (Frankel, 2014). In this paper, we consider 2 commodity volatility series, which are the CBOE's Crude Oil ETF (US Oil Fund, L.P.) volatility index (OVX) and Gold ETF (SPDR Gold Shares) volatility index (GVZ).[7] All these 10 implied volatility indices are model-free measures for the market's expectation of 30-day volatility and their squares approximate the model-free implied variance of Britten-Jones and Neuberger (2000) and the risk-neutral expected value of return variance of Carr and Wu (2009) over a 30-day horizon.

[Table 1 here]

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[6] We focus primarily on developed equity markets because of the availability of implied volatility data. Some emerging markets have had implied volatility indices only recently.

[7] Although metals and agricultural products also form a significant portion of the commodity market, we do not include them in the study because their implied volatility indices are not readily available.

We also include a widely-followed measure of US bond yield volatility, MOVE, the Bank of America Merrill Lynch's Treasury Option Volatility Estimate Index.[8] It has been widely cited among practitioners that MOVE is the US government bond market's equivalent to US VIX. 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.

Our sample runs from June 2008 when the Gold VIX index became available to April 2013 for 1218 daily observations. As shown in Figure 1, all volatility indices increased sharply during the 2008 global financial crisis and have generally decreased since then, albeit with some smaller spikes. Stock and commodity market volatilities of VIX indices range from 10% to 100%, while Treasury bond yield volatilities are much smaller with the value of MOVE in the range of between 0.5% and about 2.5%. The similar patterns of volatility movements suggest a strong spillover effect. However, a first glance at Figure 1 does not reveal the structure and dynamics of global volatility spillover, which will be explored below.

[Figure 1 here]

Following the literature (Ang, Hodrick, Xing, and Zhang, 2006; Dennis, Mayhew, and Stivers, 2006), we take first-differences of the above volatility series and summarize their statistics in Table 1. The daily changes of implied volatilities are quite small while their standard deviation ranges from 0.05% for MOVE to 2.51% for French VIX. Although the skewnesses and

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

kurtosises of all implied volatility changes are positive, the magnitudes of fat tails are much greater than those of their long tail counterparts. Jarque-Bera tests indicate that all daily changes of implied volatilities are not normally distributed. AR1 tests suggest strong serial autocorrelations for most volatility changes. Also, ADF tests show that all implied volatilities are stationary in the first differences.

For simplicity, they are called US VIX, German VIX, French VIX, UK VIX, Swiss VIX, Japanese VIX, Korean VIX, Hong Kong VIX, Oil VIX, Gold VIX, and Treasury bond yield volatilities and hereafter are referred to as “US”, “DE”, “FR”, “UK”, “CH”, “JP”, “KR”, “HK”, “OIL”, “GOLD” and “MOVE” respectively.

3. Empirical Methodology

To address nonsynchronous trading issues, we follow Forbes and Rigobon (2002) and compute a two-day rolling-average of first differences of volatility indices.[9] With these series of volatility changes, we examine volatility spillovers across countries and asset classes in a two-pass procedure.

3.1. A Refined Structural VAR

We first run the vector autoregressive (VAR) for a vector of rolling-average, two-day changes in implied volatility indices, $\Delta\mathbf{IV_t}$, as follows,

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

where **C** is a vector of constants**,** $\mathbf{\Phi}$ is the matrix of dynamic coefficients and $\boldsymbol{\varepsilon}$ is a vector of residuals.

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[9] 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.

VAR 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, and theory-based orderings are often subjective or even arbitrary.

To overcome this problem, we let the data speak for themselves concerning the contemporaneous causal relations, thereby yielding a credible ordering of variables in the VAR. The technique we adopt is a recent advance in causality analysis, namely the direct acyclic graph (DAG). While the well-known Granger causality exploits time-series causal relations and is typically applied to two variables, DAG can uncover the contemporaneous causality network among a set of VAR variables in a data-determined and thus more credible manner (Swanson and Granger, 1997). See Pearl (2000) for more discussion of DAG and Wang, Yang and Li (2007) and Yang and Zhou (2013) for applications of DAG in finance.

DAG does not indicate the size or economic significance of the identified contemporaneous causality. However, it provides guidance for the ordering of variables and thus improves on the subsequent structural VAR analysis, which yields the size or economic significance of the associations. Specifically, we estimate the forecast error variance decomposition from the DAG-based structural VAR to quantify volatility spillover intensities and time variation. To see this, we rewrite Equation (1) as an infinite moving average process:

$$\mathbf{\Delta IV}_t = \sum_{i=0}^{\infty} \mathbf{\Omega}_i \boldsymbol{\varphi}_{t-i} \,, \qquad t = 1, 2, \ldots, T \tag{2}$$

The matrix $\sum_i$ can be interpreted intuitively as the so-called impulse response. The error from the *H*-step-ahead forecast of $\mathbf{\Delta IV}_t$ conditional on information available at *t*-1 is:

$$\xi_{t,H} = \sum_{h=0}^{H-1} \mathbf{\Omega}_h \boldsymbol{\varphi}_{t+H-h} \,, \tag{3}$$

with variance–covariance matrix

$$Cov(\xi_{t,H}) = \sum_{h=0}^{H} \mathbf{\Omega}_h \mathbf{\Sigma} \mathbf{\Omega}_h^{'} \,, \tag{4}$$

where $\mathbf{\Sigma}$ is the variance–covariance matrix of the error term in Equation (1).

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%. They are *weights* measuring how much innovation contributes to the variance of the total n-step-ahead forecast error for each element in $\mathbf{\Delta IV}_t$ and thus are the intensity of each 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*th 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

Following Diebold and Yilmaz (2014), we construct the spillover matrix based on assessing shares of forecast error variance decompositions as follows:

	ΔIV_1	ΔIV_2	…	ΔIV_N	IN
ΔIV_1	$S_{1\leftarrow 1}^{H}$	$S_{1\leftarrow 2}^{H}$	…	$S_{1\leftarrow N}^{H}$	$\sum_j S_{1\leftarrow j}^{H}$, $j \neq 1$
ΔIV_2	$S_{2\leftarrow 1}^{H}$	$S_{2\leftarrow 2}^{H}$	…	$S_{2\leftarrow N}^{H}$	$\sum_j S_{2\leftarrow j}^{H}$, $j \neq 2$
…	…	…	…	…	…
ΔIV_N	$S_{N\leftarrow 1}^{H}$	$S_{N\leftarrow 2}^{H}$	…	$S_{N\leftarrow N}^{H}$	$\sum_j S_{N\leftarrow j}^{H}$, $j \neq N$
OUT	$\sum_i S_{i\leftarrow 1}^{H}$, $i \neq 1$	$\sum_i S_{i\leftarrow 2}^{H}$, $i \neq 2$	…	$\sum_i S_{i\leftarrow N}^{H}$, $i \neq N$	$\sum_i \sum_j S_{i\leftarrow j}^{H}$, $i \neq j$

In the spillover matrix, column variables are the origin of spillovers while row variables are the spillover receivers. Spillover effects are shown in the pairwise level and also aggregated to market-wide and system-wide measures. We begin with the most disaggregated pairwise spillover effect as follows:

$$S_{i\leftarrow j}^{H}=\frac{\sum_{h=0}^{H-1}a_{ij,h}^{2}}{\sum_{h=0}^{H-1}trace(\mathbf{A_h}\mathbf{A_h^{'}})}, \tag{5}$$

where $a_{ij,h}$ is the element in the *i*-th row and the *j*-th column of the coefficient matrix of the moving average process $\mathbf{A_h}$. $\sum_{h=0}^{H-1}a_{ij,h}^{2}$ is the contribution to the *H*-step-ahead error variance in forecasting volatility *i* due to shocks to volatility *j*. $\sum_{h=0}^{H-1}trace(\mathbf{A_h}\mathbf{A_h^{'}})$ is the total *H*-step-ahead forecast error variation. Therefore, the ratio in Equation (5) is the percentage of market *i*'s variations explained by market *j*'s innovations and thus is a general measure of pairwise volatility spillover intensity from market *j* to *i*.

$S_{i\leftarrow j}^{H}$ and $S_{j\leftarrow i}^{H}$ are analogous to bilateral imports and exports of country *i* from and to country *j*, respectively. In general, $S_{i\leftarrow j}^{H}\neq S_{j\leftarrow i}^{H}$. Analogous to bilateral trade balance, the net pairwise directional spillover intensity (*NS*) can be defined as :

$$NS_{i\leftarrow j}^{H}=S_{i\leftarrow j}^{H}-S_{j\leftarrow i}^{H} \tag{6}$$

Note that net pairwise spillover effects between two markets can either be negative or positive with the property $NS_{i\leftarrow j}^{H}=-NS_{j\leftarrow i}^{H}$.

Labeled "IN" and "OUT" in the spillover matrix, the off-diagonal pairwise volatility spillover effects are aggregated on each row and column to represent the market-wide's total spillover effects from others to *i*,

$$TS^{H}_{IN,i\leftarrow\bullet} = \sum_{j} S^{H}_{i\leftarrow j} \text{ , for } i{\neq}j \tag{7}$$

and to others from *j*,

$$TS^{H}_{OUT,\bullet\leftarrow j} = \sum_{i} S^{H}_{i\leftarrow j} \text{ , for } i{\neq}j \tag{8}$$

$TS^{H}_{IN,i\leftarrow\bullet}$ and $TS^{H}_{OUT,\bullet\leftarrow j}$ are analogous to a country's total imports and exports from and to others, respectively.

Similarly, we can define a market's net total directional spillover (*NTS*) effects analogous to a country's total trade balance,

$$NTS^{H}_{i} = TS^{H}_{OUT,\bullet\leftarrow i} - TS^{H}_{IN,i\leftarrow\bullet} = \sum_{j} NS^{H}_{j\leftarrow i} \text{ ,} \tag{9}$$

and a market's gross total spillover (*GTS*) effects in Equation (10), which is analogous to a country's gross trade volume.

$$GTS^{H}_{i} = TS^{H}_{OUT,\bullet\leftarrow i} + TS^{H}_{IN,i\leftarrow\bullet} \tag{10}$$

Furthermore, the market-wide volatility spillover effects in the last row or equivalently in the last column are aggregated across markets to represent the system-wide total spillover (*STS*) effects, as follows:

$$STS^{H} = \sum_{i} TS^{H}_{IN,i\leftarrow\bullet} = \sum_{j} TS^{H}_{OUT,\bullet\leftarrow j} = \sum_{i}\sum_{j} S^{H}_{i\leftarrow j} \text{ , for } i{\neq}j \tag{11a}$$

where STS^{H} sums up the shares of the *H*-step-ahead forecast error variance of all the off-diagonal entries in the spillover matrix. A related measure proposed by Diebold and Yilmaz (2014) is the average system-wide total spillover, which is standardized by the number of markets

$$ASTS^{H} = \frac{1}{N} STS^{H} \ . \tag{11b}$$

Both measures in Equation (11a) and Equation (11b) aggregate global volatility spillovers across markets into a single value shown at the bottom right, which is analogous to total world trade.

To examine the dynamics of pairwise, market-wide and system-wide spillovers defined in Equations (5) to (11), we estimate the variance decomposition recursively each period with an expanding sample after the initial sample period. By extending Diebold and Yilmaz's (2014) rolling sample spillovers, our recursive estimation of spillovers is appealing for two reasons. First, volatility typically has a long memory in the sense that the impact of a shock in early volatility is very persistent. Thus, recursive estimation is better in modeling volatility dynamics. Second, the outcome of the recursive estimation is a sample of spillover estimates which are updated in a Bayesian matter. In particular, the initial estimate is essentially a Bayesian prior and the subsequent estimates make the best use of prior information and currently updated information.

With recursively estimated spillovers, we define marginal net pairwise directional spillover intensity (*MNS*), as follows:

$$MNS^{H}_{t,i\leftarrow j} = NS^{H}_{t,i\leftarrow j} - NS^{H}_{t-1,i\leftarrow j} = (S^{H}_{t,i\leftarrow j} - S^{H}_{t,j\leftarrow i}) - (S^{H}_{t-1,i\leftarrow j} - S^{H}_{t-1,j\leftarrow i}) \tag{12}$$

where $NS^{H}_{t,i\leftarrow j}$ is the net pairwise spillover intensity from market *j* to *i* conditional on information up to *t*. The first difference of $NS^{H}_{t,i\leftarrow j}$ measures the marginal net effect of newly updated information at time *t* on spillover intensity from market *j* to *i*. A positive (negative) $MNS^{H}_{t,i\leftarrow j}$ suggests that the net spillover intensity from market *j* to *i* increases (decreases) when an innovation (event) occurs at time *t*.

Based on Equation (12), *MNS* have the property $MNS^{H}_{t,i\leftarrow j} = -MNS^{H}_{t,j\leftarrow i}$ and thus the sum of all *MNS* in the system is equal to zero. However, this does not mean that the shock has no system-wide effect. To identify the innovations (events) which provoke significant global volatility spillovers, we sum up all positive marginal net pairwise spillover (*MNS*) as the following system-wide total positive marginal net spillover (*TPMNS*):

$$TPMNS_t^H = \sum_{MNS_{t,i\leftarrow j}^H > 0} MNS_{t,i\leftarrow j}^H \tag{13}$$

Furthermore, we can construct the following marginal net spillover matrix

	ΔIV$_1$	ΔIV$_2$	…	ΔIV$_\text{N}$	Marginal Net In
ΔIV$_1$	0	$MNS_{t,1\leftarrow 2}^H$	…	$MNS_{t,1\leftarrow N}^H$	$\sum_{\substack{j \\ j\neq 1}} MNS_{t,1\leftarrow j}^H$
ΔIV$_2$	$MNS_{t,2\leftarrow 1}^H$	0	…	$MNS_{t,2\leftarrow N}^H$	$\sum_{\substack{j \\ j\neq 2}} MNS_{t,2\leftarrow j}^H$
…	…	…	…	…	…
ΔIV$_\text{N}$	$MNS_{t,N\leftarrow 1}^H$	$MNS_{t,N\leftarrow 2}^H$	…	0	$\sum_{\substack{j \\ j\neq N}} MNS_{t,\text{N}\leftarrow j}^H$
Marginal Net Out	$\sum_{\substack{i \\ i\neq 1}} MNS_{t,i\leftarrow 1}^H$	$\sum_{\substack{i \\ i\neq 2}} MNS_{t,i\leftarrow 2}^H$	…	$\sum_{\substack{i \\ i\neq N}} MNS_{t,i\leftarrow N}^H$	

where "Marginal Net In" and "Marginal Net Out" are market-wide's total marginal net spillover (*TMNS*) effects from others to *i* and to others from *j* and defined, respectively, as follows:

$$TMNS_{IN,t,i}^H = MNS_{t,i\leftarrow\bullet}^H = \sum_j MNS_{t,i\leftarrow j}^H = \sum_j (NS_{t,i\leftarrow j}^H - NS_{t-1,i\leftarrow j}^H)\text{, for } i\neq j \tag{14}$$

and

$$TMNS_{OUT,t,j}^H = MNS_{t,\bullet\leftarrow j}^H = \sum_i MNS_{t,i\leftarrow j}^H = \sum_i (NS_{t,i\leftarrow j}^H - NS_{t-1,i\leftarrow j}^H)\text{, for } i\neq j \tag{15a}$$

We can rewrite the total marginal net out spillover in Equation (15a) as the difference between market-wide total marginal spillover effects

$$TMNS_{OUT,t,j}^H = TMS_{OUT,t,j}^H - TMS_{IN,t,j}^H\text{,} \qquad \text{for market } j \tag{15b}$$

where *TMS* is market-wide total marginal out or in spillover effect when an innovation is introduced. In particular,

$$TMS^{H}_{IN,t,j} = TMS^{H}_{t,j\leftarrow\bullet} = \sum_i S^{H}_{t,j\leftarrow i} - \sum_i S^{H}_{t-1,j\leftarrow i} \text{ , for } i\neq j \tag{16}$$

and

$$TMS^{H}_{OUT,t,j} = TMS^{H}_{t,\bullet\leftarrow j} = \sum_i S^{H}_{t,i\leftarrow j} - \sum_i S^{H}_{t-1,i\leftarrow j} \text{ , for } i\neq j \tag{17}$$

These marginal spillover measures in Equations (12) to (17) further extend Diebold and Yilmaz (2014) by capturing structural changes of global volatility spillover networks which are conditional on shocks at time *t* and providing a tool with which to conduct an event study in a network system.

4. Empirical Results

The results are organized as follows. First, there is the statics result of the network structure of global volatility spillover. Next, there is the result of market-wide and system-wide volatility spillover dynamics. Finally, we discuss the network dynamics of pairwise volatility spillover changes around various events.

4.1. Results on Statics Analysis

We first run a VAR in Equation (1) with two-day rolling average changes of the 11 implied volatility indices under consideration and lag of 2, as suggested by Schwarz's Bayesian Criterion, and then conduct the DAG analysis with the variance-covariance matrix of the VAR residuals. The resulting directed graph[10] shows that US stock and bond markets appear to be the prime volatility suppliers in contemporaneous time to other markets. US Treasury bond yield volatility (MOVE) is an exogenous source of volatility spillover and US stock volatility (VIX) is at the center of volatility spillover network as VIX is affected by MOVE and in turn affects many

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[10] The result is at the 10% significance level. It looks similar at the 5% or lower significance level. The directed graph is not reported to save space, but available from the authors upon request.

other market volatilities, such as Oil VIX, Gold VIX, German VIX, and UK VIX.

Although the contemporaneous causal pattern identified with DAG analysis of the correlation matrix does not indicate the size or economic significance, it provides a data-determined solution to the problem of ordering variables. The subsequent DAG-based structure VAR analysis and forecast error variance decomposition yield the size or economic significance of the associations. Table 2 presents the full sample spillover matrix based on relatively long term and stable 12-day-ahead forecast error variance decompositions, which describe the size or economic significance of pairwise, market-wide and system-wide spillovers.[11] Note that different horizons of variance decomposition allow for time-lagged dynamic causal linkages in addition to contemporaneous causal linkages. We report 12-day-ahead variance decompositions because they stabilize from this horizon ahead and beyond. Some highlights are as follows.

[Table 2 here]

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 German VIX (57.5%), UK VIX (47.4%), Swiss VIX (52.2%), French VIX (41.8%), Korean VIX (35.6%), Japanese VIX (22.7%), HK VIX (32.1%), Gold VIX (18.7%), and Oil VIX (23.2%). Totally, US VIX spillover to others is 333.1% whereas it only receives 13.8% spillover from others.

Second, MOVE is mostly explained by its own shocks with the variance decomposition of 92.8% for itself; this is consistent with the earlier observation in Figure 2 that Treasury bond yield volatility is largely exogenous. The total spillover from MOVE to others is 30.9%; this is much lower than its US VIX spillover counterpart. However, the total spillover MOVE receives

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[11] Note that different horizons of variance decomposition allow for time-lagged dynamic causal linkages in addition to contemporaneous causal linkages. We report 12-day-ahead variance decompositions because they stabilize from this horizon ahead and beyond.

from others is only 7.2%, thus confirming again that MOVE is exogenous relative to other markets.

Third, German VIX shock explains significant portions of variation in other European market volatilities, such as UK VIX (17.0%), Swiss VIX (22.8%), and French VIX (19.2%). Its total spillover to others is 79.2%. By contrast, the total spillover German VIX receives from others is 67.6%, mainly from US VIX. For other markets, the majority spillover they receive also comes from US VIX.

Finally, the system-wide total spillover intensity is 538.9%. Because there are 11 markets, the average total spillover to others or from others is about 49% in the system. According to this criterion, the US VIX spillover to others, 333.1%, is well above the average, whereas its spillover from others, 13.8%, is well below the average. This difference indicates that there are significant asymmetries in the roles that the US stock market spreads out and receives in terms of volatility.

Table 3 summarizes market-wide spillover effects and ranks them by their net spillover intensity. The US stock market is the biggest net sender, with a very high net US VIX spillover intensity of 319.2%. This suggests the center position of the US stock market in spreading volatility to other stock and commodity markets. The US Treasury bond market and the German stock market are also net senders with nontrivial net spillovers of 23.6% and 11.6% on other markets, respectively. In contrast, other markets are net receivers of volatility spillovers, ranging from -70.0% for the UK stock market to -19.9% for the gold market. Three major European stock markets, those in the UK, Switzerland, and France, are the ones that are most vulnerable to volatility spillovers.

[Table 3]

In Table 3, the ranking of gross total spillovers is somewhat different from that of the net total spillover. US, German and Swiss stock markets (in bold) are the top three for sending and receiving volatility. In contrast, the US Treasury bond and commodity markets (in italic type) are ranked as the bottom three for gross total spillovers, probably because they are of different asset classes other than stocks. Note that

4.2. Results on System-wide and Market-wide Spillover Dynamics

To further explore the dynamics of volatility spillovers, we estimate recursive variance decompositions each day with an expanding sample[12] and construct various volatility spillover indices. First, we aggregate all spillover effects in the whole system by summing up all off-diagonal variance decompositions each day following Equation (11a). The estimated system-wide total volatility spillover indices at various horizons are plotted in Panel A of Figure 2. There is a clear downward trend, suggesting that the total volatility spillover intensity around the world has been decreasing since 2008. This is consistent with the findings of the McKinsey Global Institute (2013) that financial globalization has been on the retreat in recent years.

[Figure 2 here]

Second, we move to market-wide total volatility spillovers to see how each market contributes to a declining world-wide spillover. In Panel B of Figure 2, US VIX total spillover to others has intensified steadily with a sharp jump on November 25, 2008 when QE1 was launched. By contrast, the outward spillover originating in other markets has been shrinking, as shown in Panel C of Figure 2. 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 world diminishes.

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[12] Long memory tests of Robinson (1995) in Table 1 suggest that the impact of a shock in early volatility is very persistent and thus recursive estimation is better in modeling volatility dynamics. The initial sample period is June 6, 2008 to November 3, 2008 and the final sample period is June 6, 2008 to April 30, 2013.

Furthermore, we take a closer look at market-wide net total spillover effects. Figure 3 plots the 12-day-ahead net spillover indices.[13] Although we do not include the figures for other horizons in order to save space, the patterns are generally similar. The net US VIX spillover index documents an intensifying pattern, similar to its total spillover to others in Panel B of Figure 2. It suggests that the US stock market spreads out more and more volatility than it receives over time. Also, the US Treasury bond market is always a net sender of volatility spillover because the MOVE net spillover index has fluctuated in a positive range with smaller magnitude. In particular, the US VIX and MOVE net spillover indices jumped with the initiation of QE1, thus suggesting that the US's QE1 is an important source of international volatility spillovers. They also record big changes around other events, such as the US stock market flash crash, Japan's earthquake and tsunami and the US credit rating downgrade.

[Figure 3 here]

The dynamics of the German VIX net spillover effect starts with a sharp jump from the negative range around QE1 and then follows an increasing trend in positive range. It implies that the German stock market was a net volatility receiver before QE1 and that it has become a net sender thereafter, spreading out more and more volatility than it receives. Notably, the magnitude of the German VIX net spillover effect is much smaller than that of VIX, although their patterns are similar. The index also appears to reflect net spillover around important events.

We can also see from Figure 3 that other markets are net volatility receivers because their net spillover indices have fluctuated in negative ranges.[14] Among them, the Japanese VIX net spillover index has bounded back since the earthquake and tsunami in March 2011, and this has

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[13] Variance decompositions stabilize from 12 days ahead and beyond. Therefore, 12-day-ahead volatility spillover indices are more robust.

[14] One exception is that the gold net spillover index starts with a positive range and jumps sharply down to negative range around QE1.

intensified the volatility spillover from the Japanese stock market, although volatility spillover into the Japanese stock market is still larger. By contrast, European stock markets and commodity markets have receive more and more volatilities than they spread. Therefore, their net spillover indices follow a decreasing trend in negative range. As for the Korean and Hong Kong stock markets, their net spillover effects were relatively stable and negative during the sample period.

Table 4 reports summary statistics of the 12-day-ahead volatility spillover indices recursively estimated from November 3, 2008 to April 30, 2013. The mean of the system-wide total volatility spillover is 561.88% with an average contribution of 51.12% from each market. For market-wide spillovers, the rankings of net and gross spillovers are similar to those in Table 3. The US VIX net and gross spillovers have much higher means and standard deviations than other volatility counterparts, reflecting its systemic importance in the global financial network. Other statistics indicate significant variations, tails and ranges of different volatility spillovers across markets.

[Table 4 here]

4.3. Results on Network Dynamics of Pairwise Spillover Changes

Having examined the dynamics of system-wide and market-wide volatility spillovers, we further explore network dynamics of pairwise spillover changes around some important events. First, it is important to identify the significant innovations (events) which provoke intensive global volatility spillovers. To this end, we estimate the total positive marginal net spillover (*TPMNS*) index. As shown in Figure 4, the initiation of QE1 is the most crucial event to induce volatility spillovers as the *TPMNS* records the biggest increase on November 25, 2008. The index also jumped dramatically during several other episodes, such as the US stock market flash crash, Japan's earthquake and tsunami and the US credit rating downgrade. Most of these shocks originated from US financial markets, except for the unexpected disturbance caused by Japan's earthquake and tsunami. Next, we proceed to focus on two important identified events, namely QE1 and the US credit rating downgrade, and conduct the network dynamics analysis as follows.[15]

[Figure 4 here]

Table 5 summarizes the market-wide total marginal spillover effects around QE1. We rank markets by their total marginal net spillovers for three business days.[16] When QE1 was announced on November 25, 2008, US VIX was at the lowest end of the ranking, meaning that the net spillover from the US stock market records the biggest decrease (-2.6%) across markets on the QE1 announcement. However, on the next two business dates, US VIX ranked at the very top with the biggest increases of total marginal net spillovers. Moreover, the increase of net US VIX spillover becomes much stronger from 4.9% on November 26 to 33.4% on November 28, mainly due to a stronger increase of outward spillover from 4.2% to 30.1%. Intuitively, the US stock market spreads out substantially more volatility than on the previous day.

[Table 5 here]

To see the source of the market-wide total marginal spillover effects, we decompose them to pairwise volatility spillover changes and then present marginal net spillover matrices around QE1, as shown in Table 6. In the upper 11×11 submatrix, a positive (negative) value of the *ij*-th entry suggests that net spillover intensity from market *j* to *i* increased (decreased) around QE1. In order to highlight the important net spillover changes, we mark the top first and five percentiles of all pairwise marginal net spillovers from November 3, 2008 to April 30, 2013 with triple stars

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[15] The results of the network dynamics analysis around other events are repressed to save space, but are available from the authors upon request.

[16] The three business dates are November 25, 26 and 28. November 27, 2008 was US Thanksgiving holiday.

and double stars, respectively. As shown in Panel A, on November 25, 2008, the US stock market was not a significant origin of a net spillover increase because only marginal net spillover of US VIX to its UK counterpart was in the top five percentiles. By contrast, there are five marginal net spillovers of MOVE in the top five percentiles, thereby suggesting that the US Treasury bond market is a network origin of net spillover increase. Other network origins are the Hong Kong stock market and commodity markets when QE1 was announced. In Panel B, immediately after the QE1 announcement, US VIX became the biggest network origin of net spillover increase; this is because three marginal net spillovers of US VIX were in the top first percentile and another six were in the top fifth percentile on November 26, 2008. In Panel C, the status of US VIX as the biggest network origin was reinforced on November 28, 2008, because all but one marginal net spillovers of US VIX were in the top first percentile and another one was in the top fifth percentile.

[Table 6 here]

Based on the top first and five percentiles of pairwise marginal net spillovers, as shown in Table 6, we present structural changes of volatility spillover networks in Figure 5.[17] Each node represents one market with the node size indicating the number of positive pairwise marginal net spillovers from this market. The thick and thin links correspond to the top first and five percentiles of pairwise marginal net spillovers, respectively. From Figure 5, we can see two important changes of volatility spillover networks around QE1. One is that spillover networks became more complex and integrated in the two trading days after the QE1 announcement, November 26 and 28 in Figure 5(b) and 6(c). More important, the US stock market moved to center stage of spillover networks, as indicated by the larger node size of US VIX, and the increases of net US VIX spillover to other markets are substantial and universal, as indicated by

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[17] Those pairwise marginal net spillovers, which are not in the top five percentiles, do not show up in Figure 5.

the number and thickness of links starting from US VIX. In sum, the QE1 announcement has intensified spillover network linkages centering on the US stock market; this is consistent with Yang and Zhou (2017) who stated that the US's QE is a primary driver of intensifying volatility spillovers from the US to the rest of the world.

[Figure 5 here]

Finally, we discuss the spillover network dynamics around the US credit rating downgrade. Table 7 summarizes the market-wide total marginal spillover effects around this credit event. On August 4, 2011, before the announcement, investors had expected the downgrade *ex ante* with growing concerns over financial risk. Therefore, the US financial markets started to spread out significantly more volatility and thus US VIX and MOVE ranked among the top two large increases of total marginal net spillovers across the markets. When the downgrade was announced on August 5, 2011, the increases of net spillover from the US stock and Treasury bond markets became stronger to 3.8% and 1.44%, respectively. On the next trading day of August 8, 2011,[18] MOVE moved to the highest ranking with a 4.80% further increase of net spillover, and US VIX ranked second with a 3.64% further increase of net spillover, which was mainly driven by 4.66% and 4.07% increases of MOVE and US VIX outward spillovers respectively. An intuitive story is that the US financial markets, especially the US Treasury bond market, were the network origins of increased volatility spillovers caused by the US credit rating downgrade.

[Table 7 here]

Table 8 shows marginal net spillover matrices in which market-wide total marginal spillover effects, as shown in Table 7, break down into pairwise volatility spillover changes. On August 4, 2011, as shown in Panel A of Table 8, there were five marginal net spillovers of US

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[18] Note that August 6 and 7, 2011 both fell on a weekend.

VIX in the top fifth percentiles, thereby suggesting that the US stock market is a network origin of net spillover increase. In Panel B, MOVE started to emerge as an origin of net spillover increase with three in the top fifth percentile when the downgrade occurred on August 5, 2011, while US VIX remained the biggest network origin with eight marginal net spillovers in the top fifth percentile. In Panel C on August 8, 2011, MOVE replaced US VIX and became the biggest network origin because all but one marginal net spillovers of MOVE were in the top fifth percentile.

[Table 8 here]

The top fifth percentile of pairwise marginal net spillovers in Table 8 are plotted in Figure 6, where the spillover network became more complex with intensifying linkages when the credit event occurred. Also, it is clear from Figure 6 that the US stock and Treasury bond markets were the network origins with substantial increases of net spillover to other markets. The finding extends Yang and Zhou (2017), which documents that the US is the center of the international volatility spillover network.

[Figure 6 here]

5. Conclusions

In this study, we provide a new tool for event studies in a network setting and document systemic risk in the networks of implied volatility spillovers across global financial markets. In particular, network linkages are sufficiently asymmetric because the US stock and bond markets play as dominant volatility suppliers to other countries and markets. The shocks from the US, such as US QE1 and credit downgrade, generate intensifying volatility spillovers and thus potential systemic risk. It offers new evidence for the recent theory that idiosyncratic shocks may lead to sizable aggregate fluctuations in the system if network linkages are sufficiently asymmetric.

References

Acemoglu, D., Carvalho, V.M., Ozdaglar, A., Tahbaz-Salehi, A., 2012. The network origins of aggregate fluctuations. *Econometrica* 80, 1977-2016.

Acemoglu, D., Ozdaglar, A., Tahbaz-Salehi, A., 2015. Systemic Risk and Stability in Financial Network. *American Economic Review* 105: 564-608.

Allen, F., Babus, A., 2009. Networks in finance. The network challenge. Edited by Paul Kleindorfer and Jerry Wind. Wharton School Publishing, 367-382.

Allen, F., D. Gale. 2000. Financial Contagion. *Journal of Political Economy* 108, 1-33.

Ang, A., Hodrick, R., Xing, Y., Zhang, X., 2006. The cross-section of volatility and expected returns. Journal of Finance 61, 259–299.

Bessler, D.A., Yang. J., 2003. The Structure of interdependence in international stock markets. Journal of International Money and Finance 22, 261-287.

Black, F., 1976, Studies of stock price volatility changes. *Proceedings of the 1976 ASA Meeting of Business and Economic Statistics Section*, 177-181.

Britten-Jones, M., Neuberger, A., 2000, Option prices, implied processes, and stochastic volatility. *Journal of Finance* 59, 711-753.

Carr, P., Wu, L., 2009, Variance risk premiums. *Review of Financial Studies* 22, 1311-1341.

Dennis, P., Mayhew, S., Stivers, C., 2006. Stock returns, implied volatility innovations and the asymmetric volatility phenomenon. *Journal of Financial and Quantitative Analysis* 41, 381-406.

Diebold, F.X., Yilmaz, K., 2014. On the network topology of variance decompositions: measuring the connectedness of financial firms. Journal of Econometrics 182, 119-134.

Elliott, M., Golub, B., Jackson, M., 2014. Financial Networks and Contagion. *American*

Economic Review 104, 3115-3153.

Engle, R.F. Gallo, G.M., Velucchi, M., 2012. Volatility spillover in east Asian financial markets: a MEM-based approach. *Review of Economics and Statistics* 58, 222-233.

Financial Stability Board, 2009. Guidance to assess the systemic importance of financial instituitions, markets and instruments. Report to G20 Finance Ministers and Governors.

Forbes, K. J., Rigobon, R., 2002. No contagion, only interdependence: measuring stock market comovements. *Journal of Finance* 57, 2223-2261.

Frankel, J.A. 2014. Effects of Speculation and Interest Rates in a “Carry Trade” Model of Commodity Prices. *Journal of International Money and Finance* 42, 88-112.

Koutmos, G., Booth, G.G., 1995. Asymmetric Volatility Transmission in International Stock Markets. *Journal of International Money and Finance*. 14, 747-762

McKinsey Global Institute, 2013. Financial globalization: retreat or reset. Reports on State of Global Capital Markets.

Pearl, J., 2000, Causality: Models, Reasoning, and Inference. Cambridge, UK: Cambridge University Press.

Solnik, B., T. Watewai. 2016. International Correlation Asymmetries: Frequent-but-Small and Infrequent-but-Large Equity Returns. *Review of Asset pricing Studies*, forthcoming.

Swanson, N., Granger, C.W.J., 1997. Impulse response functions based on a causal approach to residual orthogonalization in vector autoregression. *Journal of the American Statistical Association* 92, 357-367.

Wang, Z., Yang, J., Li., Q., 2007. Interest rate linkages in the Eurocurrency market: contemporaneous and out-of-sample granger causality tests. *Journal of International Money and Finance* 26, 86-103.

Yang, J., Zhou, Y., 2013, Credit risk spillover among financial institutions around the global credit crisis: firm-level evidence. Management Science 59, 2343-2359.

Yang, Z., Zhou, Y., 2017. Quantitative easing and volatility spillover across countries and asset classes. *Management Science* 63, 333-354.

Zhou, Y., 2014. Modeling the joint dynamics of risk neutral stock index and bond yield volatilities. *Journal of Banking and Finance* 38, 216-228.

Table 1. Summary of Daily Implied Volatility Indices

This table summarizes the daily implied volatility indices 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. “French VIX” (hereafter FR) is the Euronext-Paris’s CAC-40 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. “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. “Oil VIX” (hereafter OIL) is the CBOE Crude Oil ETF Volatility Index. “Gold VIX” (hereafter GOLD) is the CBOE Gold ETF Volatility Index. MOVE is the Bank of America Merrill Lynch’s US Treasury Option Volatility Estimate Index. The first order autocorrelation AR1, the Jarque–Bera, 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 June 6, 2008–April 30, 2013. *Nobs* denotes the number of observations.

Index	*Abbreviation*	*Underlying index or asset*	*Pricing model*	Summary statistics for daily changes in the implied volatility indices							
				mean	*Std.dev*	*skewness*	*kurtosis*	*Jarque-Bera*	*AR1*	*ADF*	*Nobs*
US VIX	US	S&P500	Model-free	0.002	2.379	0.661	15.482	327.28***	-0.088***	-15.223***	1217
German VIX	DE	DAX30	Model-free	-0.008	2.020	1.488	22.053	561.975***	0.101***	-19.584***	1217
UK VIX	UK	FTSE100	Model-free	-0.014	2.024	0.760	15.368	345.923***	-0.011	-15.766***	1217
Swiss VIX	CH	SMI	Model free	-0.012	1.624	0.366	27.824	366.865***	0.196***	-15.523***	1217
French VIX	FR	CAC40	Model free	-0.004	2.513	0.694	24.883	406.391***	-0.094***	-29.693***	1217
Korean VIX	KR	KOSPI 200	Model-free	-0.026	2.064	2.267	31.005	776.374***	-0.137***	-25.031***	1217
Japanese VIX	JP	Nikkei 255	Model-free	0.002	2.402	2.168	32.654	763.498***	0.006	-22.369***	1217
HK VIX	HK	Hang Seng Index	Model-free	-0.027	2.051	1.505	18.890	542.299***	-0.056**	-16.276***	1217
Gold VIX	GOLD	SPDR Gold EFT	Model-free	-0.015	1.510	1.841	16.568	594.761***	0.003	-28.084***	1217
Oil VIX	OIL	Crude oil ETF	Model-free	-0.023	2.160	1.223	14.686	439.533***	-0.148***	-14.753***	1217
MOVE	MOVE	US Treasury options	Black (1976)	-0.001	0.048	0.374	11.661	232.534***	0.106***	-14.382***	1217

Table 2. Spillover Matrix of Daily Implied Volatility Indices

This table reports the full sample spillover matrix among volatilities of global financial markets from June 6, 2008 to April 30, 2013. Column variables are the origin of spillovers while row variables are the spillover receivers. The ij-th entry of the upper-left 11×11 submatrix is the pairwise spillover intensity from volatility j to i in Eq. (5), which is 12-day-ahead forecast error variance decomposition (percentage points) of volatility i explained by shocks from j. The variance decomposition is from a structural VAR based on the direct acyclic graph given in Figure 2. The rightmost ("IN") column summarizes the market-wide's total spillover effects from all others to i in Eq. (7), which is the row sum of the off-diagonal pairwise spillover. The bottom-most ("OUT") row summarizes the market-wide's total spillover to all others from j in Eq. (8), which is the column sum of the off-diagonal pairwise spillovers. The bottom-right element (in boldface) is the system-wide total spillover in Eq. (11a), which is the sum of "IN" spillovers or, equivalently, the sum of "OUT" spillovers. The average system-wide total spillover in Eq. (11b) is also reported in parentheses.

	US	MOVE	UK	DE	FR	CH	JP	HK	KR	GOLD	OIL	IN
US	86.2	4.3	0.2	1.5	1.9	0.8	0.0	1.8	2.7	0.6	0.0	13.8
MOVE	1.9	92.8	0.3	1.7	1.2	1.3	0.2	0.4	0.1	0.0	0.0	7.2
UK	47.4	2.8	23.2	17.0	1.9	3.8	0.0	0.7	2.9	0.4	0.0	76.8
DE	57.5	3.2	0.1	32.4	0.5	1.3	0.2	0.8	3.1	0.8	0.0	67.6
FR	41.8	2.9	3.1	19.2	28.6	0.8	0.0	0.5	1.9	1.1	0.3	71.4
CH	52.2	2.4	0.1	22.8	1.4	17.1	0.0	1.2	2.3	0.4	0.0	82.9
JP	22.7	1.7	0.7	2.1	1.7	1.1	55.7	8.6	5.6	0.0	0.0	44.3
HK	32.1	4.5	1.1	2.6	5.6	0.6	0.1	51.2	0.9	1.0	0.2	48.8
KR	35.6	2.6	0.9	7.5	2.7	1.2	0.0	10.5	38.3	0.7	0.0	61.7
GOLD	18.7	4.9	0.2	0.4	0.1	1.4	0.4	0.6	0.7	72.6	0.1	27.4
OIL	23.2	1.6	0.1	4.4	0.0	0.9	0.0	1.4	2.7	2.6	63.1	36.9
OUT	333.1	30.9	6.8	79.2	17.1	13.1	1.0	26.5	23.0	7.6	0.7	**538.9** **(49.0)**

Table 3. Market-wide Spillover Effects and Ranking of Net Senders and Receivers

This table summarizes market-wide spillover effects and the ranking of volatility indices from high to low net spillover. IN and OUT are market-wide's total spillover effects from and to all other markets defined in Eq. (7) and Eq. (8), respectively. NET is the difference between "OUT" and "IN" defined in Eq. (9). GROSS is the sum of "OUT" and "IN" defined in Eq. (10). The predictive horizon is 12 days and the variance decomposition is from a structural VAR based on the direct acyclic graph given in Figure 2.

Rank	Index		NET	OUT	IN	GROSS
1	US	**Net Senders**	319.2	333.1	13.8	**346.9**
2	MOVE		23.6	30.9	7.2	*38.1*
3	DE		11.6	79.2	67.6	**146.8**
4	GOLD	**Net Receivers**	-19.9	7.6	27.4	*35.0*
5	HK		-22.2	26.5	48.8	75.3
6	OIL		-36.2	0.7	36.9	*37.6*
7	KR		-38.7	23	61.7	84.7
8	JP		-43.3	1	44.3	45.3
9	FR		-54.3	17.1	71.4	88.5
10	CH		-69.8	13.1	82.9	**96.0**
11	UK		-70.0	6.8	76.8	83.6

Table 4. Summary Statistics of Daily System-wide and Market-wide Volatility Spillover Indices

This table presents summary statistics for daily system-wide and market-wide volatility spillover indices from November 3, 2008 to April 30, 2013. The system-wide total spillover index and the corresponding average index with its summary statistics reported in parentheses are recursive variance decomposition estimates based on Eq.(11a) and Eq.(11b), respectively. The market-wide net total and gross total spillover indices are recursive variance decomposition estimates based on Eq. (9) and Eq. (10), respectively.

Level of Aggregation	*Source Market(s)*	*Spillover index*	*Nobs*	*Mean*	*Std Dev.*	*Skew*	*Kurt*	*Min*	*Max*
system-wide	all markets	Total	1124 (1124)	561.88 (51.12)	27.51 (2.62)	2.45 (2.60)	10.51 (11.53)	535.80 (48.71)	720.24 (66.63)
market-wide	US stocks	Net total	1124	296.28	20.08	-1.21	6.97	192.10	321.08
market-wide	US Treasury bonds	Net total	1124	23.01	5.88	0.91	9.17	5.15	61.05
market-wide	Germany stocks	Net total	1124	9.28	3.36	-2.41	13.33	-11.39	16.32
market-wide	Gold	Net total	1124	-13.90	6.58	0.67	2.88	-21.70	17.36
market-wide	Hong Kong stocks	Net total	1124	-19.69	3.17	0.36	2.03	-28.42	-7.67
market-wide	Oil	Net total	1124	-28.92	6.38	0.15	1.81	-37.07	-8.97
market-wide	Korean stocks	Net total	1124	-38.00	2.22	3.83	41.58	-46.21	-12.95
market-wide	French stocks	Net total	1124	-46.82	5.68	0.26	1.83	-54.34	-26.01
market-wide	Japanese stocks	Net total	1124	-49.14	6.52	0.17	1.31	-57.84	-38.18
market-wide	UK stocks	Net total	1124	-65.84	5.86	4.10	24.02	-70.15	-19.86
market-wide	Swiss stocks	Net total	1124	-66.26	4.04	1.73	9.59	-71.03	-38.73
market-wide	US stocks	Gross total	1124	333.26	12.40	-0.56	4.33	276.16	349.37
market-wide	Germany stocks	Gross total	1124	147.98	1.78	3.43	33.01	145.52	171.57
market-wide	Swiss stocks	Gross total	1124	100.50	4.54	2.09	11.34	96.05	131.99
market-wide	Korean stocks	Gross total	1124	95.98	10.62	1.49	6.25	84.65	152.81
market-wide	French stocks	Gross total	1124	90.46	3.54	4.00	22.27	87.85	115.78
market-wide	UK stocks	Gross total	1124	88.70	7.49	3.36	17.36	83.57	136.38
market-wide	Hong Kong stocks	Gross total	1124	81.52	7.20	2.17	9.61	74.62	119.54
market-wide	Japanese stocks	Gross total	1124	55.72	10.26	0.41	2.22	43.16	90.40
market-wide	US Treasury bonds	Gross total	1124	47.35	11.31	3.28	16.18	38.03	115.98
market-wide	Gold	Gross total	1124	44.96	9.85	2.77	13.36	35.04	111.40
market-wide	Oil	Gross total	1124	38.22	4.26	4.54	25.93	34.81	69.17

Table 5. Market-wide Total Marginal Spillovers Effects around QE1

This table presents market-wide total marginal spillover effects around the QE1 announcement on November 25, 2008. $TMS^{12}_{IN,t,j}$ and $TMS^{12}_{OUT,t,j}$ are the total marginal spillover effects at the horizon of 12 days from others to j and to others from j defined in Eq. (16) and Eq. (17), respectively. As a measure of the total marginal net spillover effects to others from j, $TMNS^{12}_{OUT,t,j}$ is the difference between "$TMS^{12}_{OUT,t,j}$" and "$TMS^{12}_{IN,t,j}$" defined in Eq. (15b). The variables are ranked from the highest to lowest total marginal net spillover effects each day.

2008/11/25					2008/11/26					2008/11/28				
Rank	Market	$TMNS^{12}_{OUT,t,j}$	$TMS^{12}_{OUT,t,j}$	$TMS^{12}_{IN,t,j}$	Rank	Market	$TMNS^{12}_{OUT,t,j}$	$TMS^{12}_{OUT,t,j}$	$TMS^{12}_{IN,t,j}$	Rank	Market	$TMNS^{12}_{OUT,t,j}$	$TMS^{12}_{OUT,t,j}$	$TMS^{12}_{IN,t,j}$
1	HK	3.0	2.1	-0.9	1	US	4.9	4.2	-0.6	1	US	33.4	30.1	-3.3
2	OIL	2.0	0.1	-1.9	2	FR	3.0	2.0	-1.0	2	FR	7.5	6.4	-1.1
3	FR	1.7	0.9	-0.8	3	KR	2.9	2.3	-0.5	3	JP	0.7	0.4	-0.2
4	GOLD	0.2	0.9	0.7	4	OIL	2.3	1.7	-0.7	4	CH	0.4	0.5	0.1
5	JP	0.2	-0.5	-0.6	5	DE	0.5	0.2	-0.3	5	KR	0.2	0.0	-0.2
6	DE	-0.2	-0.2	-0.0	6	GOLD	-0.3	0.9	1.2	6	DE	-0.3	-0.4	-0.2
7	MOVE	-0.3	-0.7	-0.4	7	JP	-0.7	-0.4	0.3	7	GOLD	-2.8	-3.7	-0.9
8	CH	-0.5	-0.3	0.2	8	CH	-1.2	-1.1	0.2	8	UK	-4.8	-4.4	0.4
9	KR	-1.2	-1.2	0.0	9	UK	-2.7	-2.2	0.5	9	HK	-6.4	-5.9	0.4
10	UK	-2.5	-2.0	0.5	10	HK	-4.2	-4.0	0.2	10	OIL	-9.9	-10.4	-0.5
11	US	-2.6	-2.1	0.4	11	MOVE	-4.4	-4.4	0.0	11	MOVE	-17.9	-18.1	-0.2

Table 6. Marginal Net Spillover Matrices around QE1

This table reports the marginal net spillover matrix among volatilities of US security bonds, stock markets and commodities around the QE1 announcement on November 25, 2008. The *ij*-th entry of the upper-left 11×11 submatrix is the marginal net pairwise directional spillover from volatility *j* to *i* defined in Eq. (12). The positive(negative) value in the entry suggests that net spillover intensity from market *j* to *i* increases (decreases) when an innovation (event) occurs at time *t*. The value in the entries with “***” and “**” corresponds to the first and fifth percentiles of all marginal net pairwise directional spillover from November 3, 2008 to April 30, 2013. The predictive horizon is 12 days and the variance decomposition is from a structural VAR based on the direct acyclic graph given in Figure 2. The rightmost (“Marginal Net In”) column summarizes the market-wide’s total marginal net spillover effects from all others to *i* in Eq. (14), which is row sums of the off-diagonal marginal net pairwise spillover. The bottom-most (“Marginal Net Out”) row summarizes the market-wide’s total marginal net spillover to all others from *j* in Eq. (15a), which is column sums of the off-diagonal pairwise spillovers. The positive(negative) value of “Marginal Net Out” suggests that net spillover intensity from market *j* to all others increases (decreases) when an innovation (event) occurs at time *t*.

Panel A: Marginal Net Spillover Effects on Nov. 25, 2008

	US	MOVE	UK	DE	FR	CH	JP	HK	KR	GOLD	OIL	Marginal Net In
US	0.0	0.8^{***}	-0.5	0.3^{**}	0.1	0.2^{**}	0.3^{**}	0.2^{**}	0.3^{**}	0.3^{**}	0.5^{**}	2.6
MOVE	-0.8	0.0	-0.7	0.0	-0.2	-0.4	0.6^{**}	0.5^{**}	0.4^{**}	-0.3	1.1^{***}	0.3
UK	0.5^{**}	0.7^{**}	0.0	-0.2	0.6^{**}	0.2^{**}	-0.1	0.4^{**}	-0.1	1.0^{***}	-0.6	2.5
DE	-0.3	0.0	0.2^{**}	0.0	0.0	0.1	0.0	0.1	-0.3	0.3^{**}	0.1	0.2
FR	-0.1	0.2^{**}	-0.6	0.0	0.0	0.0	-0.1	-0.5	-0.3	-0.3	0.1	-1.7
CH	-0.2	0.4^{**}	-0.2	-0.1	0.0	0.0	0.0	-0.1	0.0	0.7^{**}	0.0	0.5
JP	-0.3	-0.6	0.1	0.0	0.1	0.0	0.0	0.4^{**}	-0.2	0.2^{**}	0.3^{**}	-0.2
HK	-0.2	-0.5	-0.4	-0.1	0.5^{**}	0.1	-0.4	0.0	-0.9	-0.8	-0.3	-3.0
KR	-0.3	-0.4	0.1	0.3^{**}	0.3^{**}	0.0	0.2^{**}	0.9^{***}	0.0	0.1	-0.2	1.2
GOLD	-0.3	0.3^{**}	-1.0	-0.3	0.3^{**}	-0.7	-0.2	0.8^{***}	-0.1	0.0	1.0^{***}	-0.2
OIL	-0.5	-1.1	0.6^{**}	-0.1	-0.1	0.0	-0.3	0.3^{**}	0.2^{**}	-1.0	0.0	-2.0
Marginal Net Out	-2.6	-0.3	-2.5	-0.2	1.7	-0.5	0.2	3.0	-1.2	0.2	2.0	

Table 6 (Continued)

Panel B: Marginal Net Spillover Effects on Nov. 26, 2008

	US	MOVE	UK	DE	FR	CH	JP	HK	KR	GOLD	OIL	Marginal Net In
US	0.0	-1.2	-1.1	-0.3	1.2^{***}	-0.5	-0.3	-0.3	-0.6	-0.7	-1.2	-4.9
MOVE	1.2^{***}	0.0	0.7^{**}	0.8^{***}	0.2^{**}	0.5^{**}	0.1	0.1	1.2^{***}	0.5^{**}	-0.9	4.4
UK	1.1^{***}	-0.7	0.0	0.2^{**}	-0.2	0.1	0.3^{**}	-0.3	1.3^{***}	0.1	0.9^{***}	2.7
DE	0.3^{**}	-0.8	-0.2	0.0	-0.6	-0.1	0.0	-0.3	0.1	-0.2	1.4^{***}	-0.5
FR	-1.2	-0.2	0.2^{**}	0.6^{**}	0.0	0.0	-0.4	-0.5	-0.4	-0.2	-0.8	-3.0
CH	0.5^{**}	-0.5	-0.1	0.1	0.0	0.0	0.0	-0.1	0.4^{**}	0.1	0.7^{**}	1.2
JP	0.3^{**}	-0.1	-0.3	0.0	0.4^{**}	0.0	0.0	-0.2	0.1	0.2^{**}	0.5^{**}	0.7
HK	0.3^{**}	-0.1	0.3^{**}	0.3^{**}	0.5^{**}	0.1	0.2^{**}	0.0	0.6^{**}	0.1	1.9^{***}	4.2
KR	0.6^{**}	-1.2	-1.3	-0.1	0.4^{**}	-0.4	-0.1	-0.6	0.0	0.0	-0.2	-2.9
GOLD	0.7^{**}	-0.5	-0.1	0.2^{**}	0.2^{**}	-0.1	-0.2	-0.1	0.0	0.0	0.1	0.3
OIL	1.2^{***}	0.9^{***}	-0.9	-1.4	0.8^{***}	-0.7	-0.5	-1.9	0.2^{**}	-0.1	0.0	-2.3
Marginal Net Out	4.9	-4.4	-2.7	0.5	3.0	-1.2	-0.7	-4.2	2.9	-0.3	2.3	

Table 6 (Continued)

Panel C: Marginal Net Spillover Effects on Nov. 28, 2008

	US	MOVE	UK	DE	FR	CH	JP	HK	KR	GOLD	OIL	Marginal Net In
US	0.0	-2.0	-4.5	-4.9	-2.6	-3.6	-3.8	-5.1	-3.4	-2.7	-0.6	-33.4
MOVE	2.0***	0.0	1.9***	2.5***	2.4***	1.8***	2.1***	2.9***	0.8***	1.7***	-0.2	17.9
UK	4.5***	-1.9	0.0	1.1***	1.0***	0.7**	0.8***	-1.0	0.9***	-0.3	-1.2	4.8
DE	4.9***	-2.5	-1.1	0.0	0.6**	0.4**	0.2	-1.0	0.2	-0.4	-1.0	0.3
FR	2.6***	-2.4	-1.0	-0.6	0.0	-0.7	-1.0	-1.7	-0.3	-1.0	-1.2	-7.5
CH	3.6***	-1.8	-0.7	-0.4	0.7**	0.0	0.0	-1.0	0.1	-0.5	-0.5	-0.4
JP	3.8***	-2.1	-0.8	-0.2	1.0***	0.0	0.0	-0.2	-0.1	-0.4	-1.7	-0.7
HK	5.1***	-2.9	1.0***	1.0***	1.7***	1.0***	0.2**	0.0	1.4***	-0.4	-1.6	6.4
KR	3.4***	-0.8	-0.9	-0.2	0.3**	-0.1	0.1	-1.4	0.0	-0.1	-0.6	-0.2
GOLD	2.7***	-1.7	0.3**	0.4**	1.0***	0.5**	0.4**	0.4**	0.1	0.0	-1.3	2.8
OIL	0.6**	0.2**	1.2***	1.0***	1.2***	0.5**	1.7***	1.6***	0.6**	1.3***	0.0	9.9
Marginal Net Out	33.4	-17.9	-4.8	-0.3	7.5	0.4	0.7	-6.4	0.2	-2.8	-9.9	

Table 7. Market-wide Total Marginal Spillovers Effects around the US Credit Rating Downgrade

This table presents market-wide marginal total spillover effects around Standard & Poor's U.S. Downgrade on August 5, 2011 when the US lost its AAA credit rating for the first time in the history of the rating. $TMS^{12}_{IN,t,j}$ and $TMS^{12}_{OUT,t,j}$ are the total marginal spillover effect at the horizon of 12 days from others to j and to others from j defined in Eq. (16) and Eq. (17), respectively. As a measure of the total marginal net spillover effects to others from j, $TMNS^{12}_{OUT,t,j}$ is the difference between "$TMS^{12}_{OUT,t,j}$" and "$TMS^{12}_{IN,t,j}$" defined in Eq. (15b). The variables are ranked from the highest to lowest total marginal net spillover effects each day.

2011/08/04					2011/08/05					2011/08/08				
Rank	Market	$TMNS^{12}_{OUT,t,j}$	$TMS^{12}_{OUT,t,j}$	$TMS^{12}_{IN,t,j}$	Rank	Market	$TMNS^{12}_{OUT,t,j}$	$TMS^{12}_{OUT,t,j}$	$TMS^{12}_{IN,t,j}$	Rank	Market	$TMNS^{12}_{OUT,t,j}$	$TMS^{12}_{OUT,t,j}$	$TMS^{12}_{IN,t,j}$
1	US	1.86	1.69	-0.17	1	US	3.80	3.91	0.12	1	MOVE	4.80	4.66	-0.14
2	MOVE	0.73	0.67	-0.06	2	MOVE	1.44	1.40	-0.04	2	US	3.64	4.07	0.43
3	FR	0.05	0.08	0.02	3	FR	0.32	0.55	0.23	3	FR	0.79	1.06	0.27
4	JP	-0.01	0.03	0.04	4	KR	0.08	0.30	0.22	4	KR	0.57	1.27	0.70
5	UK	-0.12	-0.08	0.05	5	HK	-0.22	0.42	0.64	5	GOLD	-0.12	0.84	0.96
6	OIL	-0.17	0.02	0.18	6	UK	-0.34	-0.09	0.25	6	CH	-0.47	-0.15	0.32
7	GOLD	-0.20	-0.08	0.12	7	GOLD	-0.35	-0.29	0.06	7	UK	-0.55	-0.03	0.52
8	HK	-0.31	-0.19	0.11	8	DE	-1.01	-0.64	0.37	8	JP	-0.87	0.38	1.24
9	KR	-0.34	-0.31	0.03	9	JP	-1.05	-0.17	0.88	9	OIL	-2.03	-0.84	1.19
10	CH	-0.72	-0.61	0.11	10	OIL	-1.06	-0.83	0.23	10	DE	-2.10	-1.52	0.58
11	DE	-0.77	-0.64	0.13	11	CH	-1.60	-1.33	0.27	11	HK	-3.67	-2.13	1.54

Table 8. Marginal Net Spillover Matrices around the US Credit Rating Downgrade

This table reports the marginal net spillover matrix among volatilities of US security bonds, stock markets and commodities around Standard & Poor's U.S. Downgrade on August 5, 2011 when the US lost its AAA credit rating for the first time in the history of the rating. The *ij*-th entry of the upper-left 11×11 submatrix is the marginal net pairwise directional spillover from volatility *j* to *i* defined in Eq. (12). The positive(negative) value in the entry suggests that net spillover intensity from market *j* to *i* increases (decreases) when an innovation (event) occurs at time *t*. The predictive horizon is 12 days and the variance decomposition is from a structural VAR based on the direct acyclic graph given in Figure 2. The rightmost ("Marginal Net In") column summarizes the market-wide's total marginal net spillover effects from all others to *i* in Eq. (14), which is row sums of the off-diagonal marginal net pairwise spillover. The bottom-most ("Marginal Net Out") row summarizes the market-wide's total marginal net spillover to all others from *j* in Eq. (15a), which is column sums of the off-diagonal pairwise spillovers. The positive(negative) value of "Marginal Net Out" suggests that net spillover intensity from market *j* to all others increases (decreases) when an innovation (event) occurs at time *t*.

Panel A: Marginal Net Spillover Effects on Aug. 4, 2011

	US	MOVE	UK	DE	FR	CH	JP	HK	KR	GOLD	OIL	Marginal Net In
US	0.00	0.11	-0.26	-0.27	-0.15	-0.26	-0.10	-0.16	-0.19	-0.10	-0.47	-1.86
MOVE	-0.11	0.00	-0.07	-0.11	-0.06	-0.10	-0.02	-0.08	-0.05	-0.07	-0.07	-0.73
UK	0.26^{**}	0.07	0.00	-0.06	0.03	-0.13	0.01	-0.03	-0.02	-0.01	0.00	0.12
DE	0.27^{**}	0.11	0.06	0.00	0.13	-0.01	0.03	0.01	0.01	0.00	0.16	0.77
FR	0.15	0.06	-0.03	-0.13	0.00	-0.05	0.00	-0.02	-0.03	-0.01	0.01	-0.05
CH	0.26^{**}	0.10	0.13	0.01	0.05	0.00	0.03	0.00	0.00	0.03	0.10	0.72
JP	0.10	0.02	-0.01	-0.03	0.00	-0.03	0.00	-0.02	-0.02	0.00	0.00	0.01
HK	0.16	0.08	0.03	-0.01	0.02	0.00	0.02	0.00	0.02	-0.01	0.01	0.31
KR	0.19^{**}	0.05	0.02	-0.01	0.03	0.00	0.02	-0.02	0.00	0.01	0.05	0.34
GOLD	0.10	0.07	0.01	0.00	0.01	-0.03	0.00	0.01	-0.01	0.00	0.03	0.20
OIL	0.47^{**}	0.07	0.00	-0.16	-0.01	-0.10	0.00	-0.01	-0.05	-0.03	0.00	0.17
Marginal Net Out	1.86	0.73	-0.12	-0.77	0.05	-0.72	-0.01	-0.31	-0.34	-0.20	-0.17	

Table 8 (Continued)

Panel B: Marginal Net Spillover Effects on Aug. 5, 2011

	US	MOVE	UK	DE	FR	CH	JP	HK	KR	GOLD	OIL	Marginal Net In
US	0.00	0.19**	-0.67	-0.39	-0.39	-0.50	-0.69	-0.60	-0.35	-0.08	-0.31	-3.80
MOVE	-0.19	0.00	-0.16	-0.17	-0.11	-0.25	-0.14	-0.15	-0.11	-0.09	-0.07	-1.44
UK	0.67**	0.16	0.00	-0.10	0.12	-0.40	-0.05	0.01	0.13	-0.05	-0.13	0.35
DE	0.39**	0.17**	0.10	0.00	0.18**	0.19**	-0.03	-0.01	0.11	-0.03	-0.06	1.01
FR	0.39**	0.11	-0.12	-0.18	0.00	-0.12	-0.10	-0.11	-0.02	-0.05	-0.12	-0.32
CH	0.50**	0.25**	0.40**	-0.19	0.12	0.00	0.14	0.11	0.17	0.03	0.07	1.60
JP	0.69***	0.14	0.05	0.03	0.10	-0.14	0.00	0.29**	-0.01	-0.01	-0.10	1.05
HK	0.60**	0.15	-0.01	0.01	0.11	-0.11	-0.29	0.00	0.06	-0.06	-0.25	0.22
KR	0.35**	0.11	-0.13	-0.11	0.02	-0.17	0.01	-0.06	0.00	-0.01	-0.09	-0.08
GOLD	0.08	0.09	0.05	0.03	0.05	-0.03	0.01	0.06	0.01	0.00	0.00	0.35
OIL	0.31**	0.07	0.13	0.06	0.12	-0.07	0.10	0.25**	0.09	0.00	0.00	1.06
Marginal Net Out	3.80	1.44	-0.35	-1.01	0.32	-1.60	-1.05	-0.22	0.08	-0.35	-1.06	

Table 8 (Continued)

Panel C: Marginal Net Spillover Effects on Aug. 8, 2011

	US	MOVE	UK	DE	FR	CH	JP	HK	KR	GOLD	OIL	Marginal Net In
US	0.00	0.81***	-0.53	-0.16	-0.18	-0.32	-0.63	-1.12	-0.61	-0.16	-0.74	-3.64
MOVE	-0.81	0.00	-0.44	-0.61	-0.33	-0.46	-0.17	-0.80	-0.40	-0.49	-0.30	-4.80
UK	0.53**	0.44**	0.00	-0.38	0.22**	-0.07	-0.08	-0.45	0.44**	0.04	-0.14	0.55
DE	0.16	0.61**	0.38**	0.00	0.52**	0.44**	-0.01	-0.24	0.09	0.10	0.05	2.10
FR	0.18**	0.33**	-0.22	-0.52	0.00	-0.10	-0.12	-0.32	-0.01	0.08	-0.11	-0.79
CH	0.32**	0.46**	0.07	-0.44	0.10	0.00	0.02	-0.32	0.19**	0.09	-0.01	0.47
JP	0.63**	0.17	0.08	0.01	0.12	-0.02	0.00	-0.13	0.03	0.06	-0.06	0.87
HK	1.12***	0.80***	0.45**	0.24**	0.32**	0.32**	0.13	0.00	0.67**	0.07	-0.45	3.67
KR	0.61**	0.40**	-0.44	-0.09	0.01	-0.19	-0.03	-0.67	0.00	0.04	-0.22	-0.57
GOLD	0.16	0.49**	-0.04	-0.10	-0.08	-0.09	-0.06	-0.07	-0.04	0.00	-0.06	0.12
OIL	0.74***	0.30**	0.14	-0.05	0.11	0.01	0.06	0.45**	0.22**	0.06	0.00	2.03
Marginal Net Out	3.64	4.80	-0.55	-2.10	0.79	-0.47	-0.87	-3.67	0.57	-0.12	-2.03	

Figure 1. Movements of Implied Volatilities

This figure plots eleven implied volatility indices from June 2008 to April 2013. “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. “French VIX” (hereafter FR) is the Euronext-Paris’s CAC-40 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. “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. “Oil VIX” (hereafter OIL) is the CBOE Crude Oil ETF Volatility Index. “Gold VIX” (hereafter GOLD) is the CBOE Gold ETF Volatility Index. MOVE is the Bank of America Merrill Lynch’s US Treasury Option Volatility Estimate Index.

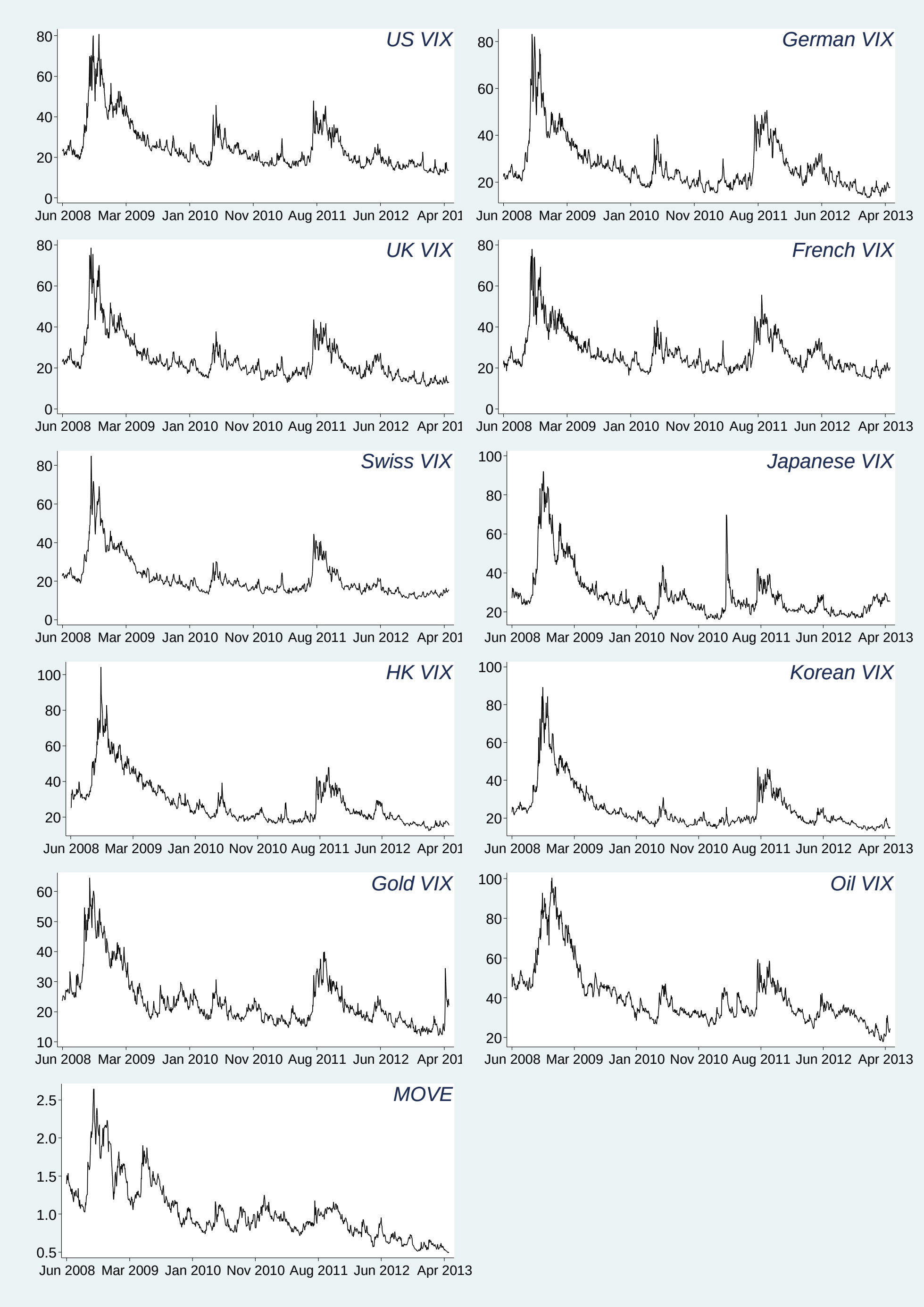
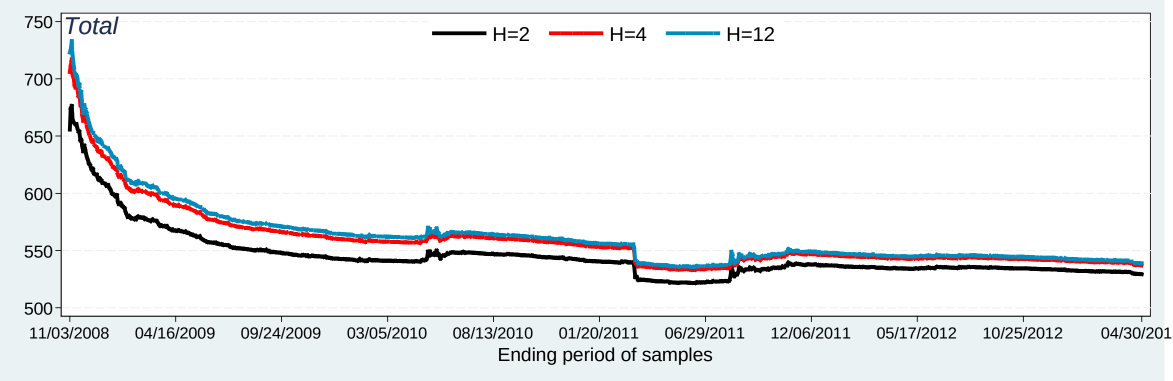


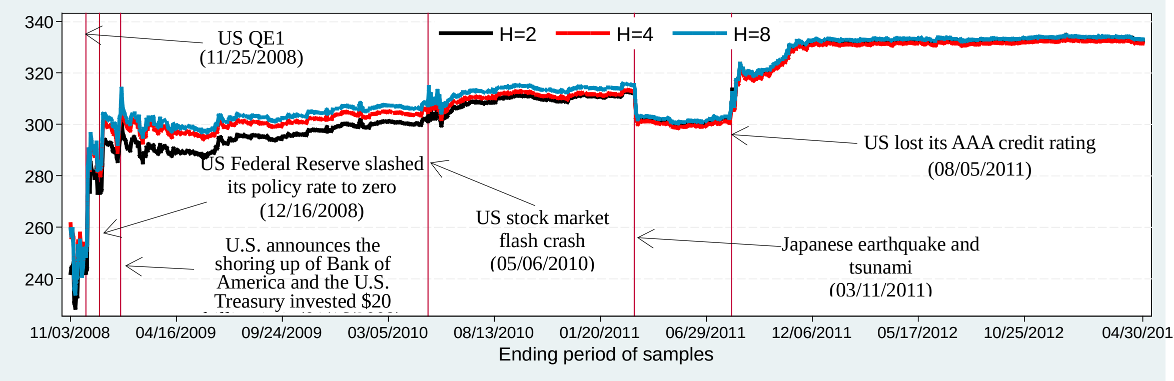
Figure 2. System-wide Total Volatility Spillover and Market-wide Total Volatility Spillovers Indices

Panel A plots system-wide total volatility spillover indices defined in Eq.(11a), and Panel B plots the total US VIX spillover indices defined in Eq.(8), while Panel C plots the other markets' outward spillover, which is the sum of spillover from all markets other than US VIX. All indices start from November 3, 2008 by estimating variance decompositions of the initial sample period from June 6, 2008 to November 3, 2008 for the predictive horizons *H* of 2, 4 and 8 days. The subsequent variance decompositions are estimated recursively each day with an expanding sample. The final sample period is June 6, 2008–April 30, 2013. All the indices of each Panel have similar patterns regardless of the choices of *H*.

Panel A : System-wide Total Volatility Spillover Effects



Panel B : Market-wide Total Spillover Effects Originating from US VIX



Panel C: Market-wide Total Spillover Effects Originating from Other Markets

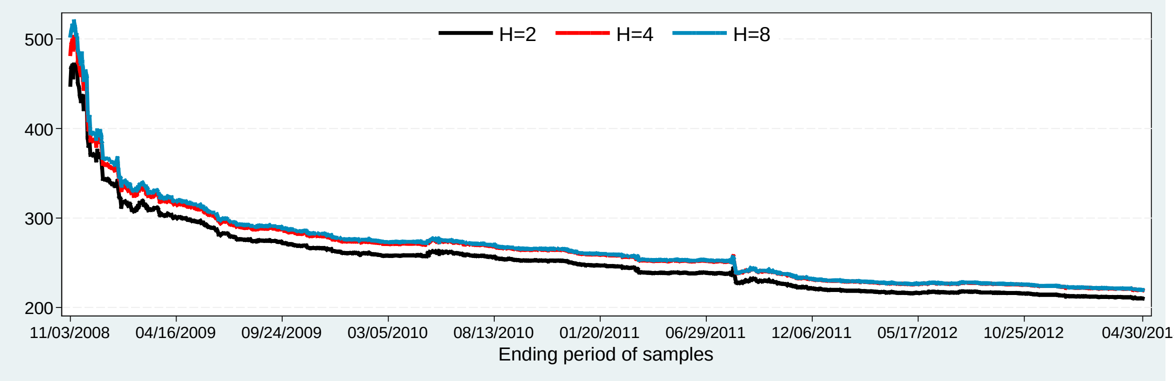


Figure 3. Net Total Volatility Spillover Indices

This figure plots 12-day-ahead net total volatility spillover indices defined in Eq.(9). All indices start from November 3, 2008 by estimating variance decompositions of the initial sample period from June 6, 2008 to November 3, 2008. The subsequent variance decompositions are estimated recursively each day with an expanding sample. The final sample period is June 6, 2008–April 30, 2013.

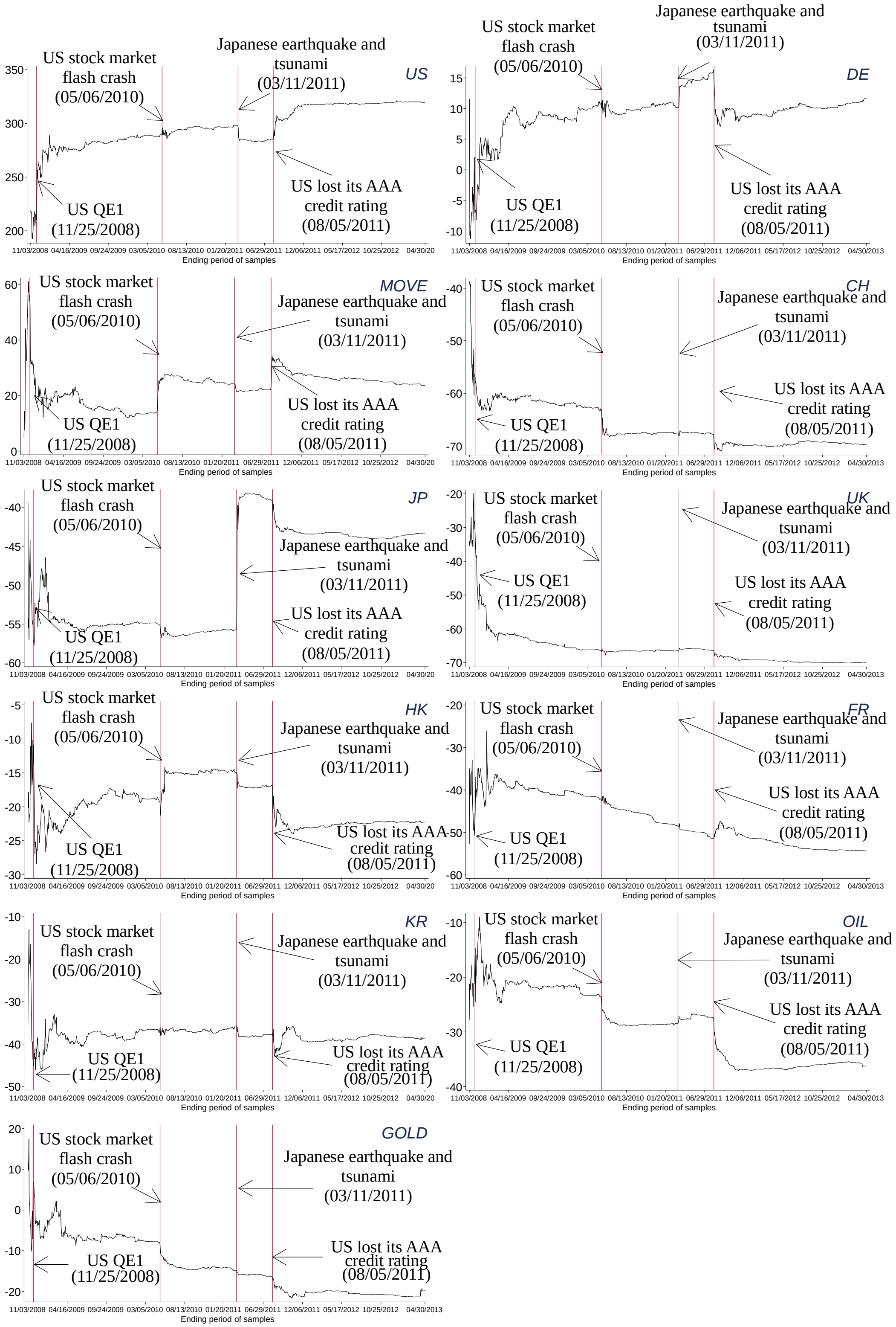


Figure 4. Total Positive Marginal Net Spillover Index

This figure plots a12-day-ahead total positive marginal net spillovers (*TPMNS*) index defined in Eq.(13), which is the sum of all positive marginal net pairwise spillover (*MNS*) of the system. The index starts from November 3, 2008 by estimating variance decompositions of the initial sample period from June 6, 2008 to November 3, 2008. The subsequent variance decompositions are estimated recursively each day with an expanding sample. The final sample period is June 6, 2008–April 30, 2013. Some events provoking significant volatility spillovers are highlighted by shading.

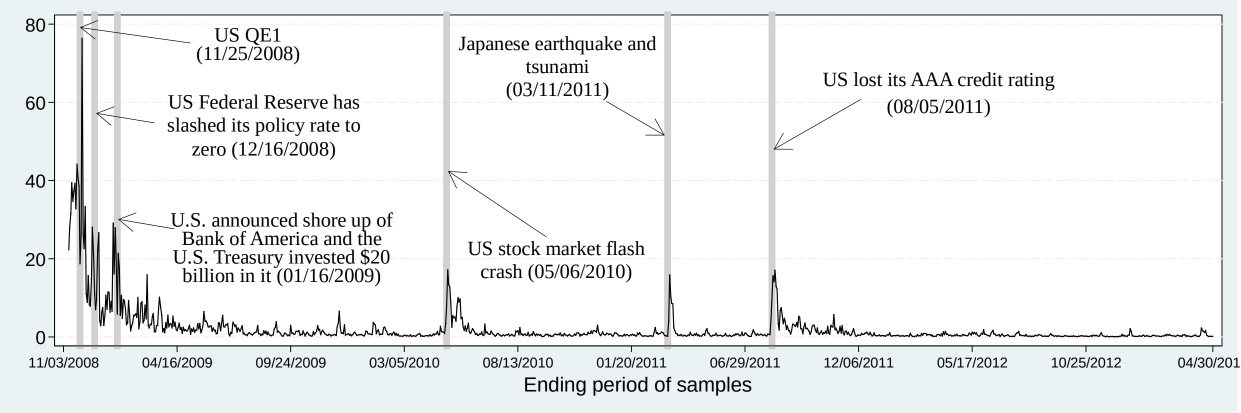
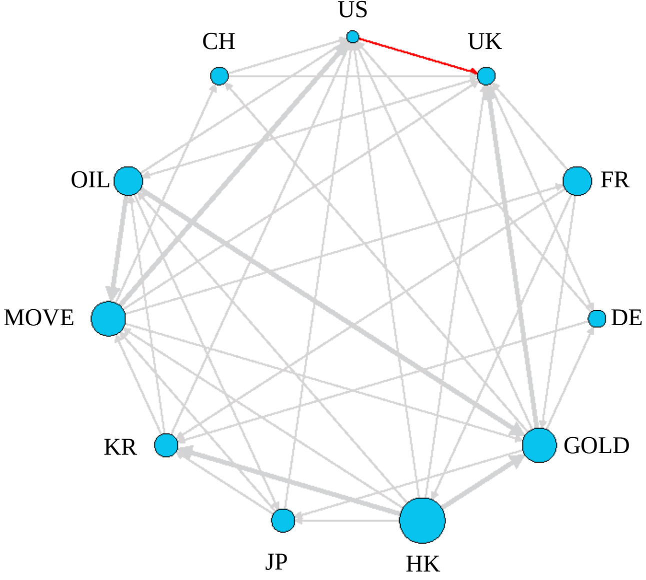
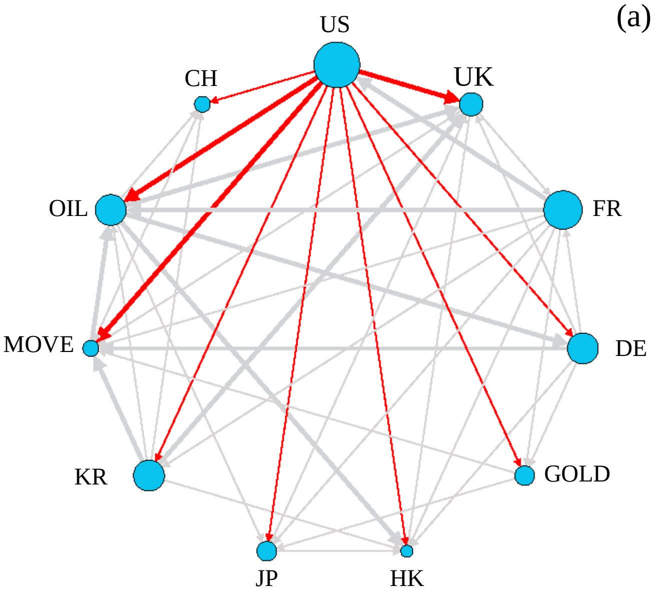


Figure 5. The Networks of Marginal Net Directional Spillover around QE1

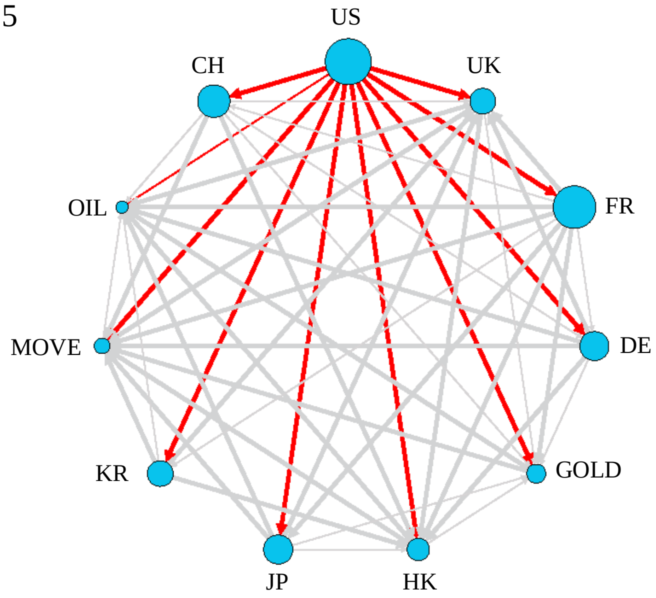
This figure presents the most important marginal net pairwise directional spillovers, as defined in Eq.(12) and summarized in table 6, among volatilities of US security bonds, stock markets and commodities around the QE1 announcement on November 25, 2008. The thick and thin links correspond to the first and fifth percentile of all marginal net pairwise directional spillovers from November 3, 2008 to April 30, 2013. "$j \rightarrow i$" denotes that net spillover intensity from market *j* to *i* increases significantly or, equivalently, that net spillover intensity from market *i* to *j* decreases significantly. The node size indicates the out-degree of a market, the number of its outgoing directed edges. In other words, the larger node size suggests the more important role of the market in significantly increasing the net spillover effects to other markets after the QE1 announcement. All red/gray links (gray /light gray when viewed in grayscale) show the increase of net spillover effects originating from US/ other markets.



(a) 2008/11/25



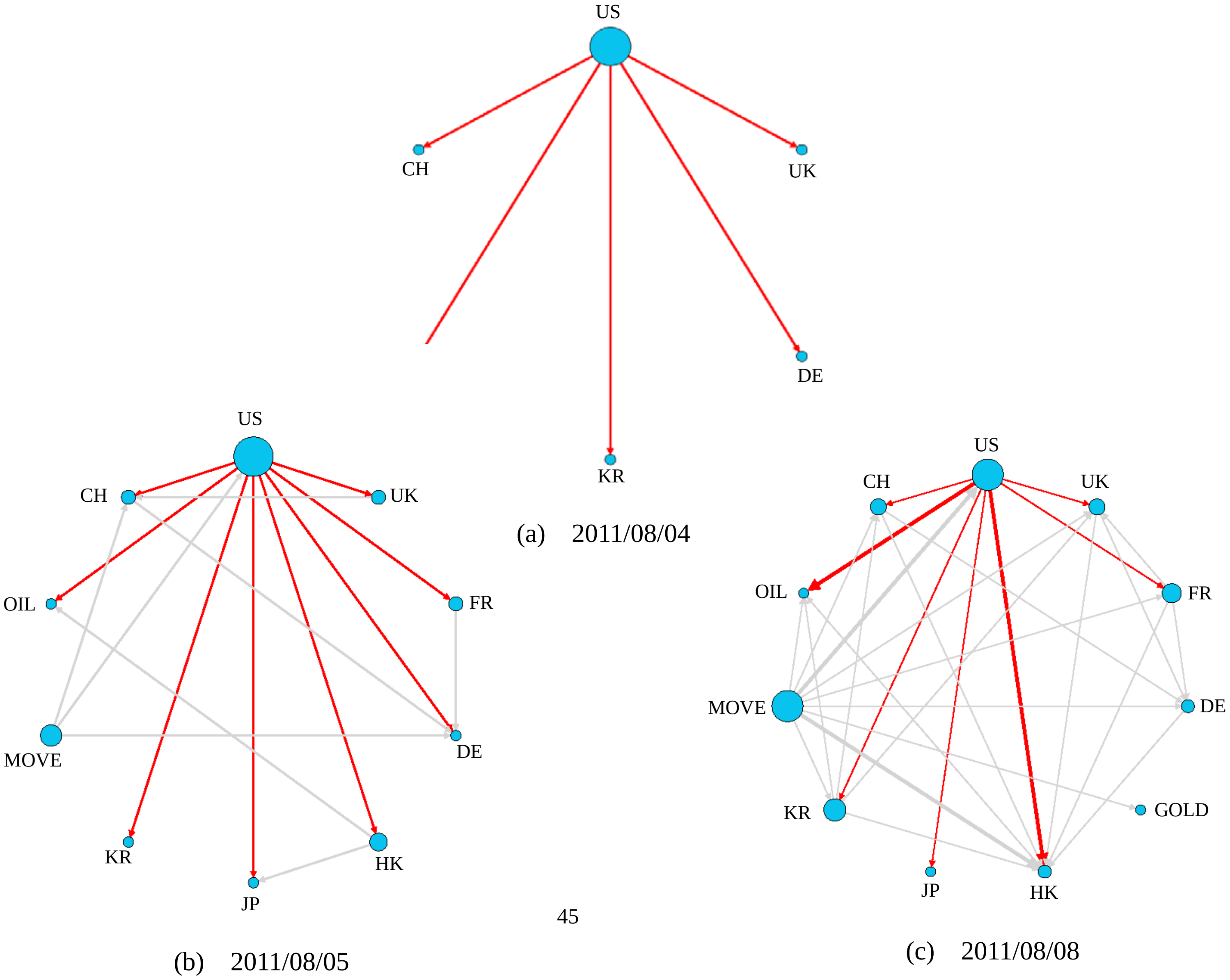
(b) 2008/11/26



(c) 2008/11/28

Figure 6. The Networks of Marginal Net Directional Spillover around the US Credit Rating Downgrade

This figure presents the most important marginal net pairwise directional spillovers, as defined in Eq.(12) and summarized in table 8, among volatilities of US security bonds, stock markets and commodities around Standard & Poor's U.S. Downgrade on August 5, 2011 when the US lost its AAA credit rating for the first time in its rating history. The thick and thin links correspond to the first and fifth percentile of all marginal net pairwise directional spillovers from November 3, 2008 to April 30, 2013. "*j* → *i*" denotes that net spillover intensity from market *j* to *i* increases significantly or, equivalently, that net spillover intensity from market *i* to *j* decreases significantly. The node size indicates the out-degree of a market, the number of its outgoing directed edges. In other words, the larger node size suggests the more important role of the market in significantly increasing the net spillover effects to other markets around the downgrade of the U.S credit rating. All red/gray links (gray /light gray when viewed in grayscale) show the increase of net spillover effects originating from US/other markets.



(a) 2011/08/04

(b) 2011/08/05

(c) 2011/08/08

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