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Quantitative Easing and Volatility Spillovers Across Countries and Asset Classes

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Abstract. We identify networks of volatility spillovers and examine time-varying spillover intensities with daily implied volatilities of U.S. Treasury bonds, global stock indices, and commodities. The U.S. stock market is the center of the international volatility spillover network, and its volatility spillover to other markets has intensified since 2008. Moreover, U.S. quantitative easing alone explains 40%–55% of intensifying spillover from the United States. The addition of interest rate and currency factors does not diminish the dominant role of quantitative easing. Our findings highlight the primary contribution of U.S. unconventional monetary policy to volatility spillovers and potential global systemic risk.

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Keywords: volatility spillover • risk-neutral volatility • quantitative easing • systemic risk • financial network • structural VAR

1. Introduction

On February 14, 2013, *The Economist* magazine asked "what QE means for the world." Quantitative easing (QE) is an unconventional monetary policy based on large-scale asset purchases. This policy was adopted by the U.S. Federal Reserve in the midst of the 2008 financial crisis. Quantitative easing has attracted heated debate because it is believed to have strong spillover effects on global financial markets and broader economic conditions. Spillovers through financial market prices are important and readily observable. For example, when the first round of U.S. quantitative easing (QE1) was announced, global stock indices jumped up, and equity risk- neutral volatilities dropped sharply.[1] Spillover in volatility is as interesting as spillover in return. As the second moment of the distribution of asset returns, volatility is an important measure of risk for asset valuation, and thus volatility spillover is essentially risk spillover. However, there is no direct evidence on the relationship between quantitative easing and patterns in volatility spillover, though there is a growing literature on cross-border effects of quantitative easing.[2]

Volatility spillover is also related to 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, p. 9). However, little research links international volatility spillovers to systemic risk in the global financial system.[3] Furthermore, given the increasing size and sophistication of derivatives markets, volatility spillovers can now be studied with implied volatility for a variety of assets including stock indices, bonds, and commodities. In contrast to ex post physical volatility measures, implied volatility is the ex ante risk-neutral expectation of future volatility and directly available at daily or even intraday frequency. However, relatively few studies have explored implied volatility spillovers across countries and asset classes, although there have been many studies of international volatility spillovers, such as Engle et al. (1990), Hamao et al. (1990), King et al. (1994), and Fleming et al. (1998). Our study attempts to fill these gaps and thereby makes several contributions to the literature.

First, we use daily implied volatilities to identify the network structure of volatility spillovers that link the

U.S. Treasury bond market and major global stock and commodity markets. A network[4] approach enriches our understanding of financial systems in general (Allen and Babus 2009) and can detect and characterize financial contagion in particular (Allen and Gale 2000). In this paper, we uncover the network of contemporaneous causal relations among implied volatilities, which in turn provides guidance for the ordering of variables and thus improves on the use of structural vector autoregression (VAR) analysis.[5] Yang and Zhou (2013) use such a refined VAR approach to study credit risk spillovers among global financial institutions. With this novel empirical method, we can more precisely detect and characterize the network of global volatility spillovers. In particular, we calculate network centrality measures (Ahern and Harford 2014) and show that the U.S. stock market is at the center of global volatility spillover network during the period from 2008 to 2013.

Second, we develop a new set of volatility spillover indices and show clearly that volatility spillover from the United States to the rest of the world has intensified steadily in the era of quantitative easing. Our spillover indices measure the direction and intensity of volatility spillover from one market to others as the percentage of variation of one or more volatility series explained by innovations in another volatility series. They are derived from the refined structural VAR recursively and extend the work of Diebold and Yilmaz (2014), who propose intuitive measures of volatility spillovers based on forecast error variance decompositions of VAR models. The spillover index that traces the impact of shocks from the U.S. stock market to other stock and commodity markets explicitly documents intensifying global volatility spillover originating in the United States since November 2008. It suggests that the systemic importance of the United States to the global financial system has increased.

More importantly, we find that U.S. quantitative easing is the primary driver of volatility spillovers from the United States to the rest of the world: it alone can explain 40% to 55% of variation in spillover. The addition of U.S. short rate and currency factors increases explanatory power by only 5%, and the inclusion of additional controls for the business cycle and macroeconomic climate do not change the dominant role of quantitative easing in driving volatility spillovers from the United States. Our findings are important to academics, practitioners, regulators, and policymakers. Typical academic studies of quantitative easing study the announcement effect of Fed asset purchases on U.S. interest rates (Gagnon et al. 2011, Krishnamurthy and Vissing-Jorgensen 2011), the U.S. dollar (Neely 2013, Glick and Leduc 2013), or global asset prices (Glick and Leduc 2011, Chen et al. 2016, Fratzscher et al. 2013). Recent literature also links monetary policy to systemic risk. For example, Jimenez et al. (2014) show that monetary policy in the form of low interest rates is a potential source of systemic risk because it leads to bank risk taking. Allen (2014) argues that systemic risk is endogenous and related to central bank policies. We support and extend this literature by explicitly documenting the central contribution of U.S. unconventional monetary policy in particular and monetary easing in general to volatility spillovers and potential systemic risk across the global financial system. From the perspective of practitioners, a deeper understanding of the impact of U.S. quantitative easing around the world provides insights for global investors faced with managing the consequences of quantitative easing and the announced Fed plan to taper the extent of the policy. For example, investors are induced to search (globally and imprudently) for yield in the era of quantitative easing. Recently, the Fed closed its asset purchase program, which has become a worry for many investors. From volatility spillover pattern and network direction, we can draw some important implications for "contagion strategy" (Kaminsky et al. 2004). Managing unconventional monetary policy also challenges regulators and policymakers across the globe. We highlight the potential systemic risk of intensifying spillover with quantitative easing and thus the importance for the Federal Reserve and other regulators to take a more systemic perspective (Bernanke 2012).

2. Data

From Bloomberg, we collect 11 implied volatility indices at a daily frequency. We begin with U.S. stock and bond risk-neutral volatilities. The VIX, the Chicago Board Option Exchange's (CBOE's) S&P 500 volatility index, is a very popular and widely used measure of U.S. stock market implied volatility. The square of the VIX approximates 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. MOVE, the Bank of America Merrill Lynch's Treasury Option Volatility Estimate Index, is the U.S. government bond market's equivalent to the VIX.[6] It is not a model-free measure, but a weighted average of the normalized implied yield volatility estimated from at-the-money one-month Treasury options using Black's (1976) model. The weights are based on estimates of option trading volumes in each maturity of 2-, 5-, 10-, and 30-year U.S. Treasury bonds.

Second, we collect implied volatilities of other major national stock market indices,[7] including the 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). For simplicity, we call them German VIX, French VIX, UK VIX, Swiss VIX, Japanese VIX, Korean VIX, and Hong Kong (HK) VIX, respectively. All these implied volatility indices apply the VIX methodology to options of the underlying stock indices.

Third, we collect two commodity volatility series, which are model-free measures for the market's expectation of the 30-day volatility of crude oil and gold prices derived from options on the respective exchange traded funds (ETFs). Specifically, "Oil VIX" (OVX) is the CBOE Crude Oil ETF (U.S. Oil Fund, L.P.) volatility index, and "Gold VIX" (GVZ) is the CBOE Gold ETF (SPDR Gold Shares) volatility index.

Summary statistics on daily implied volatility indices are reported in Table 1. The sample begins in June 2008 and ends in April 2013 for 1,218 daily observations because the Gold VIX index is only available since June 2008.[8] As shown in Table 1, the average U.S. market VIX is about 25.2% during this period, whereas other stock market volatilities range from 21.8% to 28.6%. Gold volatility is similar in scale to its stock counterparts, whereas oil is more volatile (40.8%). In contrast, Treasury bond yield volatilities are much smaller, with the average MOVE value equal to about 1%. The standard deviation of implied volatilities ranges from 0.4% for MOVE to 15% for Oil VIX. All volatility indices exhibit long tails in the right and far tails. The minimum and maximum values of the volatility indices highlight their considerable cross-sectional and time-series variation.

It is well known that volatility is very persistent and thus highly serially correlated. Therefore, we work with first differences in the VIX series rather than their levels (Ang et al. 2006). Also, given that VIX is approximately the price of a variance swap (Carr and Wu 2009), first differences can be interpreted as price changes. Following Forbes and Rigobon (2002), we compute two-day rolling averages of first differences of volatility indices to control for the fact that option markets of different countries do not operate during the same trading hours.[9] In Table 1, the smallest average daily change is for MOVE (−0.001%), and the biggest average daily change is for Oil VIX (−0.022%). The change of MOVE is the least volatile, whereas the change of Japan VIX is the most volatile. Notably, the kurtoses of volatility changes are much higher than their level counterparts, suggesting more spikes in the changes of volatility. The ranges between the minimum and maximum values of the volatility changes are substantial.

With the above series of volatility changes, we examine volatility spillovers across countries and asset classes and then relate them to economic and financial variables that can influence spillover intensity.

Table 1. Summary Statistics of Daily Implied Volatility Indices

	Mean	Std. dev.	Skew	Kurt	Min	Max
			Level (%)			
VIX	25.173	11.526	1.837	6.708	11.300	80.860
German VIX	27.065	10.886	1.799	6.990	13.310	83.230
UK VIX	23.801	10.373	1.965	7.896	10.870	78.690
Swiss VIX	21.755	10.213	2.208	8.904	10.620	84.900
French VIX	27.261	9.668	1.791	7.131	14.600	78.050
Korean VIX	25.294	12.036	2.222	8.531	13.310	89.300
Japanese VIX	28.641	12.583	2.375	9.104	15.940	92.030
HK VIX	28.230	13.306	1.714	6.360	12.280	104.290
Gold VIX	23.722	9.038	1.675	5.824	11.970	64.530
Oil VIX	40.759	14.955	1.647	5.672	17.810	100.420
MOVE	1.024	0.381	1.338	4.831	0.492	2.646
		Two-day rolling average of first differences (%)				
ΔVIX	−0.009	1.568	0.538	10.140	−8.610	8.340
ΔGerman VIX	−0.007	1.498	0.105	14.692	−12.280	10.485
ΔUK VIX	−0.003	1.426	0.392	11.009	−9.105	9.125
ΔSwiss VIX	−0.009	1.258	−0.002	33.165	−14.490	13.710
ΔFrench VIX	−0.002	1.692	0.340	14.989	−14.180	13.410
ΔKorean VIX	−0.017	1.363	1.227	20.342	−8.370	11.875
ΔJapanese VIX	−0.002	1.705	2.656	41.837	−10.360	23.220
ΔHK VIX	−0.017	1.408	1.496	25.470	−10.220	16.415
ΔGold VIX	−0.008	1.068	1.558	14.095	−4.710	9.595
ΔOil VIX	−0.022	1.401	0.947	8.537	−6.275	9.420
ΔMOVE	−0.001	0.036	0.296	9.344	−0.221	0.215

Notes. This table reports the summary statistics of daily implied volatility indices from January 2008 to April 2013. Number of observations is 1,218 in panel A and 1,216 in panel B.

Therefore, we collect the following variables from the Federal Reserve Bank of New York and the St. Louis Fed's Federal Reserve Economic Data (FRED) database.

First, much of our research is focused on understanding the impact of unconventional monetary policies. Quantitative easing is defined by Bernanke and Reinhart (2004, p. 85) as "increasing the size of the central bank's balance sheet beyond the level needed to set the short-term policy rate at zero (quantitative easing)." Unlike conventional monetary policy, which targets the price of reserves, quantitative easing expands the size of the Fed's balance sheet to affect the overall supply of reserves and the money stock. We use two proxies for the dynamics of quantitative easing operations. One is the cumulative net purchase of Treasury and agency mortgage-backed securities by the Federal Reserve Bank of New York through permanent open market operations. The other is the size of U.S. Treasury securities, agency securities, and mortgage-backed securities holdings on the Fed balance sheet from the St. Louis Fed's FRED database.[10] The frequency of the cumulative net purchase is daily, whereas the best available data for the security holding series are weekly. Over our sample period, both the Fed's security net cumulative purchases and holdings have grown more than 300%.[11]

Second, we also collect variables that capture other dimensions of the economic and financial environment. The one-month Treasury bill yield represents the U.S. short-term interest rate. It is closely associated with stock index volatility in theoretical models (Bailey and Stulz 1989, Bekaert et al. 2009) and, thus, the associated spillovers that we care about. Also, there is evidence that short-term interest rates forecast subsequent changes in the Fed's announced target rate (Hamilton and Jorda 2002, Fama 2013). This suggests that the U.S. short-term interest rate reflects the market's expectation of one dimension of the Fed's future monetary policy stance. "Quantitative easing may also work by altering expectations of future path of policy rate" (Bernanke and Reinhart 2004, p. 88). Furthermore, the interest rate has been shown to relate to expectations of real interest rates, the business cycle, and inflation (Fama and Schwert 1977). Thus, this control variable reflects a variety of macroeconomic, financial, and policy dimensions of the economy.

In addition to the short-term interest rate, we also collect U.S. dollar exchange rates (euro, British pound, Japanese yen, Swiss franc, Korean won, Hong Kong dollar, and trade-weighted U.S. dollar spot index[12]) and prices for two key commodities (oil and gold). The degree to which shocks in one country are transmitted to another can also depend on the exchange rate regime (Flood and Hodrick 1986). Conditions in one country's financial markets can be transmitted rapidly to others through portfolio flows including the so-called "carry trade." The carry trade refers to borrowing a low-yielding U.S. asset and buying a higher-yielding foreign asset to earn the interest rate differential plus the expected foreign currency appreciation. For example, Menkhoff et al. (2012) show that high-yield countries tend to offer high returns when U.S. stock volatility decreases, which attracts more carry trade and induces more spillover. Frankel (2014) presents a carry trade model of commodity prices with a clear analogy to currency carry trades.[13]

We also measure the extent of central bank liquidity swaps (SWAPs). They can be an additional source of spillover because they allow foreign central banks to draw U.S. dollars and lend to financial institutions in their jurisdictions, which in turn provide more liquidity to traders in their home markets.[14] The most frequent available data for this instrument are weekly.

Finally, spillover intensity can relate to the state of the business cycle (Baele 2005, p. 395). We use financial variables that are available at weekly or daily frequency and empirically have been found to have predictive power for the business cycle. One set of business cycle proxies we choose includes term spread, default spread, and TED spread. The term spread is the difference between the 10-year and three-month Treasury yields. Most recessions are preceded by a sharp decline in the term spread and frequently by an inverted yield curve (Ferson and Harvey 1991). The default spread is measured as the difference between Moody BAA-rated corporate bond and 10-year Treasury bond yields. This spread is an indicator of perceived business conditions in the general economy. If business conditions are poor, then there is an increase in the likelihood of default in lower-quality corporate bonds, which leads to an increase in the default spread. Fama and French (1989) show that the term spread reflects shorter-term business conditions, whereas the default spread is a proxy for longer-term business conditions. The TED spread is the difference between the three-month LIBOR based on U.S. dollars and the three-month Treasury yield. It is a common measure of funding illiquidity in interbank markets.

Although macroeconomic variables have been used in the literature to measure the business cycle, the data typically exist only at monthly or even lower frequency. However, some daily indices have been developed to track real business conditions based on macroeconomic indicators. Aruoba et al. (2009) propose a U.S. business condition index using weekly initial jobless claims, monthly payroll employment, industrial production, personal income less transfer payments, manufacturing and trade sales, and quarterly real gross domestic product. As a successful macroeconomic indicator, this business condition index has been classified by the *Wall Street Journal* as one of the top 50 economic indicators and used in academic research (Constable and Wright 2011). The average value of this index is zero, with increases (decreases) indicating improved (deteriorating) macroeconomic conditions (Allen et al. 2012). We also follow Fratzscher et al. (2013) and use the best known daily macro surprise indices, Citigroup's economic surprise indices for the G10 and for the emerging markets, to proxy for macroeconomic climate around the world. Both the business condition and Citigroup's surprise indices are available in Bloomberg. A negative change in these indices suggests deterioration in the United States or global macroeconomic climate.

3. Empirical Methodology

We employ a two-pass procedure to describe spillovers across our daily implied volatility series and their underlying economic forces. We also develop several testable hypotheses as follows.

3.1. A Refined Structural VAR

Our starting point is the vector autoregressive model of Sims (1980):

$$\Delta \mathbf{IV}_t = \mu + \sum_{i=1}^{I} \mathbf{B}_i \Delta \mathbf{IV}_{t-i} + e_t, \tag{1}$$

where $\Delta \mathbf{IV}_t$ is a vector of rolling-average, two-day changes in implied volatility indices as described previously, and $\mathbf{B}$ is the matrix of dynamic coefficients, which have no straightforward interpretation.

To summarize the dynamic structure and provide appropriate economic interpretation (Sims 1980), we rewrite Equation (1) as an infinite moving average process:

$$\Delta \mathbf{IV}_t = \sum_{i=0}^{\infty} \mathbf{A}_i \varepsilon_{t-i}, \quad t = 1, 2, \ldots, T. \tag{2}$$

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

$$\xi_{t,H} = \sum_{h=0}^{H-1} \mathbf{A}_h \varepsilon_{t+H-h}, \tag{3}$$

with variance-covariance matrix

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

where Σ is the variance-covariance matrix of the error term in Equation (1).

The resulting forecast error variance decomposition apportions the forecast error variances of each variable to the various shocks in the system. Therefore, we can measure how much innovation contributes to the variance of the total n-step-ahead forecast error for each element in $\Delta \mathbf{IV}_t$ and thus quantify the intensity of each variable in explaining the variation of another variable.

The underlying shocks are typically assumed to have a recursive contemporaneous causal structure by using the Cholesky decomposition. However, economic theories rarely provide guidance for recursively causal orderings, making the imposed restrictions arbitrary. We overcome this problem with the directed acyclic graph (DAG) method to uncover contemporaneous causal relations of VAR residuals in a data-determined and thus more credible manner, as advocated by Swanson and Granger (1997).

The DAG technique is a recent advance in causality analysis. In contrast to the well-known Granger causality, which exploits time-series causal relations[15] and is typically applied to two variables, a DAG derives contemporaneous causality among a set of variables based on observed correlations and partial correlations. See Pearl (2000) for more discussion of DAGs, and Haigh and Bessler (2004) and Yang and Zhou (2013) for applications of DAGs in business and finance.

We first run the VAR in Equation (1) and conduct the DAG analysis with the variance–covariance matrix of the VAR residuals, Σ. Compared with the Cholesky decomposition, the DAG lets the data speak for itself about the contemporaneous causal network, thereby yielding a credible ordering of variables in the VAR. This is crucial in 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.

3.2. Dynamics and Determinants of Volatility Spillover Indices

Similar to Diebold and Yilmaz (2014), our spillover indices follow directly from the familiar notion of forecast error variance decomposition. We aggregate international volatility spillovers of the U.S. stock market into a single index, $AS_{t,H}$, which is the sum of the shares of H-step-ahead forecast error variance from VIX shocks to all other VIX series as follows:

$$AS_{t,H} = \frac{\sum_i \sum_{h=0}^{H-1} a^2_{h,(i,VIX)}}{\sum_{h=0}^{H-1} trace(\mathbf{A}_h \mathbf{A}'_h)}, \quad \text{for } i \in (\Delta UK\,VIX, \ldots, \Delta Oil\,VIX), \tag{5}$$

where $a_{h,(i,VIX)}$ is the element in the ith row, which corresponds to another VIX variable, and the VIX column of the coefficient matrix of the moving average process $\mathbf{A}_h$; $\sum_{h=0}^{H-1} a^2_{h,(i,VIX)}$ is the contribution to the H-step-ahead error variance in forecasting another VIX of equity or commodity market i due to shocks to VIX shocks; and $\sum_{h=0}^{H-1} trace(\mathbf{A}_h \mathbf{A}'_h)$ is the total H-step-ahead forecast error variation. The ratio is the percentage of all other VIX variations explained by VIX innovations and thus is a general measure of spillover intensity from VIX to all other VIXs.

Furthermore, we construct several individual indices of volatility spillovers to international stock indices and commodity prices from the U.S. stock market, $IS^i_{t,H}$. They are the shares of H-step-ahead error variance in forecasting another VIX i due to VIX shocks:

$$IS^i_{t,H} = \frac{\sum_{h=0}^{H-1} a^2_{h,(i,VIX)}}{\sum_{h=0}^{H-1} trace(\mathbf{A}_h \mathbf{A}'_h)}, \quad \text{for } i \in (\Delta UK\,VIX, \ldots, \Delta Oil\,VIX), \tag{6}$$

Our volatility spillover indices extend Diebold and Yilmaz's (2014) spillover measurement in two dimensions. First, our variance decompositions are derived from the data-driven DAG-based structural VAR, whereas Diebold and Yilmaz (2014) use the ordering-free generalized variance decompositions proposed by Pesaran and Shin (1998).[16] Second, we estimate the variance decomposition recursively each period with an expanding sample after the initial sample period. In contrast to rolling sample spillovers in Diebold and Yilmaz (2014), our recursive estimation of spillovers can better capture stock effect[17] of volatility spillovers over the course of the QE program rather than flow effect on the days when QE operations occurred. Moreover, the recursive estimates are not sensitive to the window length, and the outcome of the recursive estimation is a sample of spillover estimates, which are updated in a Bayesian manner.[18]

Next, we regress the estimated volatility spillover indices on our proxies for U.S. quantitative easing, short rate, exchange rate changes, and control variables. If these explanatory variables can predict current and future volatility spillovers, we interpret them as drivers of the spillovers in the sense of Granger causality. More specifically, we investigate international volatility spillovers from the U.S. stock market with the following regression:

$$S_{t,H} = \beta_0 + \beta_1 QE_t + Controls + \varepsilon_t, \tag{7}$$

where $S_{t,H}$ is the H-step-ahead aggregate or individual VIX spillover index defined in Equations (5) or (6). The proxy for quantitative easing, QE_t, is the cumulative net purchase of securities through permanent open market operations or the size of U.S. Treasury securities, agency securities, and mortgage-backed securities holdings on the Fed's balance sheet.

3.3. Hypothesis Development

We offer a prediction with which to interpret the estimates of quantitative easing in Equation (7) and its role in explaining spillover as follows. First, quantitative easing can affect time variation in U.S. stock volatility through several channels. Since implied volatility reflects both the market's estimate of uncertainty and the associated risk premium (Carr and Wu 2009), both changes in uncertainty and risk aversion drive changes of risk-neutral volatility. Chen (2010) shows that variation in uncertainty and risk premium influences firms' financing decisions, which in turn affect the riskiness of the firms and thus stock market volatility. Bekaert et al. (2013) find that a lax conventional monetary policy decreases both risk aversion and uncertainty, suggesting that effective monetary easing decreases risk-neutral volatility. Similarly, if quantitative easing is perceived as effective in reversing an economic downturn, it can counteract the increases of risk premiums and economic uncertainty in bad times and thus restrain or even reverse risk-neutral volatility increases. Furthermore, monetary easing can increase funding liquidity and thus market liquidity, which in turn affects market volatility through margins (Brunnermeier and Pedersen 2009). The scale of quantitative easing can affect the size of changes in economic uncertainty, risk premiums, investors' beliefs, liquidity, and, ultimately, the risk-neutral volatility of the U.S. stock market.

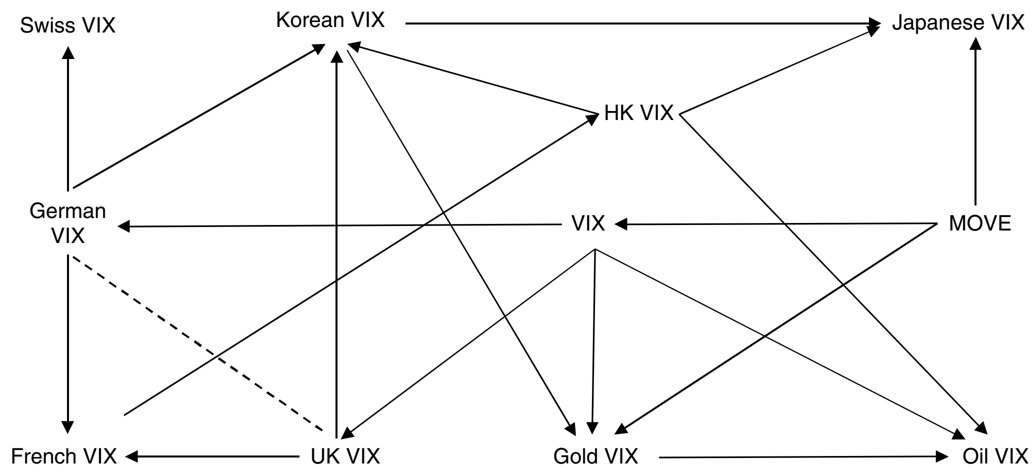
Second, the effects of quantitative easing on U.S. stock volatility can propagate across markets and borders. Lower uncertainty in the U.S. economy can increase U.S. demand for imports, thereby reducing uncertainty in the global economy through trade. U.S. banks can increase liquidity in other countries or markets through direct or interbank cross-border lending. U.S. investors can rebalance their portfolios by increasing their exposure to other stock and commodity markets due to decreases in risk aversion. A reappraisal of the U.S. economy, financial markets, and policies can also lead to revisions of the risks and uncertainty of other countries or markets.[19] The spillover intensity can grow with the scale of quantitative easing. Therefore, our hypothesis is that $\beta_1 > 0$ in specification (7) above, that is, VIX spillover intensity to other stock and commodity markets increases with the size of U.S. quantitative easing.

4. Empirical Results

4.1. DAG and Structural VAR Results

Schwarz's Bayesian criterion suggests an optimal lag of $k = 2$ for all the model specifications under consideration. Thus, 11-variable VARs with a lag of 2 are estimated to summarize dynamic interactions among two-day rolling-average changes of the 11 implied volatility indices. Based on the VAR residual correlation matrix, the resulting directed graph at the conventional 10% significance level is plotted in Figure 1,[20] where we can see how volatility spreads from one market to another.[21] U.S. Treasury bond yield volatility (MOVE) appears to be an exogenous source of volatility spillover in contemporaneous time: it affects the VIX, Japanese VIX, and Gold VIX, but does not receive

Figure 1. Contemporaneous Causal Flow Patterns among Changes of Implied Volatilities for the Period from 2008 to 2013



Notes. This figure shows the contemporaneous causal flow patterns among changes of implied volatilities. The analysis is conducted using a DAG with the resulting graph at the conventional 10% significance level.

inbound volatility from any other market. Similarly, U.S. stock volatility (VIX) is a prime source of volatility in contemporaneous time to other markets, such as the Oil VIX, Gold VIX, German VIX, and UK VIX, whereas it only receives volatility spillover from MOVE.

As explained by Swanson and Granger (1997), the contemporaneous causal pattern identified with DAG analysis of the correlation matrix provides a data-determined solution to the problem of ordering variables in a VAR, a critical step prior to forecast error variance decomposition of a structural VAR. Based on the identified causal network given in Figure 1, we can write the following innovation correlation matrix:[22]

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & b_{1,11} \\ b_{2,1} & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ b_{3,1} & b_{3,2} & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & b_{4,2} & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & b_{5,2} & b_{5,3} & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & b_{6,2} & b_{6,3} & 0 & 0 & 1 & 0 & b_{6,8} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & b_{7,6} & 1 & b_{7,8} & 0 & 0 & b_{7,11} \\ 0 & 0 & 0 & 0 & b_{8,5} & 0 & 0 & 1 & 0 & 0 & 0 \\ b_{9,1} & 0 & 0 & 0 & 0 & b_{9,6} & 0 & 0 & 1 & 0 & b_{9,11} \\ b_{10,1} & 0 & 0 & 0 & 0 & 0 & 0 & b_{10,8} & b_{10,9} & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{8}$$

Based on the structural VAR as identified in (8), forecast error variance decompositions are computed. They are presented in Table 2 as the percentage of forecast error variance at horizon H that is attributable to earlier shocks from each series including itself. The percentage describes the size or economic significance of causal linkages. Horizon H allows for time-lagged dynamic causal linkages in addition to contemporaneous causal linkages. The table presents several horizons of variance decomposition.

First, the variance decomposition of MOVE is 100% for itself at day zero, meaning that MOVE is driven entirely by its own shocks. This is consistent with the earlier observation in Figure 1 that Treasury bond yield volatility is largely exogenous in contemporaneous time. As the horizon increases, it has the largest percentage (93% to 97%) of variation explained by its own shocks. Meanwhile, MOVE exerts nontrivial and persistent influence (4.3% to 4.4%) on VIX at all horizons.

More striking evidence in Table 2 is that the VIX shock explains significant portions of variation in German VIX (44% to 58%), UK VIX (36% to 47%), Swiss VIX (30% to 52%), French VIX (27% to 42%), Korean VIX (10% to 36%), Japanese VIX (2% to 23%), HK VIX (4% to 32%), Gold VIX (16% to 19%), and Oil VIX (22% to 23%) at all horizons. No other market is such an extensive and significant source of volatility spillover. This underscores the uniqueness of the U.S. stock market in spreading volatility to other stock and commodity markets. Put another way, the U.S. stock market is at the center of the global volatility network from 2008 to 2013.[23]

To quantify how important one market in a network is relative to other markets, we follow Diebold and Yilmaz (2014) to calculate marketwide spillover intensity in Table 2A of the online appendix. As shown in panel A for the period from 2008 to 2013, the 12-day-ahead VIX spillover intensity to others is the highest of 333.1%, much higher than other market counterparts. We can also see how important the peripheral markets are relative to the core markets in affecting worldwide volatility spillover. For example, the German VIX spillover intensity to others is 79.2%, about one quarter of the VIX counterpart.[24]

Furthermore, we follow Ahern and Harford (2014) to calculate two measures of network centrality in Table 3.

Table 2. Forecast Error Variance Decomposition Results for the Period from 2008 to 2013

Day	VIX	German VIX	UK VIX	Swiss VIX	French VIX	Korean VIX	Japanese VIX	HK VIX	Gold VIX	Oil VIX	MOVE
Variance of MOVE explained by shocks to the implied volatilities											
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00
1	0.79	0.68	0.18	0.62	0.77	0.02	0.08	0.19	0.00	0.01	96.68
2	0.74	1.33	0.24	1.15	1.16	0.09	0.17	0.37	0.00	0.02	94.73
3	1.21	1.65	0.25	1.32	1.19	0.11	0.22	0.39	0.01	0.02	93.62
12	1.87	1.75	0.25	1.33	1.19	0.13	0.25	0.40	0.04	0.03	92.76
30	1.87	1.75	0.25	1.33	1.19	0.13	0.25	0.40	0.04	0.03	92.76
Variance of VIX explained by shocks to the implied volatilities											
0	95.73	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.27
1	89.10	0.68	0.12	0.53	1.60	1.76	0.01	1.30	0.47	0.01	4.43
2	86.49	1.30	0.15	0.82	1.92	2.59	0.02	1.79	0.60	0.01	4.31
3	86.29	1.48	0.15	0.83	1.89	2.63	0.03	1.77	0.60	0.01	4.31
12	86.16	1.49	0.15	0.84	1.92	2.65	0.03	1.80	0.61	0.01	4.33
30	86.16	1.49	0.15	0.84	1.92	2.65	0.03	1.80	0.61	0.01	4.33
Variance of German VIX explained by shocks to the implied volatilities											
0	43.94	54.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.96
1	58.29	35.72	0.13	0.78	0.16	1.26	0.11	0.22	0.29	0.01	3.02
2	58.06	32.76	0.13	1.22	0.42	2.65	0.16	0.65	0.68	0.03	3.24
3	57.28	32.67	0.13	1.31	0.48	3.10	0.17	0.81	0.81	0.04	3.21
12	57.54	32.36	0.13	1.31	0.49	3.12	0.17	0.82	0.81	0.05	3.21
30	57.54	32.36	0.13	1.31	0.49	3.12	0.17	0.82	0.81	0.05	3.21
Variance of UK VIX explained by shocks to the implied volatilities											
0	36.01	25.86	36.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.61
1	48.20	17.93	25.81	2.45	1.44	1.14	0.00	0.23	0.14	0.00	2.66
2	47.45	16.90	23.93	3.61	1.91	2.48	0.00	0.58	0.32	0.00	2.81
3	46.90	17.13	23.57	3.81	1.92	2.87	0.00	0.65	0.37	0.00	2.77
12	47.41	17.00	23.19	3.77	1.92	2.89	0.00	0.67	0.38	0.01	2.77
30	47.41	17.00	23.19	3.77	1.92	2.89	0.00	0.67	0.38	0.01	2.77
Variance of French VIX explained by shocks to the implied volatilities											
0	26.57	27.10	3.89	0.00	41.26	0.00	0.00	0.00	0.00	0.00	1.19
1	41.46	20.17	3.23	0.36	30.73	0.75	0.04	0.00	0.52	0.17	2.56
2	41.86	19.23	3.15	0.66	29.11	1.58	0.04	0.30	0.95	0.24	2.88
3	41.39	19.30	3.14	0.76	28.89	1.85	0.04	0.47	1.05	0.25	2.85
12	41.80	19.17	3.11	0.77	28.59	1.87	0.05	0.48	1.05	0.25	2.86
30	41.80	19.17	3.11	0.77	28.59	1.87	0.05	0.48	1.05	0.25	2.86
Variance of Swiss VIX explained by shocks to the implied volatilities											
0	29.86	36.77	0.00	32.04	0.00	0.00	0.00	0.00	0.00	0.00	1.33
1	49.92	26.52	0.06	19.63	0.74	0.41	0.00	0.40	0.10	0.01	2.20
2	52.78	23.21	0.06	17.40	1.30	1.55	0.00	0.97	0.31	0.01	2.41
3	52.13	22.88	0.06	17.25	1.42	2.23	0.00	1.21	0.42	0.01	2.39
12	52.19	22.79	0.07	17.10	1.42	2.35	0.00	1.23	0.43	0.01	2.41
30	52.19	22.79	0.07	17.10	1.42	2.35	0.00	1.23	0.43	0.01	2.41
Variance of Korean VIX explained by shocks to the implied volatilities											
0	9.59	9.78	1.41	0.00	1.03	61.94	0.00	15.83	0.00	0.00	0.43
1	32.52	8.19	0.97	0.39	2.03	42.72	0.00	10.63	0.27	0.02	2.27
2	35.69	7.37	0.95	0.95	2.62	38.80	0.01	10.44	0.54	0.03	2.60
3	35.24	7.44	0.96	1.15	2.67	38.68	0.01	10.59	0.64	0.03	2.58
12	35.64	7.49	0.95	1.16	2.67	38.31	0.01	10.49	0.65	0.03	2.60
30	35.64	7.49	0.95	1.16	2.67	38.31	0.01	10.49	0.65	0.03	2.60
Variance of Japanese VIX explained by shocks to the implied volatilities											
0	2.37	2.42	0.35	0.00	0.87	7.51	72.14	13.26	0.00	0.00	1.08
1	19.05	1.79	0.58	0.27	1.07	5.32	60.74	9.56	0.00	0.00	1.62
2	22.65	1.74	0.68	0.79	1.61	5.27	56.80	8.78	0.02	0.01	1.66
3	22.44	1.97	0.71	1.05	1.73	5.56	56.16	8.71	0.03	0.01	1.63
12	22.65	2.10	0.72	1.09	1.73	5.60	55.73	8.65	0.04	0.01	1.69
30	22.65	2.10	0.72	1.09	1.73	5.60	55.73	8.65	0.04	0.01	1.69

Table 2. (Continued)

Day	VIX	German VIX	UK VIX	Swiss VIX	French VIX	Korean VIX	Japanese VIX	HK VIX	Gold VIX	Oil VIX	MOVE
				Variance of Hong Kong VIX explained by shocks to the implied volatilities							
0	3.63	3.70	0.53	0.00	5.63	0.00	0.00	86.34	0.00	0.00	0.16
1	28.17	2.45	0.96	0.00	4.20	0.00	0.10	59.94	0.46	0.23	3.50
2	32.22	2.28	1.08	0.26	5.30	0.43	0.09	52.71	0.87	0.25	4.51
3	31.68	2.45	1.09	0.52	5.68	0.84	0.09	51.84	0.99	0.24	4.57
12	32.10	2.57	1.08	0.58	5.64	0.93	0.10	51.23	1.00	0.24	4.54
30	32.10	2.57	1.08	0.58	5.64	0.93	0.10	51.23	1.00	0.24	4.54
				Variance of Gold VIX explained by shocks to the implied volatilities							
0	15.74	0.13	0.02	0.00	0.01	0.80	0.00	0.20	80.69	0.00	2.42
1	18.17	0.11	0.14	0.77	0.02	0.66	0.18	0.55	75.58	0.02	3.79
2	18.71	0.22	0.19	1.22	0.04	0.69	0.30	0.58	73.40	0.05	4.60
3	18.59	0.37	0.20	1.37	0.06	0.72	0.34	0.58	72.84	0.06	4.86
12	18.70	0.45	0.21	1.40	0.07	0.73	0.35	0.58	72.55	0.06	4.91
30	18.70	0.45	0.21	1.40	0.07	0.73	0.35	0.58	72.55	0.06	4.91
				Variance of Oil VIX explained by shocks to the implied volatilities							
0	21.66	0.04	0.01	0.00	0.03	0.03	0.00	0.47	3.22	73.28	1.27
1	23.52	1.85	0.04	0.75	0.03	1.85	0.00	1.12	2.74	66.53	1.55
2	22.62	3.74	0.06	0.90	0.03	2.63	0.01	1.31	2.63	64.49	1.59
3	22.80	4.35	0.10	0.90	0.03	2.68	0.01	1.36	2.59	63.62	1.57
12	23.15	4.41	0.12	0.90	0.03	2.69	0.01	1.40	2.58	63.13	1.56
30	23.15	4.41	0.12	0.90	0.03	2.69	0.01	1.40	2.58	63.13	1.56

Notes. This table reports the results of forecast error variance decomposition (percentage points) among volatilities of U.S. security bonds, stock markets, and commodities. The variance decomposition is based on the directed graph on innovations given in Figure 1.

Degree centrality is the average of column sum of the off-diagonal total pairwise spillover intensities in the network's adjacency matrix. Simply speaking, a market is more central if its total spillover intensity from and to others is stronger. Eigenvector centrality is defined as the principal eigenvector of the network's adjacency matrix. Intuitively, a market is considered more central if it is connected to other markets that are themselves central. Both centrality measures for the VIX are the highest, confirming the result that the U.S. stock market is at the center of global volatility spillover network during the period from 2008 to 2013.[25]

4.2. Results on Volatility Spillover Indices

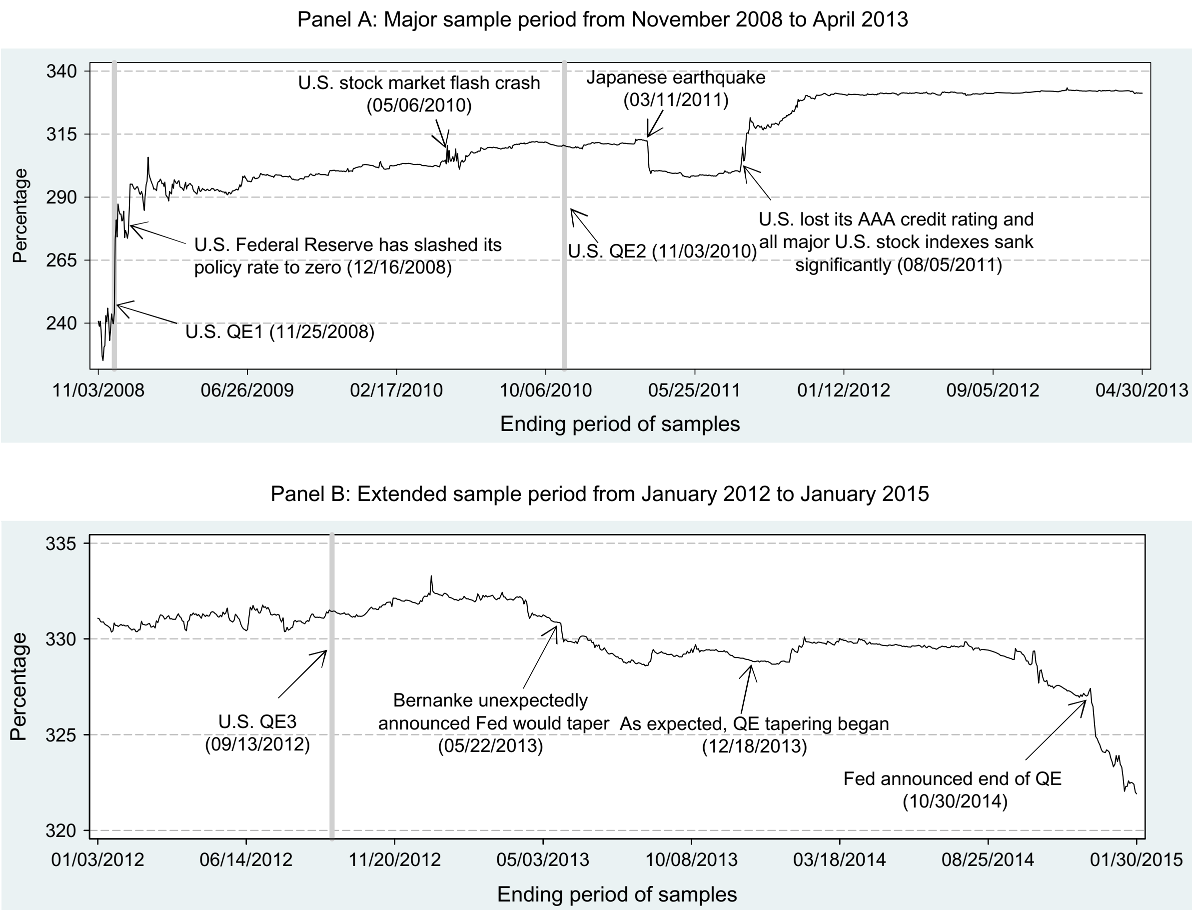
To further explore time-varying spillover intensity, we construct volatility spillover indices by estimating

Table 3. Network Centrality for the Period from 2008 to 2013

	VIX	MOVE	UK VIX	German VIX	French VIX	Swiss VIX	Japanese VIX	HK VIX	Korean VIX	Gold VIX	Oil VIX
VIX	0	6.2	47.6	59	43.7	53	22.7	33.9	38.3	19.3	23.2
MOVE	6.2	0	3.1	4.9	4.1	3.7	1.9	4.9	2.7	4.9	1.6
UK VIX	47.6	3.1	0	17.1	5	3.9	0.7	1.8	3.8	0.6	0.1
German VIX	59	4.9	17.1	0	19.7	24.1	2.3	3.4	10.6	1.2	4.4
French VIX	43.7	4.1	5	19.7	0	2.2	1.7	6.1	4.6	1.2	0.3
Swiss VIX	53	3.7	3.9	24.1	2.2	0	1.1	1.8	3.5	1.8	0.9
Japanese VIX	22.7	1.9	0.7	2.3	1.7	1.1	0	8.7	5.6	0.4	0
HK VIX	33.9	4.9	1.8	3.4	6.1	1.8	8.7	0	11.4	1.6	1.6
Korean VIX	38.3	2.7	3.8	10.6	4.6	3.5	5.6	11.4	0	1.4	2.7
Gold VIX	19.3	4.9	0.6	1.2	1.2	1.8	0.4	1.6	1.4	0	2.7
Oil VIX	23.2	1.6	0.1	4.4	0.3	0.9	0	1.6	2.7	2.7	0
Degree centrality	34.69	3.81	8.36	14.69	8.85	9.61	4.52	7.53	8.47	3.50	3.77
Eigenvector centrality	0.64	0.08	0.29	0.42	0.28	0.33	0.14	0.21	0.25	0.11	0.13

Notes. This table reports network centrality of each market, which refers to how important one market in a network is relative to other markets. The upper 11×11 submatrix is an adjacency matrix in which diagonal elements are zeros and the off-diagonal elements are 12-day-ahead total pairwise volatility spillover intensity (in percentage points). For example, the total spillover intensity between VIX and MOVE is 6.2%, which is the sum of the VIX spillover to MOVE, 1.9%, and the MOVE spillover to VIX, 4.3%, in Table 2. The second to last row shows degree centrality, which is simply the average of column sum of the off-diagonal total pairwise spillovers. The last row of the matrix shows eigenvector centrality, defined as the principal eigenvector of the network's adjacency matrix. Intuitively, a market is considered more central if it is connected to other markets are themselves central (Ahern and Harford 2014).

Figure 2. (Color online) Aggregate Volatility Spillover Index of VIX



Notes. This figure plots the aggregate volatility spillover index of the VIX, which is the sum of all recursive variance decomposition contributions from the VIX to all other VIXs each day at horizons of 12 days. Other VIXs include the Oil VIX, Gold VIX, German VIX, French VIX, UK VIX, Swiss VIX, Japanese VIX, Korean VIX, and HK VIX. In panel B, other VIXs do not include the Oil VIX and Gold VIX. The initial sample period is from June 6, 2008, to November 3, 2008, and the variance decompositions are estimated recursively each day with an expanding sample. The final sample period is from June 6, 2008, to April 30, 2013. The whole and final sample period is from June 6, 2008, to January 30, 2015. The panel just plots the period from January 2012 to January 2015 in a larger scale.

recursive variance decompositions each day with an expanding sample.[26] We aggregate VIX spillover effects by summing up all variance decomposition contributions from the VIX to all other VIXs each day following Equation (5). The estimated 12-step-ahead volatility spillover index of the VIX is plotted in panel A of Figure 2. Clearly, the VIX spillover effect has intensified since quantitative easing was implemented, with a sharp jump in particular on November 25, 2008, when QE1 was launched.[27] In contrast, no significant movement is associated with the introduction of QE2.[28] The index also appears to reflect spillover around other important events. For example, when Lehman Brothers failed on September 15, 2008, when the Fed slashed its policy rate to zero on December 16, 2008, and when the United States lost its AAA credit rating on August 5, 2011, the VIX spillover index recorded big increases. The effect of other events such as Japan's earthquake and tsunami can also be seen in panel A of Figure 2.

We also use recursive variance decompositions to derive the individual VIX spillover indices, defined in Equation (6). Although we do not include the figures for these spillover indices to save space, they also intensified during the sample period and jumped with the initiation of QE1, confirming that U.S. quantitative easing is an important source of international volatility spillovers.

Table 4 reports summary statistics of the volatility spillover indices recursively estimated from November 3, 2008, to April 30, 2013, for horizons of 1, 3, and 12 days ahead. The means of the aggregate VIX spillover index are more than 300% across all horizons. Recall that the aggregate VIX spillover index is the percentage of all other VIX variations explained by VIX innovations. Therefore, the sum of all other nine VIX variations can be as high as 900%. The 300% average indicates that VIX shocks explain about one-third of the variance of the other nine VIXs. Other statistics indicate a significant variation, tail, and range

Table 4. Summary Statistics of Daily Volatility Spillover Indices

Spillover index	Recipient market(s)	*H*-day ahead	Mean	Std. dev.	Skew	Kurt.	Min	Max	*p*-value for ADF test	*p*-value for LP test
Aggregate	International stocks	1	306.620	11.730	−0.567	4.184	252.207	321.584	0.000	<0.010
Aggregate	and commodities	3	305.337	19.667	−0.679	4.323	220.158	330.265	0.000	<0.010
Aggregate		12	311.284	17.647	−0.989	5.961	225.112	333.298	0.000	<0.050
Individual	Germany stocks	12	53.998	3.606	−1.629	8.493	34.847	58.122	0.000	<0.010
Individual	UK stocks	12	43.117	3.390	−0.839	5.714	26.360	47.474	0.000	<0.010
Individual	Swiss stocks	12	49.650	2.688	−1.799	9.893	34.235	52.792	0.000	<0.010
Individual	French stocks	12	37.135	3.747	−0.654	3.446	22.001	41.797	0.000	<0.010
Individual	Korean stocks	12	35.622	1.226	0.010	3.647	31.627	39.701	0.069	<0.010
Individual	Japanese stocks	12	27.056	4.510	−0.094	1.198	20.299	32.724	0.087	<0.010
Individual	Hong Kong stocks	12	29.652	1.719	−0.065	1.697	25.023	32.225	0.026	0.010
Individual	Gold	12	16.919	1.890	0.186	1.654	11.505	20.305	0.000	<0.010
Individual	Oil	12	18.135	4.244	−0.506	2.303	4.941	23.275	0.043	<0.100

Notes. This table presents summary statistics for daily volatility spillover indices from November 3, 2008, to April 30, 2013. Number of observations is 1,124. As defined in Equation (5), the aggregate spillover index is the sum of all recursive variance decomposition contributions from VIX to all other VIXs of international stock and commodity markets. As defined in Equation (6), the individual volatility spillover index is the recursive variance decomposition contribution from the VIX to another market VIX. The ADF test is the augmented Dickey and Fuller (1979, 1981) unit root test for the intercept and trend case. The LP test is the Lumsdaine and Papell (1997) unit root test, which allows for structural breaks in level and trend.

of VIX spillover indices. For individual VIX spillover indices, we only report statistics for 12-day-ahead forecasts.[29] At this horizon, European stock markets receive the strongest volatility spillovers from the U.S. stock market: German, French, UK, and Swiss VIX spillovers from their U.S. counterpart are on average 54%, 49%, 43%, and 37%, respectively. The averages of VIX spillovers into Asian stock markets are also strong, ranging from 27% for Japan to 35% for Korea. Commodity markets receive relatively weak but still significant volatility spillovers with averages of 16% to 18%.

Given the intensifying spillover effects, it is important to address concerns about stationarity. Therefore, we conduct augmented Dickey and Fuller (1979, 1981) unit root tests for the case of an intercept and a time trend and Lumsdaine and Papell (1997) unit root tests allowing for unknown structural breaks in level and trend. As shown in Table 4, all *p*-values are smaller than 10%, rejecting the null hypothesis that volatility spillover indices follow unit root processes. In other words, volatility spillover indices can be considered stationary series.

Table 5 shows the daily correlation matrix for regression variables. Some highlights of the cross correlations between the 12-day-ahead aggregate volatility spillover index and our measures of macroeconomic

Table 5. Daily Correlations Among the Aggregate Volatility Spillover Index and Instruments

	Aggregate spillover	*QE*	*SHORT*	*ΔUSD*	*TERM*	*DEF*	*TED*	*ΔADSBCI*	*ΔCESG10*
QE	0.624***								
SHORT	−0.705***	−0.513***							
ΔUSD	−0.104***	−0.015	0.055*						
TERM	−0.439***	−0.663***	−0.023	−0.032					
DEF	−0.452***	−0.440***	0.231***	0.006	−0.052*				
TED	−0.788***	−0.450***	0.609***	0.108***	0.039	0.690***			
ΔADSBCI	−0.128***	−0.013	−0.176***	0.050*	0.121***	0.059**	0.011		
ΔCESG10	0.058**	−0.026	−0.024	0.024	−0.034	0.039	−0.042	0.068**	
ΔCESEM	0.038	−0.019	−0.052*	−0.041	0.026	0.008	−0.065**	−0.001	0.163***

Notes. This table reports daily correlations between the 12-day-ahead aggregate volatility spillover index and instruments. As defined in Equation (5), the aggregate spillover index is the sum of all recursive variance decomposition contributions from the VIX to all other VIXs of international stock and commodity markets. *QE* is the proxy of U.S. quantitative easing, the cumulative net purchase of U.S. Treasury and agency mortgage-backed securities. *ΔUSD* is the change of the trade-weighted U.S. dollar spot index. *SHORT* is the U.S. short rate. *ΔUSD* is the log difference of the trade-weighted U.S. dollar index. *TERM* is term spread defined as the difference between the 10-year and three-month Treasury yields. DEF_t is the default spread defined as the difference between BAA corporate bond and 10-year Treasury yields. *TED* is the spread between the three-month LIBOR based on U.S. dollars and three-month Treasury yield. *ΔADSBCI* is the change of the Aruoba et al. (2009) business condition index. *CESG10* is the change of Citigroup's economic surprise index for the G10. *ΔCESEM* is the change of Citigroup's economic surprise index for emerging markets.

*, **, *** denote significance at 10%, 5%, and 1%, respectively.

risk are as follows.[30] Consistent with our hypothesis, the aggregate spillover index rises with the QE proxy, the cumulative net purchase of securities by the Fed, at the 1% significance level. Meanwhile, the spillover index is negatively correlated with the U.S. interest rate and currency factors as well as the change of U.S. business condition at the 1% significance level.

4.3. Determinants of Volatility Spillovers

Having measured spillover originating in the U.S. stock market, we now identify the underlying economic forces that drive those spillovers using Equation (7) estimated at a daily frequency. The daily QE proxy is the cumulative net purchase of securities through permanent open market operations. For control variables, we use the variables described above.[31]

Table 6 summarizes the results of daily regression estimates of Equation (7). In Model 1, the QE proxy alone explains a big portion of volatility spillover from the U.S. stock market to other stock and commodity markets, with an adjusted R^2 ranging from 40.1% for one-day forecasts to 55.1% for three-day forecasts. It suggests that U.S. quantitative easing is the primary driver of volatility spillovers that peak in three days. Moreover, the coefficients of the QE proxy are all positive and significant at the 1% level, supporting our hypothesis that volatility spillover intensity increases with the size of U.S. quantitative easing.

In Model 2, the addition of the U.S. short rate and the change of the U.S. dollar index explains 45.7% to 61.2% of international volatility spillover depending on the horizon. The incremental explanatory power is only 5%. The coefficients on the Fed's QE proxy remain significantly positive at the 1% level. The coefficients on the U.S. short rate are negative and significant at the 1% level, suggesting that volatility spillover intensity increases with low U.S. short-term interest rates. In the era of quantitative easing, investors learn and update their beliefs that the future policy rate remains zero for a fairly long period of time, which is expected to be effective in stimulating the real economy and/or financial markets. Thus, risk-neutral volatility in the U.S. decreases and spills over to other markets. Meanwhile, the coefficients on U.S. dollar change are negative and

Table 6. Determinants of VIX Aggregate Spillovers to Other Equity and Commodity VIXs

Dependent variable	1-day ahead VIX aggregate spillover				3-day ahead VIX aggregate spillover				12-day-ahead VIX aggregate spillover			
	Model 1	Model 2	Model 3	Model 4	Model 1	Model 2	Model 3	Model 4	Model 1	Model 2	Model 3	Model 4
QE_t	1.67***	1.30***	0.43***	0.45***	2.87***	2.31***	1.03***	1.06***	2.52***	1.91***	0.77***	0.79***
	(0.06)	(0.07)	(0.13)	(0.13)	(0.08)	(0.08)	(0.15)	(0.15)	(0.08)	(0.09)	(0.16)	(0.16)
$SHORT_t$		−65.19***	−12.45**	−17.61***		−97.92***	−16.53**	−21.44***		−108.23***	−17.75**	−23.83***
		(5.97)	(6.06)	(6.31)		(7.40)	(6.91)	(7.21)		(7.95)	(7.45)	(7.77)
ΔUSD_t		−2.09**	−1.84**	−1.63**		−2.65**	−2.34***	−2.09**		−2.96**	−2.47***	−2.21**
		(1.01)	(0.76)	(0.76)		(1.25)	(0.86)	(0.86)		(1.34)	(0.93)	(0.93)
$TERM_t$			−9.87***	−9.30***			−13.45***	−12.86***			−12.61***	−11.99***
			(1.03)	(1.04)			(1.18)	(1.19)			(1.27)	(1.28)
DEF_t			8.36***	9.59***			8.35***	9.62***			11.17***	12.52***
			(0.98)	(1.02)			(1.11)	(1.17)			(1.20)	(1.26)
TED_t			−36.01***	−38.37***			−47.22***	−49.69***			−53.28***	−55.88***
			(1.76)	(1.86)			(2.01)	(2.13)			(2.17)	(2.30)
$\Delta ADSBCI_t$				−64.94***				−68.88***				−74.64***
				(11.94)				(13.65)				(14.71)
$\Delta CESG10_t$				−0.00				0.00				−0.00
				(0.09)				(0.10)				(0.10)
$\Delta CESEM_t$				−0.06				−0.00				−0.02
				(0.10)				(0.11)				(0.12)
N	1,124	1,104	1,095	1,083	1,124	1,104	1,095	1,083	1,124	1,104	1,095	1,083
Adj. R^2	0.401	0.457	0.699	0.709	0.551	0.612	0.818	0.822	0.449	0.527	0.777	0.782

Notes. This table reports the results of the following daily regressions: $AS_{t,H} = \beta_0 + \beta_1 QE_t + Controls + \varepsilon_t$, where $AS_{t,H}$ is the daily H-step-ahead aggregate volatility spillover index from VIX to other VIXs, which is the sum of the shares of recursive forecast error variance of other VIXs explained by VIX. QE_t is the proxy of U.S. quantitative easing, the cumulative net purchase of U.S. Treasury securities, agency securities, and mortgage-backed securities. Controls include the following variables: $SHORT_t$ is the U.S. short rate proxied by one-month Treasury yield. ΔUSD_t is the log difference of the trade-weighted U.S. dollar index. $TERM_t$ is term spread defined as the difference between the 10-year and three-month Treasury yields. DEF_t is the default spread defined as the difference between BAA corporate bond and 10-year Treasury yields. TED_t is the spread between the three-month LIBOR based on U.S. dollars and three-month Treasury yield. $\Delta ADSBCI_t$ is the change of the Aruoba et al. (2009) business condition index. $\Delta CESG10_t$ is the change of Citigroup's economic surprise index for the G10. $\Delta CESEM_t$ is the change of Citigroup's economic surprise index for emerging markets. The robust standard errors are reported in parentheses. N is the number of observations used in each regression. Intercepts are not reported to save space.

** and *** denote significance at 5% and 1%, respectively.

significant at the 5% level, suggesting that volatility spillover intensity increases with U.S. dollar depreciation. This implies that U.S. dollar depreciation appears to magnify the spillover effect through carry trades. In sum, U.S. quantitative easing plays a dominant role in explaining global volatility spillovers, although a low U.S. interest rate and a weakening U.S. dollar do have some power of about 5%.

With the term spread, default spread, and TED spread included in Model 3, the adjusted R^2 increases further, ranging from 69.9% to 81.8%. With this set of control variables, the findings are consistent with those in Model 2. The coefficients of U.S. quantitative easing remain significantly positive, supporting the quantitative easing effect in our hypothesis. The negative coefficients of U.S. short rate and U.S. dollar change are also quite robust. Among the other control variables, the coefficients on the term spread and default spread are negative and positive at the 1% significance level, respectively. This suggests that volatility spillover intensity increases with lower term spread and higher default spread, which signal worse business condition in the future. Having controlled for this type of spillover due to bad news, quantitative easing is still significant in explaining spillover. The TED spread is negatively associated with volatility spillover, perhaps because a lower TED spread indicates better funding liquidity, which leads to better market liquidity and higher spillover intensity.

In Model 4, we extend the set of control variables by adding the changes of U.S. business condition index described above and Citigroup's surprise indices. The adjusted R^2 is higher than that of Model 3. The inclusion of the macrovariables does not change the results as shown in Table 6. The size of U.S. quantitative easing is still significant in explaining global volatility spillovers. Among the macrovariables, the change of the U.S. business condition index is significantly negative, suggesting that VIX spillover intensity increases with deterioration in the U.S. macroeconomic climate. In contrast, the changes of Citigroup's surprise indices do not turn out to be significant in the regressions. Again, quantitative easing is remains a strongly significant source of spillover after controlling for spillover related to business conditions.

In sum, U.S. quantitative easing is the primary driver of VIX spillover to other markets and thus plays a central role in global volatility spillovers. This is beneficial if quantitative easing is effective in providing financial accommodation (Bernanke 2012) and thus lowers global volatility. However, the policy is also potentially destabilizing (Bernanke 2012) because U.S. volatility spillover to the rest of the world has intensified with quantitative easing. A rough exit from unconventional monetary policy or unexpected increases in U.S. interest rates can raise global systemic risk quickly through intensifying (volatility) spillover effects between financial markets around the world. Therefore, we find evidence to support a recent argument of Allen (2014) that systemic risk is endogenous and related to central bank policies. In other words, quantitative easing is a potential source of global systemic risk.

We further examine the determinants of international volatility spillovers of U.S. quantitative easing across each recipient market. From Table 2, variance decompositions and thus volatility spillovers stabilize from 12 days ahead and beyond. Therefore, we estimate Equation (7) with the 12-day-ahead volatility spillover indices and report the results in Table 7. The adjusted R^2 value, ranging from 41.9% for the Korean stock market to 93.0% for the oil market,[32] shows significant variation across countries and asset classes. The coefficients for the U.S. QE proxy are significantly positive for most markets, confirming our hypothesis except for the Japanese and Korean stock markets. Whereas U.S. quantitative easing has no apparent effect on volatility spillover into the Korean stock market, the result for Japan is opposite of the predication of our hypothesis because the QE coefficient is significantly negative. One possible explanation is a structural break due to Japan's earthquake and tsunami,[33] which coincides with the sudden decrease in the spillover index in Figure 2.

4.4. Robustness Checks

We begin by estimating regressions for daily volatility spillover indices for other horizons (one and three days ahead) and find similar results. Next, we insert additional controls for macroeconomic and financial conditions, the Fama and French (1989) three factors and momentum factor, which can proxy for innovations in U.S. investment opportunities (Petkova 2006) and growth rate of U.S. industrial production (Liu and Zhang 2008), respectively. We also construct a global stock risk premium and value premium, and use changes of the VIX and economic policy uncertainty index in the regressions. As shown in Table 6A of the online appendix, the results remain similar. Also, we replace recursive spillovers with rolling spillovers and combinations of recursive and rolling spillovers. As shown in Table 7A of the online appendix, the size of U.S. quantitative easing is still significant in explaining global volatility spillovers, although the adjusted R^2 is lower than that in Table 6.

Moreover, we provide weekly evidence on associations between volatility spillovers and quantitative easing. The weekly proxy of quantitative easing is the size of U.S. Treasury securities, agency securities, and mortgage-backed securities holdings on the Fed balance sheet. We also have weekly data for central banks liquidity swaps to add into the regressions. To match the weekly frequency of the QE proxy and liquidity

Table 7. Determinants of Daily VIX Spillovers to Individual Recipient Markets

	Daily 12-day-ahead individual volatility spillover from the U.S. stock market to one of the following markets								
Dependent variable	German stocks	French stocks	UK stocks	Swiss stocks	Japanese stocks	Korean stocks	Hong Kong stocks	Oil	Gold
QE_t	0.229***	0.269***	0.221***	0.203***	−0.713***	−0.016	0.132***	0.293***	0.191***
	(0.031)	(0.017)	(0.022)	(0.031)	(0.031)	(0.022)	(0.024)	(0.015)	(0.011)
$SHORT_t$	−5.850***	−0.727	−6.785***	−6.587***	12.573***	−8.172***	−9.852***	4.352***	−1.727***
	(1.510)	(0.799)	(1.077)	(1.516)	(1.476)	(1.056)	(1.155)	(0.737)	(0.542)
ΔUSD_t	−0.230**	−0.088*	−0.100	−0.047	0.203**	−0.005	0.753	−0.063***	−0.023
	(0.094)	(0.050)	(0.069)	(0.087)	(0.096)	(0.052)	(1.596)	(0.019)	(0.019)
$TERM_t$	−1.583***	−1.984***	−1.810***	−0.820***	−1.475***	−0.521***	−0.386**	−2.350***	−0.892***
	(0.248)	(0.131)	(0.177)	(0.248)	(0.243)	(0.173)	(0.190)	(0.121)	(0.089)
DEF_t	2.856***	0.492***	1.911***	3.223***	1.084***	2.436***	2.080***	−1.987***	0.529***
	(0.244)	(0.129)	(0.175)	(0.244)	(0.239)	(0.170)	(0.186)	(0.121)	(0.088)
TED_t	−12.083***	−5.699***	−8.238***	−11.573***	−8.183***	−4.807***	−4.261***	−0.226	−0.902***
	(0.446)	(0.236)	(0.319)	(0.446)	(0.436)	(0.310)	(0.340)	(0.223)	(0.159)
$\Delta ADSBCI_t$	−15.270***	−6.290***	−6.808***	−16.949***	−10.407***	−7.887***	−5.953***	−0.584	−5.174***
	(2.857)	(1.512)	(2.046)	(2.852)	(2.803)	(1.990)	(2.189)	(1.405)	(1.031)
$\Delta CESG10_t$	−0.005	0.007	0.002	−0.007	−0.008	0.004	−0.004	0.005	−0.001
	(0.020)	(0.011)	(0.015)	(0.020)	(0.020)	(0.014)	(0.016)	(0.010)	(0.007)
$\Delta CESEM_t$	0.003	0.001	−0.003	−0.008	0.002	−0.021	−0.016	0.031***	−0.004
	(0.023)	(0.012)	(0.017)	(0.023)	(0.023)	(0.016)	(0.018)	(0.011)	(0.008)
N	1,083	1,083	1,083	1,083	1,083	1,083	1,083	1,093	1,086
Adj. R^2	0.806	0.918	0.857	0.745	0.764	0.419	0.515	0.930	0.834

Notes. This table reports the result of the following daily regressions: $IS^i_{t,12} = \beta_0 + \beta_1 QE_t + Controls + \varepsilon_t$, where $IS^i_{t,12}$ is daily 12-day-ahead individual volatility spillover index from the U.S. stock market to another market. As defined in Equation (6), the individual spillover index is a recursive forecast error variance decomposition contribution from VIX to another market VIX; and QE_t is the proxy of U.S. quantitative easing, the cumulative net purchase of U.S. Treasury securities, agency securities, and mortgage-backed securities. Controls include the following variables: $SHORT_t$ is the U.S. short rate proxied by one-month Treasury yield; and ΔUSD_t is the change of foreign currency per U.S. dollar. In the cases of oil and gold markets, ΔUSD_t is the change of oil and gold price per U.S. dollar; $TERM_t$ is term spread defined as the difference between the 10-year and three-month Treasury yields; DEF_t is the default spread defined as the difference between BAA corporate bond and 10-year Treasury yields; TED_t is the spread between the three-month LIBOR based on U.S. dollars and three-month Treasury yield; $\Delta ADSBCI_t$ is the Aruoba et al. (2009) business condition index; $\Delta CESG10_t$ is Citigroup's economic surprise index for the G10; and $\Delta CESEM_t$ is Citigroup's economic surprise index for emerging markets. The robust standard errors are reported in parentheses. N is the number of observations used in each regression. Intercepts are not reported to save space.

*, **, *** denote significance at 10%, 5%, and 1%, respectively.

swaps, we use weekly spillover indices (observed each Friday) as the dependent variable.

Table 8 shows the results of weekly regressions in Equation (7). Consistent with the results in Tables 6 and (7), there is strong and robust evidence to confirm our hypothesis that U.S. quantitative easing explains global volatility spillovers. The additional explanatory variable of central bank liquidity swaps is significantly positive, suggesting that volatility spillover intensity increases with the dollar amount drawn from central bank liquidity swaps. According to Brunnermeier and Pedersen (2009), the increased dollar funding liquidity improves foreign market liquidity and lowers volatility. The spillover effect on non U.S. markets grows as the amount that foreign central banks draw from swap lines with the Fed increases. For the weekly three-day-ahead individual volatility spillover effect, the results are consistent with their daily counterparts in Table 7, and there is strong evidence that the coefficients on liquidity swaps are significantly positive, except for Japan.[34] Also, the results for weekly individual VIX spillovers for other horizons (1 and 12 days ahead) are similar.

To make sure that the results in Table 8 are not driven by the choice of data from Fridays, we use another set of weekly spillover indices (Wednesdays) as dependent variables and obtain similar results. In addition, we use the weekly cumulative net purchase of securities by the Fed of every Wednesday or Friday as the proxy of quantitative easing and find similar results.

U.S. short rate has been essentially zero in the era of quantitative easing. Therefore, it has become difficult to accurately assess the monetary policy stance using the nominal short rate. To address this issue of zero lower bound (ZLB) constraint, we construct the real short rate by subtracting the inflation rate. Still, most coefficients of real short rates are (significantly) negative in the daily and weekly regressions, as shown in Table 8A of the online appendix.[35] We also use the shadow policy rate constructed by Lombardi and Zhu (2014), which provides a reasonable gauge of the

Table 8. Determinants of Weekly VIX Spillovers

	Weekly VIX aggregate spillovers			Weekly (Friday) 3-day-ahead individual VIX spillover to one of the following markets								
Dependent variable	1-day ahead	3-day ahead	12-day ahead	German stocks	French stocks	UK stocks	Swiss stocks	Japanese stocks	Korean stocks	Hong Kong stocks	Oil	Gold
QE_t	0.84**	1.52***	1.19***	0.522***	0.463***	0.233***	0.478***	−0.727***	−0.018	0.021	0.462***	0.183***
	(0.39)	(0.42)	(0.46)	(0.080)	(0.042)	(0.061)	(0.081)	(0.085)	(0.054)	(0.060)	(0.034)	(0.026)
$SHORT_t$	−29.69**	−42.09***	−41.67**	−8.937***	−5.084***	−12.246***	−7.691**	16.960***	−10.136***	−11.692***	2.772**	−2.031**
	(14.43)	(15.64)	(17.02)	(2.989)	(1.566)	(2.238)	(3.069)	(3.154)	(2.054)	(2.250)	(1.226)	(0.950)
ΔUSD_t	−2.28***	−2.32**	−2.47**	−0.212**	−0.136***	−0.136*	−0.017	−0.001	−0.091*	−0.241	0.013	−0.040**
	(0.85)	(0.92)	(1.00)	(0.096)	(0.050)	(0.069)	(0.086)	(0.100)	(0.050)	(1.467)	(0.018)	(0.017)
$SWAP_t$	5.17**	5.15**	5.58**	1.051**	0.427*	0.594*	1.313***	−1.022**	1.170***	1.048***	0.028	0.588***
	(2.14)	(2.32)	(2.52)	(0.444)	(0.233)	(0.336)	(0.454)	(0.475)	(0.300)	(0.339)	(0.186)	(0.144)
$TERM_t$	−9.44***	−14.03***	−13.03***	−0.934**	−1.985***	−2.763***	−0.282	−0.341	−1.009***	−2.149***	−2.181***	−1.704***
	(2.17)	(2.35)	(2.56)	(0.446)	(0.234)	(0.340)	(0.451)	(0.473)	(0.302)	(0.338)	(0.187)	(0.146)
DEF_t	8.59**	9.47**	11.29***	4.017***	1.533***	1.105**	4.011***	0.709	0.808*	−0.527	−0.558*	−0.424*
	(3.48)	(3.77)	(4.10)	(0.717)	(0.375)	(0.548)	(0.715)	(0.751)	(0.483)	(0.538)	(0.306)	(0.230)
TED_t	−44.75***	−52.21***	−60.23***	−12.567***	−5.345***	−6.637***	−12.813***	−8.891***	−4.980***	−3.641***	0.659	0.025
	(5.39)	(5.84)	(6.35)	(1.122)	(0.588)	(0.848)	(1.129)	(1.163)	(0.744)	(0.828)	(0.518)	(0.353)
$\Delta ADSBCI_t$	−17.65**	−15.29**	−17.55**	−3.301**	−1.065	−0.801	−4.000***	−5.605***	−2.018**	−0.309	0.844	0.127
	(7.05)	(7.65)	(8.32)	(1.468)	(0.769)	(1.110)	(1.476)	(1.566)	(0.989)	(1.111)	(0.618)	(0.478)
$\Delta CESG10_t$	−0.10	−0.08	−0.10	−0.015	−0.004	−0.013	−0.023	0.002	−0.011	−0.019	0.001	−0.004
	(0.09)	(0.10)	(0.11)	(0.019)	(0.010)	(0.014)	(0.019)	(0.020)	(0.013)	(0.014)	(0.008)	(0.006)
$\Delta CESEM_t$	0.05	0.07	0.07	0.012	0.013	0.010	0.006	−0.008	0.001	0.017	0.023**	0.006
	(0.10)	(0.11)	(0.12)	(0.022)	(0.011)	(0.016)	(0.022)	(0.023)	(0.015)	(0.016)	(0.009)	(0.007)
N	217	217	217	217	217	217	217	217	217	217	220	219
Adj. R^2	0.697	0.822	0.781	0.834	0.941	0.873	0.773	0.704	0.489	0.646	0.957	0.889

Notes. This table reports the results of the following weekly regressions: $S_{t,H} = \beta_0 + \beta_1 QE_t + Controls + \varepsilon_t$, where $S_{t,H}$ is the weekly (Friday) H-step-ahead aggregate or individual VIX spillover index defined earlier; and QE_t is the proxy of U.S. quantitative easing, the sum of U.S. Treasury securities, agency securities, and mortgage-backed securities holdings on the Fed balance sheet. Controls include the following variables: $SHORT_t$ is the U.S. short rate proxied by the one-month Treasury yield; and ΔUSD_t is the change of foreign currency per U.S. dollar. At the aggregate level, ΔUSD_t is the log difference of the trade-weighted U.S. dollar index. In the case of two commodity markets, ΔUSD_t is the log difference of oil and gold prices per U.S. dollar; $SWAP_t$ is the dollar amount foreign central banks draw from liquidity swaps with the Federal Reserve; $TERM_t$ is term spread defined as the difference between the 10-year and three-month Treasury yields; DEF_t is the default spread defined as the difference between BAA corporate bond and 10-year Treasury yields; TED_t is the spread between the three-month LIBOR based on U.S. dollars and three-month Treasury yield; $\Delta ADSBCI_t$ is the change of the Aruoba et al. (2009) business condition index; $\Delta CESG10_t$ is the change of Citigroup's economic surprise index for the G10; and $\Delta CESEM_t$ is the change of Citigroup's economic surprise index for emerging markets. The robust standard errors are reported in parentheses. N is the number of observations used in each regression. Intercepts are not reported to save space.

*, **, *** denote significance at 10%, 5%, and 1%, respectively.

U.S. monetary policy stance when the ZLB becomes binding, and obtain similar results.

For exchange rate, we can further test a basic textbook prediction: if a country fixes its exchange rate and has perfect capital mobility, capital flows will determine the country's money supply, making it impossible to run an independent monetary policy. Put another way, U.S. monetary policy can spill over to an economy with an exchange rate pegged or fixed against the U.S. dollar. By contrast, there is no spillover from U.S. monetary policy on an economy whose currency floats freely against the U.S. dollar. If we compare different exchange rate regimes under U.S. monetary easing, economies with a more flexible exchange rate regime should display less spillover from the United States. To test this, we construct a daily measure of rolling variance in the foreign rate to proxy for the flexibility of the country's or market's exchange rate regime and add it into daily regressions. As shown in Table 9, most coefficients of exchange rate variances are significantly negative, supporting the exchange rate flexibility effect.[36]

Furthermore, to address the concern about the possibility of spurious regressions,[37] we use the difference rather than level of cumulative net purchases to proxy for quantitative easing and add dummy variables to control for important events in Figure 2. The augmented daily regression is as follows:

$$S_{t,H} = \beta_0 + \beta_1 \Delta QE_t + \beta_2 D_t^{QE} + \beta_3 D_t^{Quake} + \beta_4 D_t^{AAA} + Controls + \varepsilon_t, \quad (9)$$

where S is either the daily aggregate or individual spillover index defined above; ΔQE_t is the QE proxy in difference of the Fed's cumulative net purchases; D_t^{QE} is the QE dummy defined as 1 since November 25, 2008, and 0 otherwise; D_t^{Quake} is the dummy of Japan's earthquake and tsunami, defined as 1 since March 11,

Table 9. Determinants of Daily VIX Spillovers with Additional Proxy for Exchange Rate Flexibility

	VIX aggregate spillovers			12-day-ahead individual VIX spillover to one of the following markets								
Dependent variable	1-day ahead	3-day ahead	12-day ahead	German stocks	French stocks	UK stocks	Swiss stocks	Japanese stocks	Korean stocks	Hong Kong stocks	Oil	Gold
QE_t	0.35***	0.95***	0.68***	0.229***	0.269***	0.190***	0.204***	−0.709***	−0.033	0.123***	0.290***	0.182***
	(0.13)	(0.15)	(0.16)	(0.031)	(0.016)	(0.021)	(0.031)	(0.031)	(0.021)	(0.024)	(0.015)	(0.010)
$SHORT_t$	−11.39*	−14.70**	−16.73**	−4.720***	0.391	−7.812***	−6.884***	12.903***	−8.441***	−9.743***	4.518***	−1.671***
	(6.17)	(7.07)	(7.63)	(1.559)	(0.818)	(0.994)	(1.521)	(1.475)	(1.016)	(1.151)	(0.739)	(0.499)
ΔUSD_t	−1.86**	−2.35***	−2.48***	−0.233**	−0.091*	−0.045	−0.054	0.231**	0.017	0.549	−0.051***	−0.011
	(0.73)	(0.84)	(0.91)	(0.093)	(0.049)	(0.063)	(0.087)	(0.096)	(0.051)	(1.591)	(0.020)	(0.018)
$RVAR_t$	−10.40***	−11.28***	−11.86***	−0.216***	−0.216***	−0.600***	0.083**	−0.222***	−0.169***	−62.470***	−0.002**	−0.098***
	(1.27)	(1.46)	(1.57)	(0.080)	(0.042)	(0.043)	(0.040)	(0.074)	(0.018)	(19.685)	(0.001)	(0.007)
$TERM_t$	−9.85***	−13.45***	−12.61***	−1.583***	−1.987***	−1.857***	−0.803***	−1.421***	−0.560***	−0.436**	−2.384***	−0.993***
	(1.01)	(1.16)	(1.25)	(0.247)	(0.130)	(0.163)	(0.247)	(0.243)	(0.167)	(0.190)	(0.122)	(0.083)
DEF_t	9.26***	9.27***	12.15***	2.923***	0.554***	1.768***	3.181***	1.064***	2.065***	1.967***	−2.081***	0.331***
	(0.99)	(1.14)	(1.23)	(0.244)	(0.128)	(0.161)	(0.245)	(0.239)	(0.169)	(0.189)	(0.129)	(0.082)
TED_t	−34.26***	−45.24***	−51.20***	−12.085***	−5.688***	−6.765***	−11.516***	−7.901***	−3.180***	−4.157***	0.001	−0.173
	(1.88)	(2.16)	(2.33)	(0.445)	(0.233)	(0.312)	(0.447)	(0.444)	(0.346)	(0.341)	(0.248)	(0.156)
$\Delta ADSBCI_t$	−64.37***	−68.44***	−74.10***	−15.799***	−6.649***	−4.962***	−16.931***	−10.141***	−8.011***	−6.421***	−0.150	−4.487***
	(11.64)	(13.34)	(14.39)	(2.859)	(1.500)	(1.895)	(2.863)	(2.805)	(1.922)	(2.194)	(1.433)	(0.953)
$\Delta CESG10_t$	0.03	0.03	0.03	−0.003	0.009	0.009	−0.008	−0.011	0.006	−0.004	0.005	−0.002
	(0.08)	(0.09)	(0.10)	(0.020)	(0.011)	(0.013)	(0.020)	(0.020)	(0.014)	(0.016)	(0.010)	(0.007)
$\Delta CESEM_t$	−0.06	−0.01	−0.03	0.003	0.001	−0.006	−0.006	0.005	−0.019	−0.013	0.031***	−0.003
	(0.09)	(0.11)	(0.12)	(0.023)	(0.012)	(0.015)	(0.023)	(0.023)	(0.016)	(0.018)	(0.011)	(0.008)
N	1,083	1,083	1,083	1,083	1,083	1,083	1,083	1,083	1,083	1,083	1,093	1,086
Adj. R^2	0.726	0.831	0.793	0.807	0.920	0.879	0.746	0.765	0.463	0.519	0.931	0.860

Notes. This table reports the results of the following weekly regressions: $S_{t,H} = \beta_0 + \beta_1 QE_t + Controls + \varepsilon_t$, where $S_{t,H}$ is the weekly (Friday) H-step-ahead aggregate or individual VIX spillover index defined earlier; and QE_t is the proxy of U.S. quantitative easing, the cumulative net purchase of U.S. Treasury securities, agency securities, and mortgage-backed securities. Controls include the following variables: $SHORT_t$ is the U.S. short rate proxied by the one-month Treasury yield. ΔUSD_t is the change of foreign currency per U.S. dollar. At the aggregate level, ΔUSD_t is the log difference of the trade-weighted U.S. dollar index. In the case of two commodity markets, ΔUSD_t is the log difference of oil and gold prices per U.S. dollar. $RVAR_t$ is rolling variance in the foreign currency per U.S. dollar with a weekly moving window. $TERM_t$ is term spread defined as the difference between the 10-year and three-month Treasury yields. DEF_t is the default spread defined as the difference between BAA corporate bond and 10-year Treasury yields. TED_t is the spread between the three-month LIBOR based on U.S. dollars and three-month Treasury yield. $\Delta ADSBCI_t$ is the change of the Aruoba et al. (2009) business condition index. $\Delta CESG10_t$ is the change of Citigroup's economic surprise index for the G10. $\Delta CESEM_t$ is the change of Citigroup's economic surprise index for emerging markets. The robust standard errors are reported in parentheses. N is the number of observations used in each regression. Intercept results are not reported to save space.

*, **, *** denote significance at 10%, 5%, and 1%, respectively.

2011, and 0 otherwise; and D_t^{AAA} is the dummy of U.S. credit rating downgrade from AAA, which is 1 since August 5, 2011, and 0 otherwise.

Table 10 shows the results of daily regression estimates of Equation (9). For aggregate spillover regressions, the coefficients for the QE proxy in difference are all positive and significant across various horizons. For individual spillover regressions,[38] the coefficients for the QE proxy in difference are significantly positive for most markets, including the Japanese stock market.[39] In sum, the relations between volatility spillover and quantitative easing are quite robust.

4.5. Further Analysis of Longer Periods and Other Volatility Spillovers

We extend the sample back to include the period prior to June 2008 and examine volatility spillover well before quantitative easing. The extended sample starts from January 2004 and ends in April 2013. It excludes the VIX indices for gold and oil because those series do not extend back far enough. To check that the previous results are not an artifact of the use of the DAG-based structural VAR, we follow Diebold and Yilmaz (2014) and estimate the generalized VAR proposed by Pesaran and Shin (1998). Then we construct volatility spillover indices by estimating generalized variance decompositions recursively and run the following augmented regression at the weekly frequency:

$$AS_{t,H} = (\beta_{01} + \beta_{02} D_t^{QE}) + (\beta_{11} + \beta_{12} D_t^{QE}) \times Holding_t + Controls + \varepsilon_t, \qquad (10)$$

where $AS_{t,H}$ is the weekly H-step-ahead aggregate volatility spillover to other stock (but not commodity) markets; D_t^{QE} is the QE dummy defined earlier; and $Holding_t$ is the size of securities holdings on the Fed's

Table 10. Determinants of VIX Spillovers: Robustness Check with the QE Proxy in Difference

	Daily VIX aggregate spillovers			Daily 3-day-ahead individual volatility spillover from the U.S. stock market to one of the following markets								
Dependent variable	1-day ahead	3-day ahead	12-day ahead	German stocks	French stocks	UK stocks	Swiss stocks	Japanese stocks	Korean stocks	Hong Kong stocks	Oil	Gold
ΔQE_t	17.08**	24.87***	24.95**	4.317**	3.970***	3.829***	3.612*	2.915***	−0.119	1.182	3.581***	1.978***
	(7.83)	(9.37)	(10.14)	(2.057)	(1.002)	(1.273)	(2.099)	(0.924)	(0.972)	(1.056)	(0.669)	(0.587)
D_t^{QE}	4.52***	4.92***	7.59***	0.997***	−0.476***	1.699***	1.293***	0.325**	1.875***	2.255***	−1.954***	−1.036***
	(1.19)	(1.42)	(1.54)	(0.311)	(0.152)	(0.193)	(0.318)	(0.140)	(0.148)	(0.160)	(0.101)	(0.088)
D_t^{Quake}	−11.08***	−10.16***	−13.15***	0.002	0.754***	−0.262	−0.123	−10.644***	−0.952***	−0.635***	1.526***	0.244**
	(1.40)	(1.67)	(1.81)	(0.367)	(0.179)	(0.227)	(0.375)	(0.165)	(0.174)	(0.188)	(0.119)	(0.105)
D_t^{AAA}	2.67	4.32*	1.91	−1.565***	0.305	1.169***	−1.781***	−0.683***	1.405***	2.488***	1.846***	1.291***
	(1.87)	(2.24)	(2.42)	(0.492)	(0.240)	(0.304)	(0.504)	(0.221)	(0.233)	(0.253)	(0.160)	(0.140)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	1,091	1,091	1,091	1,091	1,091	1,091	1,091	1,091	1,091	1,091	1,102	1,086
Adj. R^2	0.621	0.746	0.686	0.692	0.902	0.839	0.600	0.903	0.468	0.709	0.952	0.858

Notes. This table reports the results of the following daily regressions: $S_{t,H} = \beta_0 + \beta_1 \Delta QE_t + \beta_2 D_t^{QE} + \beta_3 D_t^{Quake} + \beta_4 D_t^{AAA} + Controls + \varepsilon_t$, where $S_{t,H}$ is the daily H-step-ahead aggregate or individual volatility spillover index defined earlier; ΔQE is the QE_t proxy in difference, defined as the difference of the cumulative net purchase of U.S. Treasury securities, agency securities, and mortgage-backed securities; D_t^{QE} is the QE dummy variable taking the value 1 since November 25, 2008, and 0 otherwise; D_t^{Quake} is the dummy variable for Japan's earthquake and tsunami taking the value 1 after March 11, 2011, and 0 otherwise; and D_t^{AAA} is the dummy variable for U.S. AAA credit rating downgrade and is defined as 1 since August 5, 2011, and 0 otherwise. Controls include the following variables: $SHORT_t$ is the U.S. short rate proxied by the one-month Treasury yield, and ΔUSD_t is the log difference of the trade-weighted U.S. dollar index in the aggregate spillover regressions or the change of foreign currency per U.S. dollar in the individual spillover regressions. In the cases of oil and gold markets, ΔUSD_t is the change of oil and gold price per U.S. dollar; $TERM_t$ is term spread defined as the difference between the 10-year and three-month Treasury yields; DEF_t is the default spread defined as the difference between BAA-rated corporate bond and 10-year Treasury yields; and TED_t is the spread between the three-month LIBOR based on U.S. dollars and three-month Treasury yield. The robust standard errors are reported in parentheses. N is the number of observations. Intercept and control variable results are not reported to save space.

*, **, *** denote significance at 10%, 5%, and 1%, respectively.

balance sheet, which is not necessarily a proxy of U.S. quantitative easing in the extended sample. Instead, the interactive term between the QE dummy and the Fed's securities holdings captures the scale of quantitative easing. The regression coefficient β_{11} measures the effect of the Fed's securities holdings on volatility spillover before quantitative easing. In the era of quantitative easing, the QE dummy takes a value of 1, and the impact of the Fed's securities holdings is measured not only by the regression coefficient β_{12}, but also by the sum of regression coefficients $\beta_{11} + \beta_{12}$.

Panel A of Table 11 shows the results of weekly regression estimates of Equation (10) using aggregate volatility spillover indices as dependent variables and the interest and currency factors as well as macrovariables as controls. The estimated coefficients for the QE dummy are all significant and positive, suggesting that volatility spillovers from the U.S. stock market to other stock markets increase under the Fed's quantitative easing program. Moreover, the coefficients of the Fed's securities holdings are significantly negative ($\beta_{11} < 0$), whereas the coefficients of its interactive term with the QE dummy are significantly positive ($\beta_{12} > 0$). The F-tests further show that the sum of these two regression coefficients is significantly positive ($\beta_{11} + \beta_{12} > 0$). These results extend our hypothesis: volatility spillover intensity increases with the size of the Fed's securities holdings in the era of quantitative easing, whereas this positive relation between volatility spillover and the Fed's securities holdings is reversed (negative) before quantitative easing. We do not report the results for individual spillover indices because they are generally similar. Overall, we confirm our previous findings that quantitative easing is the primary driver of intensifying volatility spillover from the United States to the rest of the world.

We also extend the sample to cover the period when the U.S. quantitative easing program is tapered and terminated. The extended 12-step-ahead volatility spillover index of VIX is plotted in panel B of Figure 2. Starting from May 22, 2013, when Fed chairman Bernanke unexpectedly talked about tapering QE, the VIX spillover effect diminished in the summer of 2013. In contrast, the spillover did not change significantly when tapering actually commenced on December 18, 2013. However, the decreasing trend of spillover became clearer by the end of October 2014, when QE was fully terminated. To see the association between spillover and QE tapering, we run the following daily regressions for the extended sample from November 2008 to January 2015:

$$AS_{t,H} = \beta_0 + \beta_1 QE_t + \beta_2 D_t^{QE} + \beta_3 D_t^{Quake} + \beta_4 D_t^{AAA} + \beta_5 D_t^{Bernake} + \beta_6 D_t^{taper} + \beta_7 D_t^{QE\_end} + Controls + \varepsilon_t, \quad (11)$$

Table 11. Further Analysis of VIX Spillovers with the Extended Samples

Panel A: sample period from January 2004 to April 2013

	1 day ahead	3 days ahead	12 days ahead
D_t^{QE}	18.31***	16.09***	17.28***
	(3.15)	(3.22)	(3.27)
$Holdings_t$	−2.47***	−3.08***	−3.10***
	(0.54)	(0.55)	(0.56)
$Holdings_t \times D_t^{QE}$	2.70***	3.28***	3.28***
	(0.51)	(0.53)	(0.53)
Controls	Yes	Yes	Yes
$\beta_{11}+\beta_{12}$	0.23	0.20	0.18
F-test for $\beta_{11}+\beta_{12}=0$	6.52** [0.01]	4.92** [0.03]	3.47* [0.06]
N	447	447	447
Adj. R^2	0.955	0.952	0.952

Panel B: sample period from November 2008 to January 2015

	1 day ahead		3 days ahead		12 days ahead	
QE_t	0.32***	0.56***	0.63***	0.86***	0.54***	0.82***
	(0.09)	(0.12)	(0.10)	(0.13)	(0.10)	(0.14)
D_t^{QE}	53.97***	53.42***	63.16***	62.19***	71.96***	71.52***
	(2.46)	(2.38)	(2.74)	(2.65)	(2.89)	(2.80)
D_t^{Quake}	−9.05***	−9.98***	−7.54***	−8.24***	−10.67***	−11.81***
	(1.08)	(1.08)	(1.20)	(1.20)	(1.27)	(1.27)
D_t^{AAA}	15.80***	16.75***	21.30***	22.51***	21.43***	22.39***
	(1.28)	(1.24)	(1.43)	(1.39)	(1.51)	(1.46)
$D_t^{Bernanke}$		−4.24***		−4.55***		−4.65***
		(1.18)		(1.32)		(1.39)
D_t^{taper}	−1.41*		−2.03**		−1.32	
	(0.84)		(0.93)		(0.98)	
$D_t^{QE\_end}$	−8.26***	−8.26***	−7.31***	−7.44***	−7.44***	−7.37***
	(1.03)	(1.01)	(1.15)	(1.12)	(1.21)	(1.19)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
N	1,508	1,508	1,508	1,508	1,508	1,508
Adj. R^2	0.822	0.823	0.905	0.905	0.883	0.884

Notes. This table reports the results of extended samples. In panel A, the following weekly regressions are run for the extended sample from January 2004 to April 2013: $AS_{t,H} = \beta_{01} + \beta_{02}D_t^{QE} + (\beta_{11} + \beta_{12}D_t^{QE}) \times Holdings_t + Controls + \varepsilon_t$, where $AS_{t,H}$ is the weekly (Friday) aggregate VIX spillover to other stock markets; and *Holdings* is the Fed's holdings of U.S. Treasury securities, agency securities, and mortgage-backed securities. In panel B, the daily regressions are run for the extended sample from November 2008 to January 2015: $AS_{t,H} = \beta_0 + \beta_1 QE_t + \beta_2 D_t^{QE} + \beta_3 D_t^{Quake} + \beta_4 D_t^{AAA} + \beta_5 D_t^{Bernake} + \beta_6 D_t^{taper} + \beta_7 D_t^{QE\_end} + Controls + \varepsilon_t$, where $AS_{t,H}$ is the daily aggregate VIX spillover to other stock and commodity markets; QE_t is the Fed's cumulative net purchase of U.S. Treasury securities, agency securities, and mortgage-backed securities; D_t^{QE} is the QE dummy defined as 1 since November 25, 2008, and 0 otherwise; D_t^{Quake} is the Japanese earthquake dummy taking 1 after March 11, 2011, and 0 otherwise; D_t^{AAA} is the U.S. credit downgrade dummy defined as 1 since August 5, 2011, and 0 otherwise; $D_t^{Bernake}$ is the dummy for Bernanke's talk, defined as 1 since May 22, 2013, and 0 otherwise; D_t^{taper} is the QE tapering dummy, defined as 1 since December 18, 2013, and 0 otherwise; $D_t^{QE\_end}$ is the QE end dummy, which is 1 since October 31, 2014, and 0 otherwise. Controls are defined earlier. The robust standard errors are in parentheses, whereas p-values are in square brackets. The number of observations is shown as N. Intercept and control variable results are not reported to save space.

*, **, *** denote significance at 10%, 5%, and 1%, respectively.

where $AS_{t,H}$ is the daily H-step-ahead aggregate volatility spillover to other stock and commodity markets defined earlier; and D_t^{QE}, D_t^{Quake}, and D_t^{AAA} are the QE dummy, the Japanese earthquake dummy, and the U.S. credit downgrade dummy defined earlier. In addition, we construct two QE tapering dummies. One is the dummy for Bernanke's talk about tapering, $D_t^{Bernake}$, defined as 1 since May 22, 2013, and 0 otherwise. The other is the dummy of QE tapering which really happened, D_t^{taper}, defined as 1 since December 18, 2013, and 0 otherwise. $D_t^{QE\_end}$ is the dummy for the end of U.S. quantitative easing, which takes the value 1 since October 31, 2014, and 0 otherwise.

Panel B of Table 11 shows the daily results of Equation (11). The estimated coefficients for QE dynamics, the QE dummy, the Japanese earthquake dummy,

Table 12. Daily Determinants of Other Volatility Spillovers

	MOVE spillovers to VIX						Oil spillovers to other markets			Gold spillovers to other markets		
Dependent variable	1 day ahead		3 days ahead		12 days ahead		1 day ahead	3 days ahead	12 days ahead	1 day ahead	3 days ahead	12 days ahead
QE_t	0.01		0.01*		0.02***		−0.02	0.00	−0.02	0.02	−0.03	−0.01
	(0.01)		(0.01)		(0.01)		(0.02)	(0.03)	(0.03)	(0.03)	(0.05)	(0.05)
$TREAST_t$		0.09***		0.07***		0.06***						
		(0.01)		(0.01)		(0.01)						
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adj. R^2	0.755	0.661	0.763	0.697	0.760	0.723	0.888	0.889	0.892	0.856	0.874	0.880

Notes. This table reports the results of determinants of other volatility spillovers. For MOVE spillovers to VIX, the daily regressions are as follows: $IS^{MOVE}_{t,H} = \beta_0 + \beta_1 QE_t + Controls + \varepsilon_t$ and $IS^{MOVE}_{t,H} = \beta_0 + \beta_1 TREAST_t + Controls + \varepsilon_t$, where $IS^{MOVE}_{t,H}$ is daily H-step-ahead individual spillover intensity from MOVE to VIX. Two measures of U.S. quantitative easing are considered: QE_t is the Fed's cumulative net purchase of U.S. Treasury securities, agency securities, and mortgage-backed securities; and $TREAST_t$ is the Fed's cumulative net purchase of U.S. Treasury bonds. Controls include the following variables: the U.S. short rate proxied by the one-month Treasury yield, the term spread defined as the difference between the 10-year and three-month Treasury yields, the default spread defined as the difference between BAA corporate bond and 10-year Treasury yields, the TED_t spread between the three-month LIBOR based on U.S. dollars and the three-month Treasury yield, and the change of the Aruoba et al. (2009) business condition index. However, exchange rate change and Citigroup's surprise indices are excluded because MOVE spillover to VIX occurs across U.S. domestic markets. For oil or gold spillovers to other markets, the daily regressions are as follows: $AS^{Oil}_{t,H} = \beta_0 + \beta_1 QE_t + Controls + \varepsilon_t$ and $AS^{Gold}_{t,H} = \beta_0 + \beta_1 QE_t + Controls + \varepsilon_t$, where $AS^{Oil}_{t,H}$ and $AS^{Gold}_{t,H}$ are daily H-step-ahead aggregate spillover intensity from oil and gold to other markets, respectively. Controls include all interest rate and currency factors as well as macroeconomic indicators. The robust standard errors are in parentheses. Intercept and control variable results are not reported to save space.

* and *** denote significance at 10% and 1%, respectively.

and the U.S. credit downgrade dummy are consistent with those in Table 10. More interestingly, the coefficients for the Bernanke dummy are all negative at the 1% significance level, suggesting that VIX spillovers to other markets did decrease significantly with respect to the Bernanke's talk. If we replace it with the dummy of QE tapering, the coefficients are still negative but less significant. Furthermore, the dummy for the end of U.S. quantitative easing is also significantly negative. This implies decreasing VIX spillovers in the post-QE era.

Finally, we explore the determinants of other volatility spillovers. From Figure 1 and Table 2, we can see significant spillover from MOVE to VIX. A natural question is whether MOVE spillover intensity to VIX increases with the size of U.S. quantitative easing in general and the Federal Reserve's purchase or holding of U.S. Treasury bonds in particular. As shown in Table 12, most coefficients on the QE proxy are significantly positive, suggesting that QE operations in the Treasury bond market induced volatility spillover to the U.S. stock market. Meanwhile, we should expect that U.S. quantitative easing has no impact on volatility spillover from another country or market to others. In this case, commodities are a useful test asset while other countries may also implement unconventional monetary policy. As shown in Table 12, all coefficients of U.S. quantitative easing are not significant in the regressions with aggregate oil or gold spillovers to other markets as the dependent variable in Equation (7).

5. Conclusions

This study uses implied volatility indices to sort out the network of volatility spillovers among the U.S. Treasury bond market and global markets for stocks and commodities. The key finding is that the U.S. stock market is at the center of the international volatility spillover network. We measure not only spillover intensity, but also the direction and time variation of spillovers. The volatility spillover from the U.S. stock market to international stock and commodity markets has intensified three times during our sample period that spans the Fed's unconventional monetary policy. Furthermore, the size of U.S. quantitative easing alone explains 40% to 55% of variations in spillover. Although interest rate and currency factors as well as other control variables do have some power, they do not subsume our finding that U.S. quantitative easing is the primary driver of intensifying volatility spillover from the U.S. to the rest of world.

Our findings highlight the central role of U.S. unconventional monetary policy in the international financial system and offer valuable insights in an era of cheap money and excess liquidity that is apparently far from over. The possible benefits of quantitative easing must be considered alongside its potential costs. Although quantitative easing is believed to be effective in easing pressure on financial institutions and markets, it can be a source of global systemic risk. From volatility spillover pattern and network direction we document, we also offer important implications similar to the "contagion strategy" outlined by Kaminsky et al. (2004).[40] For example, the spillover patterns can suggest an investor to buy (sell) stock index futures in one market, such as FTSE100 index futures, when another market's volatility like the VIX falls (rises) and is expected to spill over to other markets. Furthermore, the investor can predict the change of the VIX by closely watching economic and financial indicators, such as dynamics of quantitative easing, and then adjusting his trading strategy based on volatility spillover patterns accordingly.

In the future, we can extend the research to investigate more thoroughly the underlying channels of spillover effects such as cross-border capital flow and risk taking (Bruno and Shin 2015) as well as foreign ownership linkages (Bartram et al. 2015). Also, the U.S. quantitative easing program has been terminated, but other central banks are still easing, and the European Central Bank announced plans to expand its use of unconventional monetary policy. As time passes and more data accumulate, we will be able to measure and discuss the effects and implications of policy divergence and coordination.

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Endnotes

[1] The FTSE (Financial Times Stock Exchange) index rose from 3,780.96 to 4,152.96, whereas its implied volatility index dropped from 70.17 to 61.21. The CAC (Cotation Assistée en Continu) 40 index jumped from 2,881.26 to 3,172.11, whereas its implied volatility index dropped from 69.33 to 55.23.

[2] See, for example, Bauer and Neely (2014), Bruno and Shin (2015), Chen et al. (2016), Chinn (2013), Fratzscher et al. (2013), Glick and Leduc (2011, 2013), Neely (2013), and others. The studies typically examine international spillover in price rather than spillover in volatility.

[3] The research on systemic risk typically explores its measurement and management rather than its sources. See Bisias et al. (2012) for a survey.

[4] A network describes a collection of nodes and the links between them. In financial systems, the nodes of the network represent financial institutions and markets, and the links represent direct or indirect relationships between two financial institutions/markets.

[5] 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.

[6] This argument has been widely cited among practitioners. As a widely followed measure of bond yield volatility, MOVE is watched by the International Monetary Fund and studied by academia (for example, Zhou 2014) along with the VIX.

[7] We focus primarily on developed equity markets because of the availability of implied volatility data. Implied volatility indices for some emerging markets are constructed only recently. Also, we include the U.S. Treasury bond market because it is closely related to quantitative easing operations. In contrast, European debt markets are not included because their implied volatility indices are not readily available, and the European debt crisis is not our focus.

[8] For a robustness check, we extend the sample back to include the period prior to June 2008 without commodity VIXs. The purpose was to examine the causes and dynamics of volatility spillover effects, which existed well before quantitative easing, in a systematic way. In §4.5, we also extend the sample to January 2015 to examine the spillover pattern when QE is tapered and terminated.

[9] Similarly, Yang and Zhou (2013) use two-day changes of credit default swaps spreads to study credit risk spillover. Although two-day averaging obscures some lead/lag effects, most lead/lag relations are still captured by lags in VAR analysis. Compared with using weekly differences of volatility indices to address the nonsynchronous trading issue, the benefit of two-day averaging is to keep as many observations as possible for VAR analysis and particularly recursive variance decompositions.

[10] Series IDs for Treasury, agency, and mortgage-backed securities held by the Federal Reserve are TREAST, FEDDT, and MBST respectively.

[11] We also use the difference of Fed's security holdings to proxy for quantitative easing in the robustness check.

[12] The dollar index measures value of U.S. dollar against the currencies of a broad group of major U.S. trading partners. Higher values of the index indicate a stronger U.S. dollar.

[13] The dollar price of a commodity is analogous to the exchange rate against the U.S. dollar. There is convenience yield from holding the stock of a commodity, such as the insurance value of having an assured supply of oil in the event of a disruption and the stable purchasing power and the psychic pleasure of holding gold. The cost of carry includes storage costs among others.

[14] The dollar value of amounts that the foreign central banks have drawn but not yet repaid is reported as "central bank liquidity swap," which measures the size of dollar liquidity provision in foreign markets via intercentral bank swaps.

[15] A cause precedes its associated effect, and an effect does not precede its cause. If the lagged information of one variable X can predict current and future information of another variable Y, we say that X Granger causes Y.

[16] Alternatively, we use the generalized variance decompositions for robustness check. The results are generally similar. But the cost is that we are not able to identify the spillover networks. Moreover, we have to assume that shocks follow normal distributions.

[17] See D'Amico and King (2013) for the difference between stock and flow effects of QE. Also, the long memory tests of Robinson (1995) suggest that the impact of a shock in early volatility is very persistent, and thus recursive estimation is better in modeling volatility dynamics.

[18] From a statistical perspective, there is a tradeoff between bias and variance when choosing to implement recursive or rolling schemes (Clark and McCracken 2009). Combining both schemes has often been found to offer an attractive alternative to the approach of seeking to identify a single best model (Elliott and Timmermann 2008). We will try both rolling and combined spillover estimates for robustness check.

[19] Forbes (2012) discusses these four main channels of a crisis or contagion ("bad" spillover). But these channels are also applied to "good" spillovers, which mitigate contagion.

[20] The result looks similar at the 5% or lower significant level.

[21] The size or economic significance of the associations is not indicated in the DAG, but measured in the subsequent DAG-based VAR analysis and variance decomposition.

[22] The order of variables is as follows: VIX, German VIX, UK VIX, Swiss VIX, French VIX, Korean VIX, Japanese VIX, HK VIX, Gold VIX, Oil VIX, and MOVE. The diagonal element is 1, and the *ij*th nondiagonal element is a parameter $b_{i,j}$ if shocks variable j contemporaneously affects variable i and 0 otherwise. For example, according to Figure 1, VIX (1st variable in the matrix) affects German VIX (the 2nd variable), UK VIX (the 3rd variable), Gold VIX (the 9th variable), and Oil VIX (the 10th variable) in contemporaneous time. Thus, we have four parameters $b_{2,1}$, $b_{3,1}$, $b_{9,1}$, and $b_{10,1}$ in the first column vector for VIX shock.

[23] The United States is not always at the core. During the precrisis period from 2005 to 2007, the German stock market was the main source of spillover, probably because Germany experienced an unexpected strong expansion (Dustmann et al. 2014). See the DAG result in Figure 1A and the variance decomposition in Table 1A of the online appendix.

[24] In contrast, the German VIX spillover intensity is the highest of 204.01% during the period from 2005 to 2007, more than twice of the VIX counterpart, as shown in panel B of Table 2A of the online appendix.

[25] In contrast, the German stock market is at the center of global volatility spillover network during the period from 2005 to 2007, as shown in Table 3A of the online appendix. We also replace French VIX and German VIX with the EU VIX (Eurex STOXX50 volatility index) and examine network centrality for two sample periods. As shown in Table 4A of the online appendix, the network centrality of VIX from 2008 to 2013 is the highest, consistent with the result in Table 3. As shown in Table 4B of the online appendix, the centrality measures of VIX decrease significantly, whereas the centrality measures of EU VIX increase significantly from 2011 to 2012. Although the United States is still the center of the network, the relative centrality of the aggregate EU stock market moved up during the European sovereign crisis.

[26] For recursive estimation, the initial sample period is from June 6, 2008, to November 3, 2008, and the final sample period is from June 6, 2008, to April 30, 2013. Thanks to referees' comments, we also extend the sample period of VAR back to January 2008, without two commodities. In the longer sample, the initial sample period for recursive estimation is from January 2, 2008, to June 2, 2008, and the final sample period is from January 2, 2008, to April 30, 2013.

[27] In Figure 2A of the online appendix with the longer sample, VIX spillover is much weaker before QE, and a sharp jump still occurs when QE1 is launched, suggesting that the jump is not due to parameter instability in the beginning of recursive estimation.

[28] This is consistent with results from Fratzscher et al. (2013), that QE1 measures have been highly effective in lowering yield worldwide, whereas QE2 measures appear to have been largely ineffective in this regard.

[29] As shown in Table 2, variance decompositions stabilize from 12 days ahead and beyond. Therefore, the statistics of longer-term forecasts are more robust.

[30] The correlations based on other horizon volatility spillover indices are in line with the results reported in Table 4.

[31] Central bank liquidity swaps are excluded because the daily data are not available. However, this variable is included in weekly regressions and discussed in the robustness check.

[32] The high R^2 value for the oil market is suspicious, perhaps because the spillover index from the U.S. stock market into the oil market is not stationary. However, the preliminary test does not support this possibility.

[33] To test this, we define a dummy variable, which is 1 after March 11, 2011, and 0 otherwise, and add it into the regression for Japan. As a result, the QE coefficient becomes significantly positive, supporting our hypothesis.

[34] When the dummy for Japan's earthquake and tsunami is added, both coefficients of U.S. quantitative easing and liquidity swaps become significantly positive, and the coefficient for short rate becomes significantly negative.

[35] For simplicity, we assume that inflation rate is the same within a month for daily and weekly samples. We also construct monthly samples and find similar results.

[36] The only exception is the Swiss franc. We also include an interaction term between exchange rate change and QE2 dummy defined as 1 between November 3, 2010, and June 30, 2011. The coefficients for exchange rate changes are still significantly Negative, whereas the interaction terms are positive but not significant.

[37] The concern is that both levels of spillover indices and the QE proxies for quantitative easing are likely to be persistent and potentially trending. However, we showed in Table 3 that volatility spillover indices are stationary. Therefore, we still use them as dependent variables.

[38] Although we only report the estimates for three-day forecasts, the results for other horizons are similar.

[39] This is consistent with the result in Table 7 because we add the dummy of Japan's earthquake.

[40] Kaminsky et al. (2004) coin the term "contagion strategy" to mean systematic selling (buying) of stocks in one country when the stock market falls (rises) in another.

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