Risk premium spillovers among stock markets: Evidence from higher-order moments [†]

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Abstract

This paper investigates the volatility, skewness and kurtosis risk premium spillovers among U.S., U.K., German and Japanese stock markets. We define risk premia as the difference between risk-neutral and realized moments. Our findings highlight that during periods of stress and after 2014, cross-market and cross-moment spillovers increase, and this is mirrored by a decrease in within spillovers. We document strong bi-directional spillovers between skewness and kurtosis risk premia and emphasize the prominent role played by the volatility risk premium. Finally, we show that several macroeconomic and financial factors increase with the intensity of risk premium spillovers.

JEL Codes: C58; G01; G15.

Keywords: Spillovers; Volatility; Skewness; Kurtosis; Risk-Neutral; Risk Premium.

1 Introduction

The collapse of Lehman Brothers in September 2008 demonstrates the importance of understanding risk transmission among stock markets. Although risk occurs in one country, it can spread to other countries, leading to potentially large financial losses. Recently, the literature has devoted considerable attention to the premium that investors require for bearing various risks, such as variance, skewness and kurtosis risk (Bollerslev, Tauchen and Zhou, 2009; Bekaert and Hoerova, 2014; Sasaki, 2016). As such, it is essential to be aware of the interactions among these risk premia.

A widely accepted definition of the variance risk premium in the literature is the difference between implied and realized variance (or volatility), which is equivalent to a positive premium (Bakshi and Madan, 2006; Bollerslev, Tauchen and Zhou, 2009; Bekaert, Hoerova and Lo Duca, 2013; Bekaert and Hoerova, 2014). This definition suggests that investors are willing to pay to hedge against upward movements in variance or, equivalently, are demanding a reward for bearing this risk given their aversion to such variance (Bakshi and Madan, 2006; Carr and Wu, 2009; Bollerslev, Tauchen and Zhou, 2009; Londono, 2015). As such, the variance risk premium may also be interpreted as a measure of risk aversion and economic uncertainty (Bollerslev, Gibson, and Zhou, 2011; Bekaert, Hoerova and Lo Duca, 2013). Moreover, studies have shown that investors' willingness to insure against variance risk is especially likely to increase after a negative shock or a market crash (Drechsler and Yaron, 2011; Ait-Sahalia, Karaman and Mancini, 2015). Thus, as higher uncertainty is associated with a higher risk perception, this might lead to a time-varying risk premium (Drechsler and Yaron, 2011). Findings also reveal that the variance risk premium has strong predictive power for stock returns (Bollerslev, Tauchen and Zhou 2009; Drechsler and Yaron, 2011; Londono, 2015).

In addition to their preferences for the mean and variance of portfolio returns, investors might have preferences for the higher-order moments (skewness and kurtosis) and, thus, may seek compensation for these moments. This is due to the important role played by the higher moments in investment decisions and risk management. While skewness might be seen as a measure of the risk associated with large jumps, kurtosis reflects investors' fears regarding tail events (Greenwood-Nimmo, Nguyen and Rafferty, 2016). Indeed, several studies show that investors prefer stocks with high positive realized skewness and low realized kurtosis (Brunnermeier, Gollier, and Parker, 2007; Barberis and

Huang, 2008; Guidolin and Timmermann, 2008). Moreover, Conrad, Dittmar and Ghysel (2013) highlight the predictive ability of implied higher-order moments for stock returns. Therefore, higher-moment-averse investors might require a reward for bearing the potential risk spillover that might reflect either the likelihood of a decline in the stock market (negative skewness) or the likelihood of tail risk (excess kurtosis).

The recent literature shows that higher-order moment risk premia have strong predictive power. For instance, Sasaki (2016) finds that the skewness risk premium (SRP) has superior predictive power for future stock returns. This is generally the case when risk aversion is high (Lehnert, Lin and Wolff, 2014). Broll (2016) shows that the SRP is a significant predictor of the majority of exchange rate markets. Higher-order moments also account for a large fraction of the variance risk premium (Todorov, 2010; Bollerslev and Todorov, 2011). In particular, Rauch and Alexander (2016) document that the variance risk premium is negatively correlated with the third-moment and skewness risk premium and positively correlated with the fourth-moment and kurtosis risk premium at different frequencies.

Given investors' possible aversion to volatility and higher moments, the difference between risk-neutral and physical moments could be a relevant determinant of their associated risk-return trade-offs. This is because the volatility, skewness and kurtosis risk premia may reflect whether investors are willing to pay a premium to be insured against future changes in volatility risk, downside risk and tail risk. Moreover, while previous studies emphasize their forecasting ability for domestic markets, especially the U.S., Bollerslev, Tauchen and Zhou (2009) and Londono (2015) find that the U.S. variance risk premium has significant predictive power for international stock returns such as those in Germany, the U.K. and Japan. This evidence on cross-country return predictability encourages us to better explore the relationships among volatility, skewness and kurtosis risk premia and raises several important questions. For instance, is the volatility risk premium (VRP) more affected by its own higher-order moments or cross-moment risk premia such as those of skewness and kurtosis? Do cross-market risk and cross-moment premium spillovers vary over time? Which of the risk premia is the most influential? To the best of our knowledge, no existing study addresses these issues using the risk premium moments. We are only aware of limited exceptions to this, such as Cipollini, Lo Cascio and Muzzioli (2013), who examine the variance risk premium spillovers among stock markets[1] and a few other studies that focus on either currencies' implied (Greenwood-Nimmo, Nguyen and Rafferty, 2016) or currency and stock markets' realized (Hong, Liu and Wang, 2009; Do, Brooks, Treepongkaruna and Wu, 2016) skewness and kurtosis spillovers. Hence, our paper is the first to explore the cross-market and cross-moment spillover effects among the three risk premia that are directly attributable to the fear of volatility risk, downside risk (SRP) and tail risk (kurtosis risk premium (KRP)).

In this study, we investigate the time-varying risk premium spillovers among the stock markets of four important advanced economies (the U.S., the U.K., Germany and Japan) from 2008 to 2016 using option and high-frequency data. The attractive property of the risk-neutral moments is their forward-looking nature (Chang, Christoffersen and Jacobs, 2013); the realized moments are appealing because of their reliability in finite samples and robustness to the presence of market microstructure noise and discontinuities (Amaya, Christoffersen, Jacobs and Vasquez, 2015).[2] Specifically, applying the approach of Diebold and Yilmaz (2012, 2014) and Greenwood-Nimmo, Nguyen and Shin (2015), we first examine the spillovers among the VRP, SRP and KRP from a cross-market and cross-moment perspective.[3] That is, we assess the spillovers among aggregate stock markets over risk premium moments (within-market and cross-market spillovers) and aggregate risk premia over stock markets (within-moment and cross-moment spillovers). Second, we further examine the relationships between several macroeconomic and financial factors (i.e., credit spread, Treasury bill eurodollar spread, Aruoba, Diebold and Scotti (2009) business conditions index and the economic policy uncertainly index of Baker, Bloom and Davis (2016)) and the aggregate cross-market and cross-moment spillovers during their high and low regimes. Our choice of this econometric setup is motivated by the interest in (i) quantifying the magnitude of cross-market and cross-moment spillovers, (ii) computing directional spillovers to identify the receivers and transmitters of shocks, and (iii) accounting for each of the three risk premia, namely

[1]The authors use a wavelet analysis based on the orthogonalization of stock market shocks in France, Germany, the U.K., Switzerland and the U.S.

[2]To compute the model-free risk-neutral volatility, skewness and kurtosis, we use a collection of out-the-money European call and put options (Bakshi and Madan, 2000; Carr and Madan, 2001; Bakshi, Kapadia, and Madan, 2003). The realized volatility, skewness and kurtosis are estimated from the 5-minute intraday squared, cubic and quartic returns (Andersen, Bollerslev, Diebold and Labys, 2003; Amaya, Christoffersen, Jacobs and Vasquez, 2015).

[3]This approach has been employed by several recent studies (Cipollini, Lo Cascio and Muzzioli, 2013; Greenwood-Nimmo, Nguyen and Rafferty, 2015, 2016; Do, Brooks, Treepongkaruna, and Wu, 2016; Baruník, Kočenda and Vácha, 2016; Zhang, 2017).

the volatility, skewness and kurtosis, as investors desire to hedge against the inter-temporal shifts in their degree of concern.

Our findings highlight the importance of considering risk premium interactions across markets and moments. First, we shed light on time-varying risk premium spillovers. We observe that during periods of stress and after 2014, there is an increase in cross-market and cross-moment spillovers, i.e., from the VRP to both skewness and kurtosis risk premia, and a reduction in the magnitude of within-spillovers. Second, we document strong bi-directional spillovers between skewness and kurtosis risk premia. In addition, we show that cross-moment effects, namely, skewness and kurtosis risk premia, have stronger impacts on the VRP than their within-higher-order effects. Third, we find that macroeconomic and financial factors are high when the risk premium spillover among markets is also high. Further, to confirm the robustness of our results, we also consider the aggregate cross-market and cross-moment implied spillovers. We show that, over time, the patterns of these implied spillovers are similar with those of risk premium spillovers, except their magnitude is higher. Overall, our results reflect (i) an increasing importance given to cross-market and cross-moment spillovers, especially during stress periods and after 2014, (ii) the prominent role of the VRP and (iii) increases in macroeconomic and financial factors with increases in the intensity of the risk premium spillover among markets.

Taken together, our empirical analyses suggest that international investors require compensation for bearing not only their own market risks (volatility, skewness and kurtosis) but also cross-market risks. Moreover, our findings also indicate that cross-market and cross-moment risk premia could have valuable predictive power for a stock market's own risk premium moments. We further extend the studies of Bollerslev, Tauchen and Zhou (2009) and Londono (2015) by demonstrating the relevance of higher-order moments, in addition to that of the variance risk premium. As such, our results raise a question regarding the predictive power of cross-moment and cross-market risk premia, especially the higher-order moments, for stock market returns. As these issues are beyond the aims of this study, we leave their investigation for future research.

The remainder of this paper is organized as follows. Section 2 outlines the methodology. Section 3 describes the data. Section 4 presents the empirical findings. Section 5 discusses the relationships between macroeconomic and financial factors and our spillovers, and Section 5 concludes.

2 Methodology

To investigate the spillovers among the volatility, skewness and kurtosis risk premia in stock markets, we apply the connectedness approach of Diebold and Yilmaz (2012, 2014). This approach relies on variance decompositions of a vector autoregressive (VAR) model, namely, it allows us to explore the H-step-ahead forecast error variance in market i's risk premium that is due to innovations (shocks) in other markets' risk premia. Moreover, it also allows us to measure the directional spillover received by market i's risk premium from the risk premia of all other markets j. To account for the block analysis, namely, the spillovers among groups of risk premium stock markets and risk premium moments, we apply Greenwood-Nimmo, Nguyen and Shin (2015)'s generalization of the standard framework of Diebold and Yilmaz (2012, 2014). The details of this approach are provided in the Appendix.

In line with Menkhoff, Sarno, Schmeling and Schrimpf (2012) and Greenwood-Nimmo, Nguyen and Rafferty (2016), we recover the innovations in each of the risk premia from a first-order autoregressive AR (1) model. Specifically, we consider the innovations in the VRP ($\boldsymbol{v}_{it}$), SRP ($\boldsymbol{s}_{it}$) and KRP ($\boldsymbol{k}_{it}$) for $i = 1, 2, ..., N$ stock markets at a daily frequency over $t = 1, 2, ..., T$ trading days. The 3×1 vector $\boldsymbol{x}_{it} = (\boldsymbol{v}_{it}; \boldsymbol{s}_{it}; \boldsymbol{k}_{it})^{'}$ captures the market-specific risk premium for the i-th stock market, and the $3N \times 1$ vector $\boldsymbol{x_t} = (\boldsymbol{x}^{'}_{1t}, \boldsymbol{x}^{'}_{2t}, ..., \boldsymbol{x}^{'}_{Nt})^{'}$ contains the risk premia for each stock market. The total number of variables in the system is $d = 3N$.

Diebold and Yilmaz (2012, 2014) suggest a p-th order reduced-form VAR for the $d \times 1$ vector of variables $\mathbf{x_t}$:

$$\mathbf{x_t} = \Sigma_{j=1}^{p} \mathbf{\Phi_j} \mathbf{x_{t-j}} + \mathbf{e_t} \tag{1}$$

where the $\mathbf{\Phi_j}$ for $j = 1, 2, ..., p$ are $d \times d$ coefficient matrices, and $\mathbf{e_t} \hookrightarrow N(\mathbf{0}, \mathbf{\Sigma_e})$ are the reduced-form residuals with covariance matrix $\mathbf{\Sigma_e}$. The H-step-ahead generalized forecast error variance decomposition for the risk premium of the i-th stock market is given by the following (Pesaran and

Shin, 1998):

$$\vartheta_{i\leftarrow j}^{(H)} = \frac{\sigma_{e,jj}^{-1}\sum_{h=0}^{H-1}\left(\boldsymbol{\epsilon}_{\mathbf{i}}^{'}\mathbf{A_h}\boldsymbol{\Sigma}_{\mathbf{e}}\boldsymbol{\epsilon}_{\mathbf{j}}\right)^2}{\sum_{h=0}^{H-1}\boldsymbol{\epsilon}_{\mathbf{i}}^{'}\mathbf{A_h}\boldsymbol{\Sigma}_{\mathbf{e}}\mathbf{A}_{\mathbf{h}}^{'}\boldsymbol{\epsilon}_{\mathbf{i}}} \tag{2}$$

for $i, j = 1, ..., d$, where the standard deviation $\sigma_{e,jj}$ is the j-th diagonal element of $\boldsymbol{\Sigma}_{\mathbf{e}}$, $\boldsymbol{\epsilon}_{\mathbf{i}}$ is a $d \times 1$ vector with its i-th element set to one and zeros otherwise, and $\mathbf{A_h}$ is defined recursively as $\mathbf{A_h} = \boldsymbol{\Phi}_{\mathbf{1}}\mathbf{A_{h-1}} + \boldsymbol{\Phi}_{\mathbf{2}}\mathbf{A_{h-2}} + ... + \boldsymbol{\Phi}_{\mathbf{p}}\mathbf{A_{h-p}}$ for $h = 1, 2, ...$ with $\mathbf{A_0}$ being a $d \times d$ identity matrix, and $\mathbf{A_h} = 0$ for $h < 0$. $\vartheta_{i\leftarrow j}^{(H)}$ captures the share of the H-step-ahead forecast error variance of stock market i that is due to stock market j's shocks. Generalized forecast error variance decomposition has the benefit of being order invariant, i.e., the variance decompositions are invariant to ordering. Due to the non-zero correlation among shocks, the $\sum_{j=1}^{d}\vartheta_{i\leftarrow j}^{(H)} > 1$. Following Diebold and Yilmaz (2012, 2014), the percentage interpretation of the forecast error variance shares can be achieved by normalizing each entry of the variance decomposition matrix by the row sum as follows: $\psi_{i\leftarrow j}^{(H)} = 100 \times \left(\vartheta_{i\leftarrow j}^{(H)}/\sum_{j=1}^{d}\vartheta_{i\leftarrow j}^{(H)}\right)\%$. $\psi_{i\leftarrow j}^{(H)}$ is a measure of pairwise spillover from variable j to variable i at horizon H, and $\psi_{i\leftarrow j}^{(H)} \neq \psi_{j\leftarrow i}^{(H)}$.

Diebold and Yilmaz (2012, 2014) further construct the H-step-ahead $d \times d$ connectedness matrix among the d variables in $\mathbf{x_t}$ as

$$\mathbf{C}^{(H)} = \begin{bmatrix} \psi_{1\leftarrow 1}^{(H)} & \psi_{1\leftarrow 2}^{(H)} & ... & \psi_{1\leftarrow d}^{(H)} \\ \psi_{2\leftarrow 1}^{(H)} & \psi_{2\leftarrow 2}^{(H)} & ... & \psi_{2\leftarrow d}^{(H)} \\ \vdots & \vdots & \ddots & \vdots \\ \psi_{d\leftarrow 1}^{(H)} & \psi_{d\leftarrow 2}^{(H)} & ... & \psi_{d\leftarrow d}^{(H)} \end{bmatrix} \tag{3}$$

Using the connectedness matrix, we can define the following spillovers:

$$O_{i\leftarrow i}^{(H)} = \psi_{i\leftarrow i}^{(H)};\ S_{i\leftarrow \bullet}^{(H)} = \sum_{j=1, j\neq i}^{d}\psi_{i\leftarrow j}^{(H)};\ S_{\bullet\leftarrow i}^{(H)} = \sum_{j=1, j\neq i}^{d}\psi_{j\leftarrow i}^{(H)}. \tag{4}$$

where the own variance share $O_{i\leftarrow i}^{(H)}$ indicates the share of the H-step-ahead of the i-th stock market risk premium that is due to own shocks, $S_{i\leftarrow \bullet}^{(H)}$ shows the total spillover from the risk premium of all stock markets to the risk premium of the i-th stock market (the from spillover), and $S_{\bullet\leftarrow i}^{(H)}$ captures the total spillover from the risk premium of the i-th stock market to the risk premium of all stock markets (the to spillover). By construction, the $O_{i\leftarrow i}^{(H)} + S_{i\leftarrow \bullet}^{(H)} = 100\%$ and $S_{\bullet\leftarrow i}^{(H)}$ might exceed 100%. Finally, we define the aggregate spillovers as follows:

$$S^{(H)} = \frac{1}{d}\sum_{i=1}^{d} S_{i\leftarrow \bullet}^{(H)}; O^{(H)} = 100 - S^{(H)} \tag{5}$$

where $S^{(H)}$ and $O^{(H)}$ denote the aggregate spillover index from other markets and the own aggregate spillover index, respectively.

3 Data

We explore the connectedness among innovations in the VRP, SRP and KRP for stock markets in the U.S., the U.K., Germany and Japan. The data are obtained from Thomson Reuters Tick History and cover the period from January 2008 to December 2016. Using high-frequency data, we compute the realized volatility, skewness and kurtosis as in Amaya, Christoffersen, Jacobs and Vasquez (2015), where their computation relies on sums of 5-minute returns. The risk-neutral moments, namely, implied volatility, skewness and kurtosis, are estimated following the model-free methodology of Bakshi, Kapadia and Madan (2003). Further details on their computation are provided in the Appendix. We then follow Bollerslev, Tauchen and Zhou (2009) to compute the risk premium moments as the difference between implied and realized moments. Finally, while throughout the analysis, we use the volatility, skewness and kurtosis risk premium innovations, namely, $\boldsymbol{v}_{it}$, $\boldsymbol{s}_{it}$ and $\boldsymbol{k}_{it}$, to facilitate the interpretation of the results, we refer to the VRP, SRP and KRP as the innovations.

Table 1 reports the descriptive statistics, i.e., the mean and standard deviation, of the realized moments (Panel A), implied moments (Panel B), risk premium moments (Panel C) and risk premium innovations (Panel D). Panels A and B show that implied volatility is higher than its realized counterpart for all countries. We observe that the implied skewness is negative, with its highest mean being observed in the U.S. stock market. The realized skewness is also negative in all countries. These findings indicate that the risk-neutral distribution of stock returns is more left skewed than the realized distribution of stock returns. We further note that the implied kurtosis is lower than the realized kurtosis except in the U.S., where the risk-neutral left tail displays more excess kurtosis than the physical tail. This might suggest that in aftermath of the Global Financial Crisis, market participants accord greater weight to tail risk.

The statistics in Panel C show that the risk-neutral moments are generally larger (in absolute value) than the realized moments. Specifically, this is the case for volatility (Bollerslev, Tauchen and Zhou, 2009), skewness (Christoffersen, Fournier, Jacobs and Karaoui, 2016) and kurtosis for the U.S. overall (Christoffersen, Jacobs and Heston, 2013). The fact that implied moments are higher than realized moments indicates that, on average, investors' fears of negative future outcomes are not reflected in the realized moments. Note that the VRP is positive in all countries, ranging from 0.007 in Germany to 0.0049 in Japan. As such, risk-averse investors from the U.S., the U.K., Germany and Japan might be willing to pay a premium to hedge against upward movements in stock market volatilities.

The skewness risk premia are negative, and the highest mean value is observed in the U.S. stock market. These statistics indicate that stock market investors might consider paying a premium for insurance against future market downside risks, including jump risks. The KRP is negative except in the U.S. stock market. These statistics reflect U.S. investors' willingness to pay a large premium to be insured against future tail risks. Regarding the standard deviation, Panels A, B, C and D show that its magnitude is similar across all stock markets, namely, for each of the volatility, skewness and kurtosis moments and risk premia.

INSERT TABLE 1 HERE

4 Empirical results

In this section, we begin by studying the connectedness across the full sample. We then explore the relationships among the aggregate stock markets across moments (within-market and cross-market risk premium spillovers) and among the aggregate risk premium moments across stock markets (total within-moment and cross-moment risk premium spillovers). Finally, using rolling window estimation, we emphasize the importance of time variation in these interactions.

4.1 *Connectedness among risk premia*

The starting point of our analysis is the estimation of a VAR model across the full sample period using a forecast horizon of ten trading days (Greenwood-Nimmo, Nguyen and Rafferty, 2016). Using the Akaike Information Criterion, we find a lag length of one day to be optimal. Table 2 shows the (12×12) connectedness matrix among the volatility, skewness and kurtosis risk premia of stock markets in the U.S., the U.K., Germany and Japan. While the main diagonal captures the spillovers due to own-market effects, the off-diagonal entries capture the directional spillovers due to the risk premium effects from other markets. Specifically, Table 2 presents the 10-day-ahead percentage contribution of shocks to each risk premium to explaining the share of the total variance of the risk premium in stock markets.

A large share of the VRP in stock markets is due to own-moment effects, ranging from approximately 62% in Germany to 85% in the U.K. Moreover, the cross-VRP effects on different stock markets have high impacts on volatility premia, accounting for more than 10% of their own variance, e.g., 21% in the U.S., 11% in the U.K., 34% in Germany and 17% in Japan. We further document that typically the contribution of own and cross-SRP to the VRP is greater than that of the KRP. Moreover, we highlight the important role of the VRP: its contribution to own SRP and KRP is greater than vice versa.

Regarding interactions between skewness and kurtosis premia, we identify stronger own effects than in the case of the VRP, with the exception being the Japanese KRP. Specifically, we find that while their own effects explain between approximately 75% and 94% of their variance, the cross-SRP and cross-KRP spillovers account for less than approximately 3.5% and 14%, respectively. In addition to these effects, close to 1%, 3%, 10%, and 11% of the U.K., Japanese, German and U.S. variances are explained by own risk premium effects. These findings indicate the existence of strong bi-directional spillovers between own-moment risk premia, i.e., skewness and kurtosis, especially in the U.S. and Germany.

INSERT TABLE 2 HERE

Our analyses thus far reveal strong spillovers among volatility, skewness and kurtosis risk premia within each of the stock markets. We highlight the importance of cross-moment effects, especially

VRP spillovers. Additionally, we emphasize the relevance of taking into consideration the SRP since it has a larger impact on the volatility premium than the KRP. Moreover, we document high bi-directional risk premium spillovers between skewness and kurtosis in the U.S. and German stock markets.

4.2 *Connectedness among aggregate stock markets and aggregate risk premium moments*

In this section, following Greenwood-Nimmo, Nguyen and Rafferty (2016), we investigate the relationships among block aggregations of the connectedness matrix presented in Table 2. Specifically, we explore the percentage share of shocks to each of the aggregate stock markets across risk premium moments (within-market and cross-market risk premia) and aggregate risk premia across stock markets (total within-moment and cross-moment risk premia) in explaining the share of the total variance of stock markets and risk premia, respectively. Table 3 and Table 4 report the connectedness among stock markets and risk premium moments, respectively.

Table 3 presents the (4×4) connectedness matrix that captures, along the prime diagonal, the total risk premium spillovers for each stock market that are due to own-market effects, namely, the within-market spillovers, and the off-diagonal elements contain the total directional risk premium spillovers between stock market pairs, namely, the cross-market effects. Note that while the own-market risk premium effects have a dominant role, accounting for 85% of the German and Japanese variances and 89% of the U.S. and U.K. variances, the magnitude of cross-market risk premium spillovers from other stock markets varies from approximately 11% to 16%. Notice that the spillover effects from the Japanese stock market to the other stock markets have coefficients below 1%. These findings indicate that European markets and the U.S. stock market are less affected by the Japanese stock market. In contrast, the U.K. risk premium appears to have the highest influence on the other risk premia.

INSERT TABLE 3 HERE

Table 4 presents the (3×3) connectedness matrix among aggregate risk premium moments. Specifically, it examines the interactions among groups of risk premia, namely, the VRP, SRP and KRP, across all four stock markets. The main diagonal and off-diagonal entries consist of the total within-moment spillovers and total cross-moment spillovers, respectively. Our findings show that the within-VRP spillover is higher than the within-SRP and within-KRP spillovers, being approximately 96% versus 90%. In line with the full sample connectedness results reported in Table 2, approximately 7% and 9% of the SRP and KRP variances are explained by the other's risk premium effects. In addition, we document the existence of higher bi-directional spillovers between VRP and SRP than between VRP and KRP. Moreover, while VRP explains approximately 5.53% (1.82% + 3.71%) of the higher-order moment variances (SRP and KRP), higher-order moments only explain approximately 4.42% of VRP.

INSERT TABLE 4 HERE

In sum, we emphasize the important influence of cross-market and cross-moment effects, in addition to that of total within-market and total within-moment spillovers. Additionally, we again confirm strong bi-directional skewness and kurtosis risk premium spillovers and highlight the influential role of VRP.

4.3 *Connectedness over time*

As the relationships among risk premia might vary over time, this section focuses on capturing this time variation by applying a rolling window estimation. Specifically, we conduct our investigation based on a rolling window of 250 trading days with a forecast horizon of 10 trading days.[4]

Figure 1 shows the time-varying connectedness among aggregate stock markets across all three risk premium moments, namely, volatility, skewness and kurtosis (i.e., within-market, cross-market and other-market risk premium spillovers). This aggregation enables us to assess how the risk premium relationships among stock markets vary over time and, especially, during stress periods. Specifically, Figure 1 consists of four panels for each i-th stock market, and each panel consists of three plots showing the within-market effect, the total inward (outward) spillover from all stock markets (stock market i) to stock market i (all stock markets), namely, the from (to) spillover, and

[4] The choices of the rolling window and forecast horizon are in line with Greenwood-Nimmo, Nguyen and Rafferty (2016). Their study shows that neither the choice of rolling window (200, 250 or 300 trading days) nor the choice of the forecast horizon (5, 10 or 15 trading days) has a substantial impact on the spillovers among returns or the implied volatility and skewness of the currencies.

the individual spillover from each of the stock markets to stock market i. Essentially, the latter plot allows us to identify which stock market contributes the most to the total inward spillover for each of the stock markets.

We observe that the risk premium spillovers within each stock market are high, with their values varying between approximately 60% and 90%. This indicates that, over time, investors are mainly paying attention to the idiosyncratic risk premia of stock markets. Exceptions are financial crises, such as the Global Financial Crisis and the European Debt Crisis, during which we observe a decrease in their magnitude. During most such periods, we also observe an increase in the between-market spillovers, namely, the inward and outward risk premium spillovers. Thus, during stress periods, the cross-market risk premium is of major concern for investors. Starting in 2014, there is however a substantial decrease in the magnitude of within-market spillovers that reflects the increasing importance that investors assign to risk premium effects in other stock markets, i.e., cross-market effects. These findings are in line with Chabi-Yo, Ruenzi and Weigert (2017), who show that investors tend to overstate their fear related to a future market crash when they can acknowledge the occurrence of an existing one (Gennaioli, Shleifer and Vishney, 2015). In our case, the results indicate that investors are taking into account the financial crises and, thus, require higher compensation for the cross-market risks.

Considering the U.S. risk premium relationships in Panel A, we find that until close to the beginning of 2014, the inward spillover is greater than the outward spillover. During this period, the U.K.'s risk premium has a higher contribution to the total inward spillover than risk premium of the German and Japanese stock markets. Toward summer 2013, we document an increase in the risk premium spillover from Germany to the U.S. stock market. This finding could be related to the German election in September 2013. However, beginning in summer 2015, the U.K. risk premium's contribution to the U.S. risk premium is higher than that of other stock markets. This result might reflect the European Union Referendum Act of 2015 regarding the U.K.'s decision to hold a referendum either to remain in or leave the European Union. Moreover, it might also be related to the U.K.'s vote to leave the European Union in June 2016, which had implications and gave rise to many concerns not only for the U.K.'s own economy but also for its economic partners, such as the European Union and U.S. In addition, the political uncertainty surrounding the 2016 U.S.

presidential election might also have increased the perceived risk in the world economy.

Panel B, which presents the U.K. risk premium relationships, shows that the until circa the beginning of 2013, the inward spillover is lower than the outward spillover, fluctuating between approximately 10% and 15% versus 30% and 60%, respectively. Moreover, its highest magnitude is observed during the Global Financial Crisis and European Debt Crisis. The risk premium in Germany also has a considerable impact on the U.K. risk premium. This suggests that Germany increased its influence in the wake of the European Debt Crisis.

Regarding the German risk premium interactions, Panel C displays the high total inward versus outward spillover observed until the middle of 2012, when there is an increase in the outward spillover. We find that of the risk premia considered here, the U.K. risk premium has the largest influence on the German risk premium.

In Panel D, we further note that the Japanese inward spillover is slightly higher than its outward spillover. Moreover, during the middle of 2015, the increase in the inward spillover's magnitude is due primarily to the effects of the U.S. and U.K.'s risk premia.

INSERT FIGURE 1 HERE

Overall, during the stress periods and after 2014, our findings reveal large cross-market risk premium spillovers. We underline the influential role of the U.K. risk premium in the risk premia of the other stock markets we consider. Taken together, these findings clearly emphasize that investors might consider requiring compensation not only for their own-market risks but also for those of certain other markets and cross-market risks. As such, these results might also imply cross-market predictive power for the own-market risk premia. Moreover, these outcomes also raise a question regarding the impact of announcements on cross-market risk premia. As these questions are beyond the scope of this paper, we leave them for future investigations.

Figure 2 presents the time-varying connectedness among aggregate risk premium moments across stock markets in the U.S., U.K., Germany and Japan (i.e., within-moment, cross-moment and each moment risk premium spillovers). By doing so, we shed light on how the interactions among the VRP (Panel A), SRP (Panel B) and KRP (Panel C) of stock markets vary over time. These relationships are presented in three panels, the structure of which maps onto the structure of Table 4 and follows the structure of Figure 1. In addition, we decompose each element of Table 4, i.e., the total within-moment and total cross-moment spillovers, into a moment-within-market and moment-between-market effect. To facilitate interpretation, we refer to these effects as the within-moment and between-moment (cross-moment) effects. Specifically, the panels' upper plots show the connectedness among moments within the same stock market (within-moment), while the lower plots show the connectedness among moments between stock markets (cross-moment).

Panel A, which reports the VRP relationships, shows that the within-VRP spillover is higher than the cross-VRP spillover, varying between approximately 50% and 70%. Starting in 2014, however, there is a large increase in the cross-VRP spillover, from 20% to 30% by the end of 2016. These findings demonstrate the increasing importance of the transmission of uncertainty across stock markets. That is, investors are paying more attention to cross-VRP effects. We also observe that the inward is lower than the outward spillover, both within and between markets, and during periods of stress, their magnitude increases. These findings are in line with the fact that both in general and especially during these periods, the cross-moment risk premia, namely, SRP and KRP, have greater impacts on the VRP than do their within-moment risk premia.

Examining the SRP relationships reported in Panel B, we document that the within-SRP spillover is higher than the cross-SRP spillover, with its coefficient varying between approximately 60% and 80%. The cross-SRP spillover increased considerably between the beginning of 2015 and 2016, from 4% to more than 10%. Contrary to patterns of the VRP inward and outward spillovers in Panel A, Panel B reveals that the SRP inward and outward spillovers are, in general, closely co-moving within and between markets. Additionally, there is a strong within-moment spillover between KRP and SRP, varying between approximately 3% and 20%, and a high cross-moment spillover between VRP and SRP.

In line with the SRP interactions presented in Panel B, the KRP relationships in Panel C show that, over time, there is a strong within-KRP spillover that varies between 50% and 80%. As in the case of SRP spillovers, generally, the KRP inward and outward spillovers co-move. We also note that the substantial impact of within-SRP on the within-KRP is similar to that of the movement in the reverse direction.

INSERT FIGURE 2 HERE

Overall, investigating the spillovers among risk premium moments, we find that the within effects are higher than the cross-moment effects. However, these cross-moment risk premium effects are relevant. We especially emphasize the large cross-market premium spillovers from volatility to both skewness and kurtosis. Moreover, contributions of the skewness and kurtosis premia in explaining the volatility premium (within and between markets) are generally of similar magnitude. In line with the results discussed in Table 4, we find time-varying, bi-directional risk premium spillovers between skewness and kurtosis.

4.3.1 *Robustness*

As a robustness check for our results on risk premium spillovers, we also examine the implied spillovers. To save space, we focus on the time-varying aggregate spillovers among markets and moments, namely, the aggregate cross-market and aggregate cross-moment spillovers. The other analyses are available on request. In particular, using the risk premium spillovers from the middle panels of Figures 1 and 2, we compute the time-varying aggregate cross-market and cross-moment spillovers as the mean of the total spillover from all markets to each of the other markets, i.e., $from$ spillovers. Similarly, we compute the time-varying aggregate cross-market and cross-moment spillovers based on the implied volatility, skewness and kurtosis. Figure 3, Panels A and B, depicts these time-varying risk premium and implied spillover effects.

Figure 3 shows that, over time, the risk premium and implied spillovers across both markets and moments behave in a similar way. Moreover, we notice that while the spillovers' magnitude across markets is similar, the risk premium spillover among moments has a slightly smaller magnitude than that of the implied spillover among moments.

INSERT FIGURE 3 HERE

The choice of the rolling window is important for the estimation of the time-varying spillovers. Diebold and Yilmaz (2014) and Baruník, Kočenda and Vácha (2016) use a rolling window of 100 and 200 trading days, respectively. As there is no consensus on the correct window, we assess the robustness of our results to these alternative windows. Additionally, we consider a forecast horizon of one trading day. In line with Greenwood-Nimmo, Nguyen and Rafferty (2016), the patterns in Figure 4 highlight the robust time-varying spillovers when using various rolling windows such as 200 and 100 trading days and forecast horizons of one day and ten trading days. In sum, neither the choice of rolling window nor the choice of forecast horizon exerts a considerable impact on the results in Figure 3.

INSERT FIGURE 4 HERE

5 Relationship to macroeconomic, financial and risk premium factors

In the previous section, we showed that spillover effects exhibit substantial time variation that is relevant. This section further explores the connection of spillovers with macroeconomic and financial factors, as well as with the volatility, skewness and kurtosis risk premia. Specifically, we investigate the extent to which large and small changes in spillover effects are related to these factors. Using the time-varying risk premium spillovers from Panel A in Figure 3, we follow Greenwood-Nimmo, Nguyen and Shin (2015) in defining two binary indicators for when these spillovers are high and low. For instance, at time t, the high binary variable takes value one if the difference between the spillover at time t and the maximum of the previous 100 days is greater than zero. In all other cases, this high binary variable takes value zero. Conversely, the low binary variable takes value one if the difference between the spillover at time t and the minimum of the previous 100 days is smaller than zero, zero otherwise.[5] Finally, we estimate individual ordinary least squares regressions in which we regress each of the macroeconomic, financial and risk premium factors on both binary variables capturing the low and high periods of the aggregate spillover among markets and moments from Figure 3. Table 5 shows the estimates of these regressions in Panel A, for the macroeconomic and financial factors, and in Panel B, for the risk premium moments.

[5] We also compute the binary variables by using the maximum and minimum of the previous 200 and 250 days. The results in Table 5 are robust and are available on request.

The macroeconomic and financial variables that we focus on are the credit spread, TED (Treasury bill eurodollar) spread, Aruoba, Diebold and Scotti (2009) business conditions index (ADS), and the economic policy uncertainly index (EPU) of Baker, Bloom and Davis (2016).[6] The credit spread is computed as the difference between the yields of the Moody's AAA and BAA corporate bonds and measures investors' appetite for the risk associated with the variation in corporate bond quality. Bollerslev, Gibson and Zhou (2011) show that as the credit spread increases, the VRP also increases. The TED spread is the difference between the 3-Month LIBOR based on U.S. dollars and 3-Month Treasury Bill and captures the funding liquidity of traders. Adrian and Shin (2010), for instance, demonstrate the predictive ability of the TED spread for the variance risk premium. The ADS index is computed by taking into account data on economic indicators such as GDP, employment, and industrial production, as well as high- and low-frequency stock and flow data. The EPU index is estimated based on the frequency of the top-ten U.S. journals containing words such as "economic" or "economy", "uncertain" or "uncertainty" and one or more of "congress", "deficit", "Federal Reserve", "legislation", "regulation" and "White House".

Panel A shows that during both low and high spillover regimes, the coefficients of the macroeconomic and financial factors are statistically significant at the 1% level, excepting the coefficient of the ADS index during the high regime. Specifically, in absolute values, the macroeconomic and financial coefficients increase from the low to high regime of the aggregate spillover among markets and decrease for the spillover among moments. We extend the evidence in Bollerslev, Gibson and Zhou (2011) by finding that the credit spread increases during the periods when the aggregate risk premium spillover among markets is high. Its more negative coefficient during these periods could be related to financial intermediaries' compensation for taking additional risk that would result in a high risk premium or to the selling of risky corporate debt during stress periods (Konstantinidi and Skiadopoulos, 2016). The high TED spread during these times could be related to the traders' liquidity constraints. Gârleanu, Pedersen and Poteshman (2009) show that when traders face these constraints, they require higher compensation to take a short option position, and thus, the VRP increases. We emphasize that this is also the case for the aggregate spillover among markets, which

[6] The credit spread, TED spread and ADS index are obtained from the St. Louis Federal Reserve Bank website, https://fred.stlouisfed.org/. The EPU index is obtained from the website of Baker, Bloom and Davis, http://www.policyuncertainty.com/.

takes into account not only the VRP but also the higher-order moments. The more negative ADS coefficient indicates that during the high spillover periods, business conditions are worse than their average. Finally, we highlight the EPU's high coefficients during the low and high regimes of the spillover among moments.

Panel's B findings highlight the significantly different patterns of the risk premium moments during the high and low periods of the aggregate spillover among markets and moments. We find that VRP is increasing and decreasing from the low to high spillover among markets regime and among moments regime, respectively. Regarding the SRP of our stock markets and equally weighted portfolio, we find that their coefficients are less negative during both low spillover among markets and moments regimes. These findings suggest investors already have a strong concern about crash risk during the low spillover periods. Moreover, they are in line with our comments on Figure 2, where during stress periods, we observe a reduction in the SRP's overall magnitude. Instead, the coefficients of the KRP are generally higher, i.e., less negative or more positive, during both high spillover among markets and moments regimes.

INSERT TABLE 4 HERE

Overall, we provide evidence that the time-varying aggregate spillovers among markets and moments are countercyclical. We find that several macroeconomic and financial factors are increasing in absolute value with spillover intensity.

6 Conclusion

This paper examines the risk premium spillovers among the stock markets of four main advanced economies (the U.S., the U.K., Germany and Japan) from 2008 to 2016. We define the risk premium moments as the difference between the implied and realized moments (Bollerslev, Tauchen and Zhou, 2009) using the model-free risk-neutral moments (Bakshi, Kapadia, and Madan, 2003) and realized moments from high-frequency data (Amaya, Christoffersen, Jacobs and Vasquez, 2015). By using Diebold and Yilmaz (2012, 2014)'s and Greenwood-Nimmo, Nguyen and Shin (2015)'s approach, we provide a better cross-market and cross-moment understanding of interactions of the volatility, skewness and kurtosis risk premia.

Our investigation reveals several important findings. First, we emphasize the time variation in the pattern of risk premium spillovers. We find that during periods of stress and after 2014, there is an increase in the cross-border spillovers across markets and risk premium moments. During these periods, the within-spillovers decrease, indicating that investors are more concerned with risk transmission across stock markets. Second, we document strong bi-directional spillovers between skewness and kurtosis risk premia. In addition, we find that the cross-moment risk premia, namely, skewness and kurtosis, have substantial impacts on the VRP. Third, we highlight the high magnitude of several macroeconomic and financial factors when the risk premium spillover among markets is high. Overall, we highlight that risk premium spillovers among stock markets are characterized by (i) increasing attention being given to the cross-market and cross-moment effects, especially during periods of stress and after 2014, (ii) the prominent role played by VRP and (iii) the existence of a relationship between risk premium spillovers and macroeconomic and financial factors.

Our findings raise at least two interesting avenues for future research. We show that when the risk premium spillovers are high, the macroeconomic and financial factors are also high. As a result, future research could explore the cross-market predictive relationship between risk premium moments and macroeconomic factors. Moreover, the existence of important cross-market and cross-moment risk premium spillovers raises the question of whether the cross-market and cross-moment risk premia have a better predictive ability for a market's returns or for a market's own volatility, skewness and kurtosis risk premia. Although these questions are beyond the scope of the current paper, they are worthy of special attention in future research.

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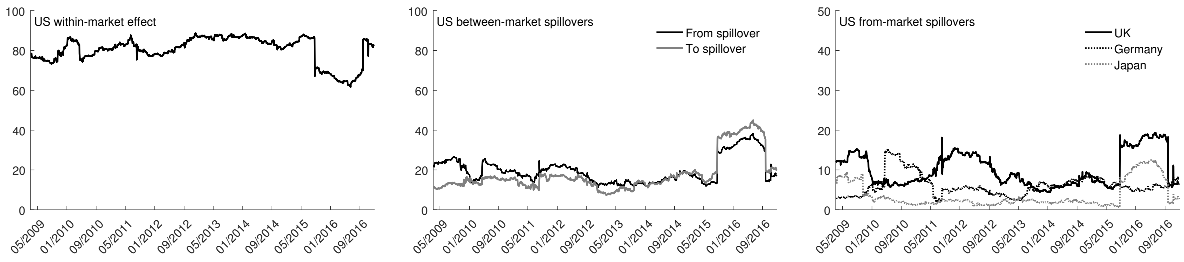
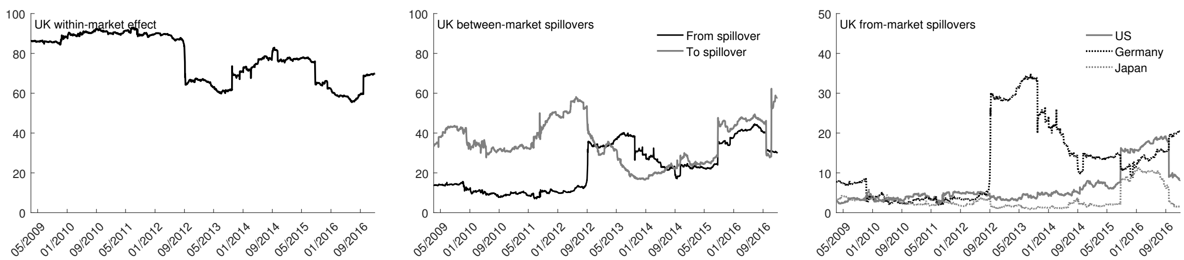
Figure 1: Time-varying connectedness among stock markets

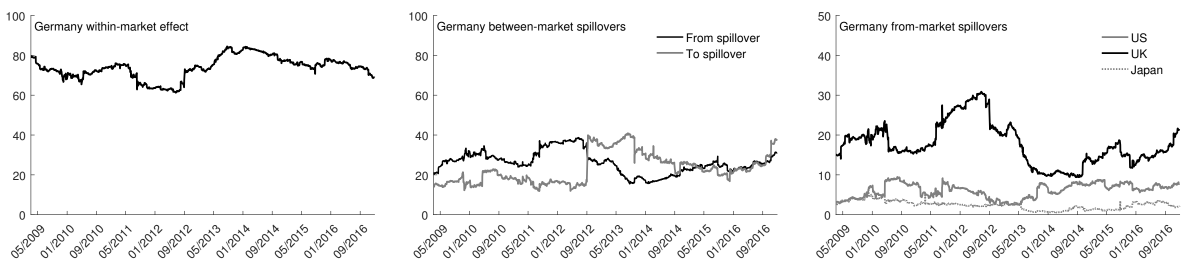
Panel A: The U.S. relationships



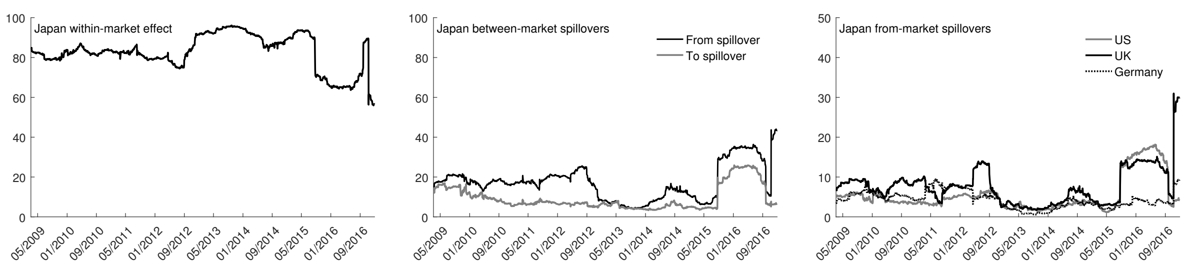
Panel B: The U.K. relationships



Panel C: The German relationships



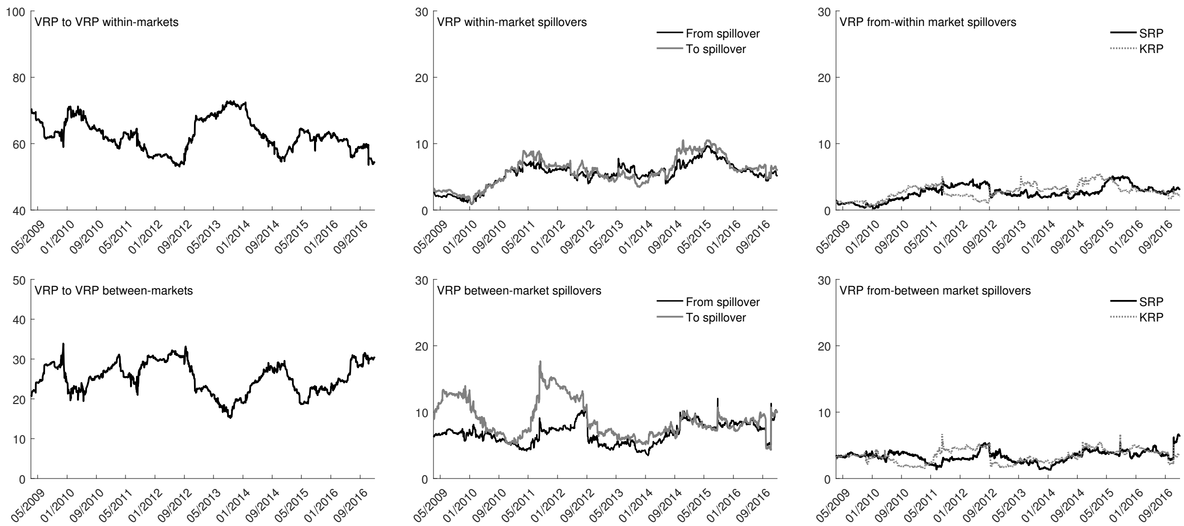
Panel D: The Japanese relationships



Note: This figure shows the rolling window estimates for the relationships among the U.S., U.K., German and Japanese stock markets (i.e., within-market, cross-market and own-market risk premium spillovers). The connectedness matrix is estimated following Diebod and Yilmaz (2012, 2014) under the block aggregation routine of Greenwood-Nimmo, Nguyen and Shin (2015). We use a rolling window length of 250 trading days with a forecast horizon of ten trading days. The panels capture the share of the variance of the risk premium in each stock market that is explained by shocks occurring in its own risk premium market and in other risk premium markets. The from (to) spillover represents the total spillover from all stock markets (stock market i) to stock market i (all stock markets).

Figure 2: Time-varying connectedness among risk premia

Panel A: The volatility risk premium relationships



Panel B: The skewness risk premium relationships

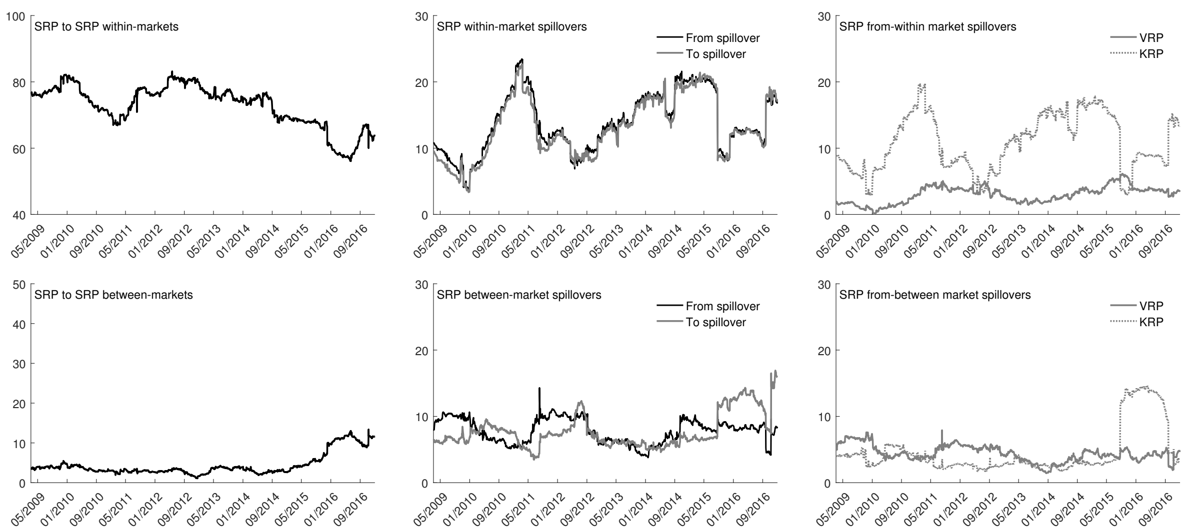
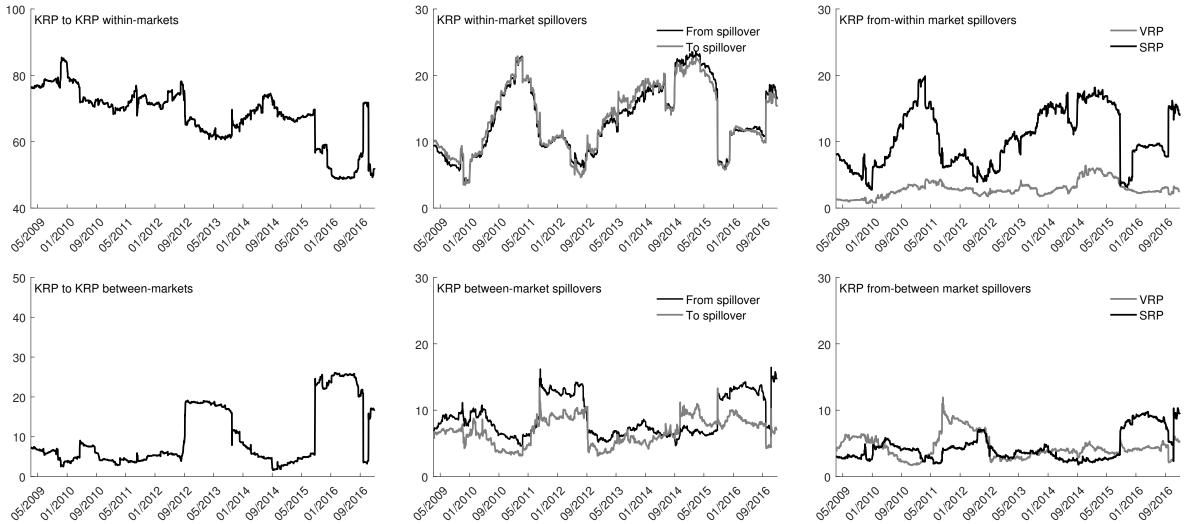


Figure 2 (continued): Time-varying connectedness among risk premia

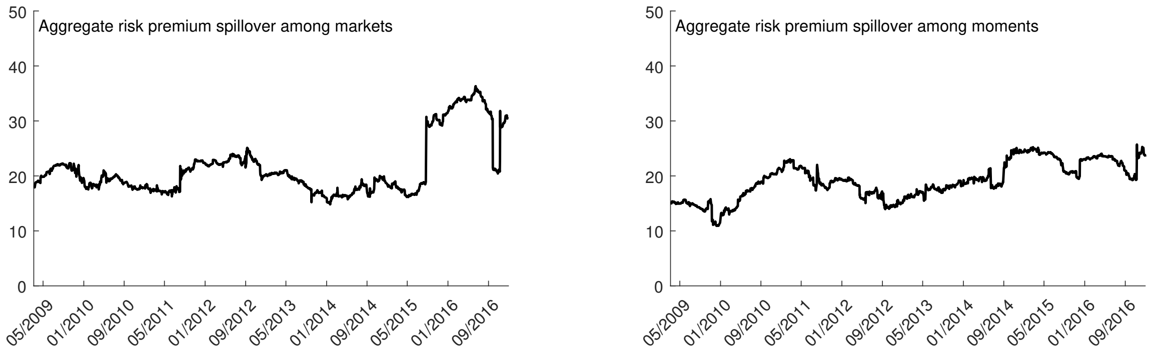
Panel C: The kurtosis risk premium relationships



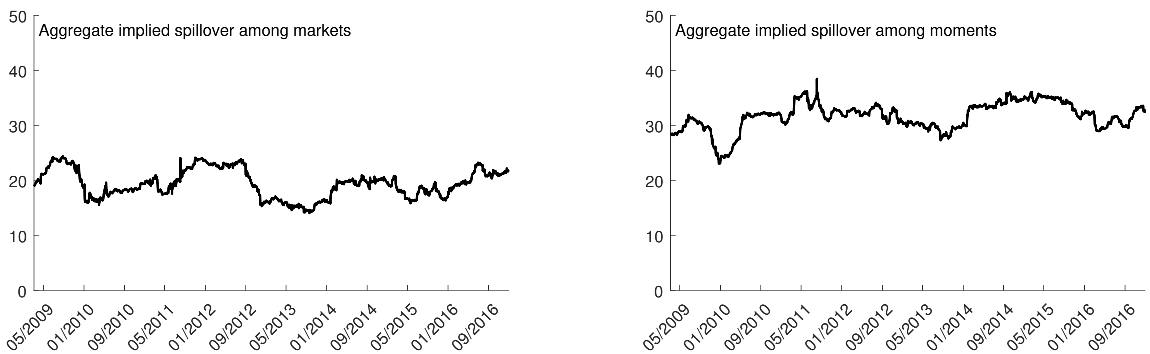
Note: This figure shows the rolling window estimates for the risk premium relationships among the U.S., U.K., German and Japanese stock markets. The connectedness matrix is estimated following Diebod and Yilmaz (2009, 2014) under the block aggregation routine of Greenwood-Nimmo, Nguyen and Shin (2015) using a rolling window length of 250 trading days with a forecast horizon of 10 trading days. The panels capture the share of the variance of each market that is explained by shocks occurring in its own market and other markets. The from (to) volatility risk premium spillover, for instance, represents the total spillover from all risk premium moments (volatility risk premium) to the volatility risk premium (all risk premium moments). The other from (to) spillovers are defined analogously. We note that each of the panels' upper plots shows the connectedness among moments within the same stock market (within-moment), while the lower plots show the connectedness among moments between stock markets (cross-moment).

Figure 3: Time-varying aggregate spillovers

Panel A: Risk premium spillovers



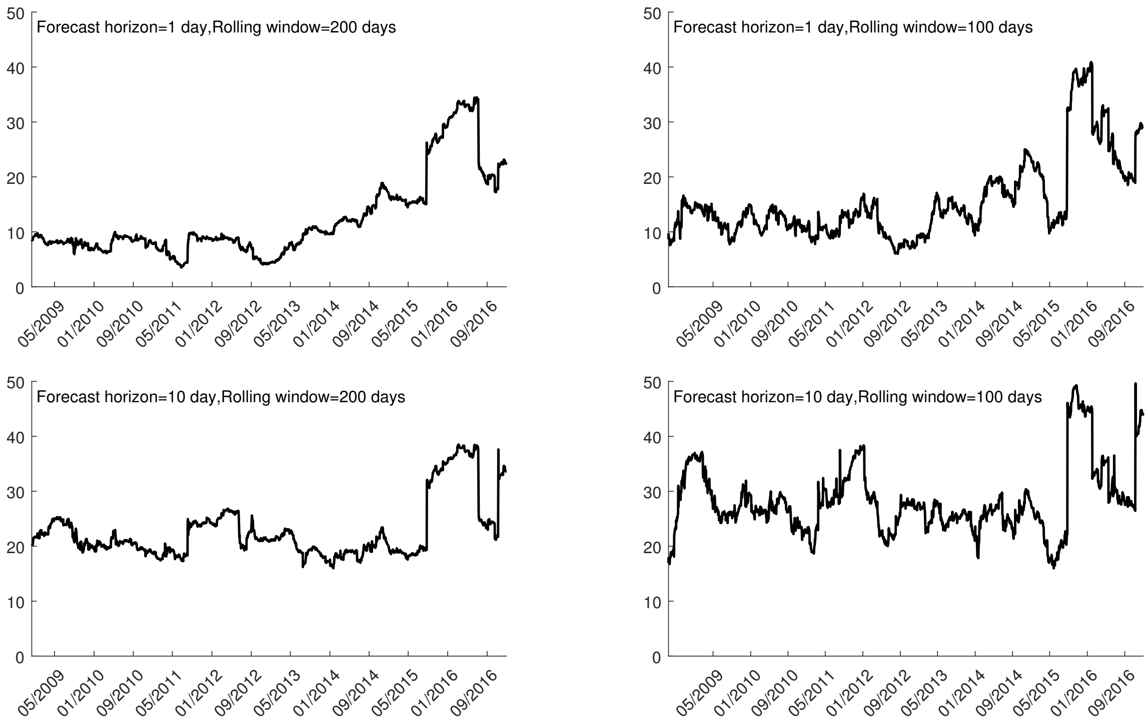
Panel B: Implied spillovers



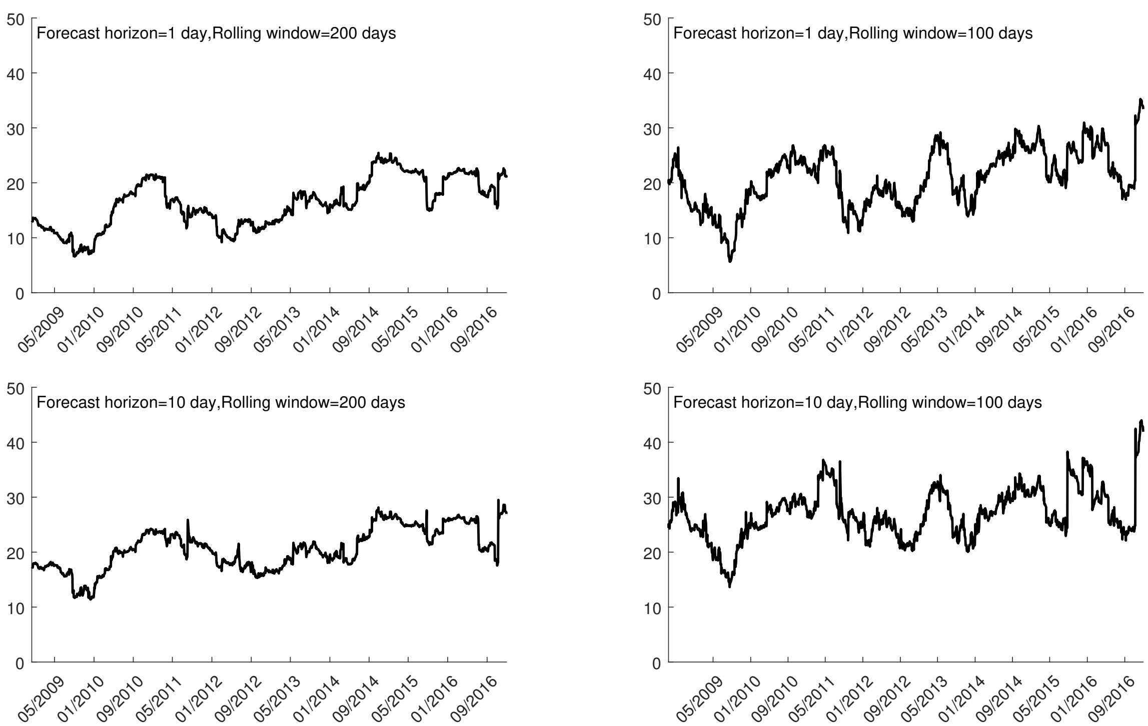
Note: This figure shows the time-varying aggregate spillovers among markets and moments. Panel A shows these spillovers based on the risk premium moments. Panel B shows them based on the implied moments. The aggregate risk premium spillover among markets is computed as the mean of $from$ spillovers from Figure 1. The aggregate risk premium spillover among moments is computed as the mean of $from$ spillovers from Figure 2. We analogously compute the implied spillovers. The connectedness matrix is estimated following Diebod and Yilmaz (2012, 2014) under the block aggregation routine of Greenwood-Nimmo, Nguyen and Shin (2015). We use a rolling window length of 250 trading days with a forecast horizon of ten trading days.

Figure 4: Time-varying aggregate spillovers with various forecast horizons and rolling windows

Panel A: Aggregate spillovers among markets



Panel B: Aggregate spillovers among moments



Note: This figure shows, in Panels A and B, the time-varying aggregate spillovers among markets and moments. The aggregate risk premium spillover among markets is computed as the mean of $from$ spillovers from Figure 1. The aggregate risk premium spillover among moments is computed as the mean of $from$ spillovers from Figure 2. We use a rolling window length of 200 and 100 trading days with a forecast horizon of one day and ten days. The connectedness matrix is estimated following Diebod and Yilmaz (2012, 2014) under the block aggregation routine of Greenwood-Nimmo, Nguyen and Shin (2015).

Table 1: Summary statistics

		U.S.	U.K.	Germany	Japan
Panel A: Realized moments					
Volatility	Mean	0.0075	0.0072	0.0110	0.0091
	Std. Dev.	0.0054	0.0038	0.0047	0.0045
Skewness	Mean	−0.0091	−0.0224	−0.0361	−0.0032
	Std. Dev.	0.0691	0.0856	0.0795	0.0981
Kurtosis	Mean	0.3078	0.3731	0.3789	0.4499
	Std. Dev.	0.1231	0.2060	0.1422	0.3851
Panel B: Implied moments					
Volatility	Mean	0.0110	0.0103	0.0118	0.0140
	Std. Dev.	0.0056	0.0049	0.0040	0.0056
Skewness	Mean	−0.3792	−0.2114	−0.1153	−0.1730
	Std. Dev.	0.1098	0.0620	0.0503	0.0727
Kurtosis	Mean	0.4084	0.1297	0.1244	0.1599
	Std. Dev.	0.1811	0.0324	0.0478	0.0491
Panel C: Risk premium moments					
VRP	Mean	0.0035	0.0031	0.0007	0.0049
	Std. Dev.	0.0028	0.0024	0.0021	0.0026
SRP	Mean	−0.3701	−0.1890	−0.0792	−0.1698
	Std. Dev.	0.1184	0.0997	0.1006	0.1221
KRP	Mean	0.1006	−0.2434	−0.2546	−0.2900
	Std. Dev.	0.1906	0.2080	0.1446	0.3874
Panel D: Risk premium innovations					
VRP	Mean	0.0000	0.0000	0.0000	0.0000
	Std. Dev.	0.0011	0.0010	0.0007	0.0010
SRP	Mean	−0.0000	0.0000	−0.0000	−0.0000
	Std. Dev.	0.0448	0.0378	0.0315	0.0446
KRP	Mean	−0.0000	−0.0000	0.0000	−0.0000
	Std. Dev.	0.0833	0.0820	0.0501	0.1346

Note: This table reports the descriptive statistics for daily realized moments, implied moments, risk premium moments and risk premium innovations (volatility, skewness and kurtosis) of the U.S., U.K., German and Japanese stock markets. Using high-frequency data, we estimate the daily realized moments as in Amaya, Christoffersen, Jacobs and Vasquez (2015). Then, following Bollerslev, Tauchen and Zhou (2009), we define the daily risk premium moments, namely, the volatility risk premium (VRP), skewness risk premium (SRP) and kurtosis risk premium (KRP), as the difference between implied and realized moments. Finally, following Menkhoff, Sarno, Schmeling and Schrimpf (2012) and Greenwood-Nimmo, Nguyen and Rafferty (2016), we recover the risk premium innovations from an AR (1) model.

Table 2: Connectedness among risk premia

To\From		U.S. VRP	U.S. SRP	U.S. KRP	U.K. VRP	U.K. SRP	U.K. KRP	Germany VRP	Germany SRP	Germany KRP	Japan VRP	Japan SRP	Japan KRP
U.S.	VRP	72.24	3.92	1.30	15.44	0.06	0.12	5.44	0.94	0.06	0.37	0.05	0.08
	SRP	4.38	81.44	11.05	1.16	0.13	0.43	1.00	0.20	0.03	0.07	0.04	0.07
	KRP	1.43	10.74	79.90	0.48	0.29	4.82	0.68	0.02	0.03	0.17	0.42	0.99
U.K.	VRP	5.20	1.13	0.57	85.23	0.02	0.47	6.04	0.83	0.39	0.09	0.02	0.01
	SRP	0.06	0.24	0.38	0.00	94.29	1.18	0.09	3.08	0.17	0.21	0.14	0.17
	KRP	0.23	0.16	5.30	0.62	0.93	84.77	0.61	0.19	6.02	0.08	0.85	0.23
Germany	VRP	7.32	0.88	0.71	25.74	0.04	0.46	62.27	1.38	0.07	1.06	0.03	0.03
	SRP	1.15	0.23	0.07	3.22	1.74	0.37	1.95	81.60	9.55	0.03	0.07	0.02
	KRP	0.17	0.02	0.03	1.04	0.09	1.67	0.22	10.18	86.37	0.06	0.03	0.11
Japan	VRP	5.50	0.78	0.32	7.30	0.28	0.25	4.25	0.84	0.10	78.83	1.05	0.50
	SRP	0.10	0.04	0.49	0.06	0.01	1.30	0.03	0.05	0.03	1.34	93.49	3.06
	KRP	0.07	0.22	1.09	0.37	6.06	10.92	0.57	1.26	1.71	0.46	2.51	74.75

Note: This table reports the full sample connectedness among the volatility risk premium (VRP), skewness risk premium (SRP) and kurtosis risk premium (KRP) of the U.S., U.K., German and Japanese stock markets. The connectedness matrix is estimated following Diebod and Yilmaz (2012, 2014) and captures the share of the variance of each risk premium moment across all four stock markets that is explained by shocks occurring in its own moment and in the risk premia of other markets. The variance decompositions are computed using a forecast horizon of ten trading days.

Table 3: Aggregate connectedness among stock markets

To\From	U.S.	U.K.	Germany	Japan
U.S.	88.80	7.64	2.80	0.76
U.K.	4.42	89.17	5.81	0.60
Germany	3.53	11.46	84.53	0.48
Japan	2.87	8.85	2.94	85.33

Note: This table reports the full sample connectedness among the U.S., U.K., German and Japanese stock markets. The connectedness matrix is estimated following Diebod and Yilmaz (2012, 2014) under the block aggregation routine of Greenwood-Nimmo, Nguyen and Shin (2015) and captures the share of the variance of each market that is explained by shocks occurring in its own market and other markets. The variance decompositions are computed using a forecast horizon of ten trading days.

Table 4: Aggregate connectedness among risk premia

To\From	VRP	SRP	KRP
VRP	95.58	3.06	1.36
SRP	3.71	89.20	7.09
KRP	1.82	8.50	89.68

Note: This table reports the full sample connectedness among the aggregated volatility risk premium (VRP), skewness risk premium (SRP) and kurtosis risk premium (KRP) of the U.S., U.K., German and Japanese stock markets. The connectedness matrix is estimated following Diebod and Yilmaz (2009, 2014) under the block aggregation routine of Greenwood-Nimmo, Nguyen and Shin (2015) and captures the share of the variance of each risk premium moment that is explained by shocks occurring in its own moment and other risk premium moments. The variance decompositions are computed using a forecast horizon of ten trading days.

Table 5: Relationship with macroeconomic, financial and risk premium factors

		Spillover among markets		Spillover among moments	
Factor\Period		Low	High	Low	High
Panel A: Macroeconomic and financial factors					
	Credit spread	−0.93***	−1.21***	−1.09***	−1.03***
		(−43.88)	(−22.84)	(−27.85)	(−22.37)
	Ted spread	0.30***	0.33***	0.31***	0.25***
		(8.64)	(21.58)	(12.97)	(15.09)
	ADS	−0.17***	−0.21***	−0.17***	−0.03
		(−2.67)	(−4.81)	(−4.76)	(−0.57)
	EPU	97.12***	78.98***	87.67***	116.39***
		(9.18)	(11.69)	(8.91)	(9.58)
Panel B: Risk premium moments					
VRP	EW	0.0027***	0.0033***	0.0033***	0.0029***
		(16.10)	(7.12)	(13.02)	(10.67)
	U.S.	0.0029***	0.0036***	0.0041***	0.0033***
		(9.08)	(6.48)	(7.21)	(10.29)
	U.K.	0.0027***	0.0038***	0.0032***	0.0030***
		(15.07)	(6.85)	(12.63)	(8.64)
	Germany	0.0014***	0.0009*	0.0015***	0.0007***
		(8.29)	(1.74)	(6.24)	(3.13)
	Japan	0.0037***	0.0049***	0.0045***	0.0045***
		(15.18)	(11.06)	(15.54)	(11.03)

(continued)

Table 5 (continued): Relationship with macroeconomic, financial and risk premium factors

		Spillover among markets		Spillover among moments	
Factor\Period		Low	High	Low	High
Panel B: Risk premium moments					
SRP	EW	−0.219***	−0.196***	−0.248***	−0.207***
		(−14.26)	(−20.12)	(−17.42)	(−25.61)
	U.S.	−0.400***	−0.390***	−0.422***	−0.402***
		(−13.64)	(−20.50)	(−21.34)	(−22.75)
	U.K.	−0.186***	−0.185***	−0.244***	−0.184***
		(−16.09)	(−12.15)	(−13.83)	(−10.88)
	Germany	−0.090***	−0.024	−0.104***	−0.075***
		(−6.07)	(−1.24)	(−6.24)	(−5.24)
	Japan	−0.200***	−0.185***	−0.222***	−0.168***
		(−5.88)	(−10.94)	(−9.41)	(−11.25)
KRP	EW	−0.187***	−0.161***	−0.196***	−0.155***
		(−13.38)	(−5.63)	(−6.72)	(−10.18)
	U.S.	0.137***	0.095**	0.078	0.175***
		(4.34)	(2.10)	(1.60)	(6.82)
	U.K.	−0.283***	−0.280***	−0.307***	−0.204***
		(−7.49)	(−4.42)	(−5.40)	(−11.42)
	Germany	−0.253***	−0.268***	−0.239***	−0.283***
		(−11.82)	(−8.76)	(−19.10)	(−9.53)
	Japan	−0.347***	−0.191***	−0.314***	−0.307***
		(−8.96)	(−5.06)	(−6.81)	(−6.99)

Note: This table presents the relationship of spillovers with macroeconomic, financial and risk premium factors. Specifically, we present the individual regressions of each of these factors on the two binary variables capturing the periods when the aggregate spillover among markets and moments is high and low. Panel A shows these estimates for the macroeconomic and financial factors, namely, credit spread, TED spread, Aruoba, Diebold and Scotti (2009) business conditions index (ADS), and the economic policy uncertainly (EPU). Panel B presents the estimates for the risk premium factors, namely, the volatility risk premium (VRP), skewness risk premium (SRP) and kurtosis risk premium (KRP) of the U.S., U.K., German and Japanese stock markets. We also compute an equally weighted variable (EW) for each of the risk premia. ***, **, * indicate significance at the 1%, 5% and 10% levels, respectively.

Appendix A. The block approach

The Diebold-Yilmaz (2012, 2014) framework can be used either to measure spillovers among individual variables or to summarize aggregate spillover activity among all variables in the system. However, it does not provide a simple way to measure spillovers among groups of variables. As such, it is not straightforward to measure spillovers among multiple markets, each of which is represented by three variables: $\boldsymbol{v}_{it}$, $\boldsymbol{s}_{it}$, and $\boldsymbol{k}_{it}$. Consequently, Greenwood-Nimmo, Nguyen and Shin (2015) develop a generalized framework that exploits block aggregation of the connectedness matrix.

A.1 The block approach per market

Suppose that the variables are in the order $\mathbf{x}_t = (v_{1t}, s_{1t}, k_{1t}; v_{2t}, s_{2t}, k_{2t}; ...; v_{Nt}, s_{Nt}, k_{Nt})'$ and that we wish to evaluate the connectedness among the N markets in the model in a combined manner that encompasses all three variables in each market. We can write the connectedness matrix $\mathbf{C}^{(H)}$ in block form with $g = N$ groups each composed of $m = 3$ variables as follows:

$$\mathbf{C}^{(H)} = \begin{bmatrix} \mathbf{B}^{(H)}_{1\leftarrow 1} & \mathbf{B}^{(H)}_{1\leftarrow 2} & ... & \mathbf{B}^{(H)}_{1\leftarrow N} \\ \mathbf{B}^{(H)}_{2\leftarrow 1} & \mathbf{B}^{(H)}_{2\leftarrow 2} & ... & \mathbf{B}^{(H)}_{2\leftarrow N} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{B}^{(H)}_{N\leftarrow 1} & \mathbf{B}^{(H)}_{N\leftarrow 2} & ... & \mathbf{B}^{(H)}_{N\leftarrow N} \end{bmatrix} \tag{6}$$

$$\mathbf{B}^{(H)}_{i\leftarrow j} = \begin{bmatrix} \psi^{(H)}_{v_i\leftarrow v_j} & \psi^{(H)}_{v_i\leftarrow s_j} & \psi^{(H)}_{v_i\leftarrow k_j} \\ \psi^{(H)}_{s_i\leftarrow v_j} & \psi^{(H)}_{s_i\leftarrow s_j} & \psi^{(H)}_{s_i\leftarrow k_j} \\ \psi^{(H)}_{k_i\leftarrow v_j} & \psi^{(H)}_{k_i\leftarrow s_j} & \psi^{(H)}_{k_i\leftarrow k_j} \end{bmatrix}$$

for i, $j = 1, 2, ..., N$ and where the block $\mathbf{B}^{(H)}_{i\leftarrow i}$ collects all the within-market effects for market i while $\mathbf{B}^{(H)}_{i\leftarrow j}$ collects all spillover effects from market j to market i. Greenwood-Nimmo, Nguyen and Shin (2015) stress that, due to the order-invariance of generalized forecast error variance decomposition, the variables in $\mathbf{x}_t$ can be re-ordered as necessary to support any desired block structure. Using (6), we can define the **total within-market** forecast error variance contribution for market i as follows:

$$M^{(H)}_{i\leftarrow i} = \frac{1}{m}\boldsymbol{u}'_{\boldsymbol{m}}\mathbf{B}^{(H)}_{i\leftarrow i}\boldsymbol{u}_{\boldsymbol{m}} \tag{7}$$

where $\boldsymbol{u}_{\boldsymbol{m}}$ is an $m \times 1$ vector of ones. As such, $M^{(H)}_{i\leftarrow i}$ measures the proportion of the H-step-ahead forecast error variance contributions of x_{it} due to shocks to x_{it}. $M^{(H)}_{i\leftarrow i}$ can be decomposed into common-variable forecast error variance contributions within market i, denoted $O^{(H)}_{i\leftarrow i}$, and cross-variable effects, denoted $A^{(H)}_{i\leftarrow i}$, as follows:

$$O^{(H)}_{i\leftarrow i} = \frac{1}{m}trace\left(\mathbf{B}^{(H)}_{i\leftarrow i}\right); A^{(H)}_{i\leftarrow i} = M^{(H)}_{i\leftarrow i} - O^{(H)}_{i\leftarrow i} \tag{8}$$

Note that $O^{(H)}_{i\leftarrow i}$ measures the proportion of the H-step-ahead forecast error variance of x_{it} that is not attributable to spillovers among the variables within market i or to spillovers from other markets to market i. By contrast, $A^{(H)}_{i\leftarrow i}$ records the total H-step-ahead spillovers among the volatility risk premium, skewness risk premium and kurtosis risk premium within market i.

The **total between-market** directional spillover from market j to market i at horizon H is given by:

$$S_{i\leftarrow j}^{(H)} = \frac{1}{m}\boldsymbol{u_m'}\boldsymbol{B}_{i\leftarrow j}^{(H)}\boldsymbol{u_m} \tag{9}$$

The aggregate from and to spillover of market i is defined as:

$$S_{i\leftarrow\bullet}^{(H)} = \sum_{j=1,j\neq i}^{N} S_{i\leftarrow j}^{(H)}; S_{\bullet\leftarrow i}^{(H)} = \sum_{j=1,j\neq i}^{N} S_{j\leftarrow i}^{(H)}. \tag{10}$$

Finally, the **aggregate between-market** and the **aggregate within-market** spillovers are defined as:

$$S^{(H)} = \frac{1}{N}\sum_{i=1}^{N} S_{i\leftarrow\bullet}^{(H)}; M^{(H)} = 100 - S^{(H)} \tag{11}$$

A.2 The block approach per moment

We apply the same approach to evaluating the connectedness among the three groups of moments for all N markets collectively, which consists in ordering the variables in the VAR to obtain $\boldsymbol{x}_t = (\boldsymbol{v}_t, \boldsymbol{s}_t, \boldsymbol{k}_t)$. In this case, we may write the H-step-ahead connectedness matrix with g = 3 groups of moments composed of $m = N$ variables:

$$\mathbf{C}^{(H)} = \begin{bmatrix} \boldsymbol{B}_{v\leftarrow v}^{(H)} & \boldsymbol{B}_{v\leftarrow s}^{(H)} & \boldsymbol{B}_{v\leftarrow k}^{(H)} \\ \boldsymbol{B}_{s\leftarrow v}^{(H)} & \boldsymbol{B}_{s\leftarrow s}^{(H)} & \boldsymbol{B}_{s\leftarrow k}^{(H)} \\ \boldsymbol{B}_{k\leftarrow v}^{(H)} & \boldsymbol{B}_{k\leftarrow s}^{(H)} & \boldsymbol{B}_{k\leftarrow k}^{(H)} \end{bmatrix} \tag{12}$$

$$\mathbf{B}_{i\leftarrow j}^{(H)} = \begin{bmatrix} \psi_{v_1\leftarrow v_1}^{(H)} & \psi_{v_1\leftarrow v_2}^{(H)} & \dots & \psi_{v_1\leftarrow v_N}^{(H)} \\ \psi_{v_2\leftarrow v_1}^{(H)} & \psi_{v_2\leftarrow v_2}^{(H)} & \dots & \psi_{v_2\leftarrow v_N}^{(H)} \\ \vdots & \vdots & \ddots & \vdots \\ \psi_{v_N\leftarrow v_1}^{(H)} & \psi_{v_N\leftarrow v_2}^{(H)} & \dots & \psi_{v_N\leftarrow v_N}^{(H)} \end{bmatrix}$$

$$\mathbf{B}_{i\leftarrow j}^{(H)} = \begin{bmatrix} \psi_{v_1\leftarrow s_1}^{(H)} & \psi_{v_1\leftarrow s_2}^{(H)} & \dots & \psi_{v_1\leftarrow s_N}^{(H)} \\ \psi_{v_2\leftarrow s_1}^{(H)} & \psi_{v_2\leftarrow s_2}^{(H)} & \dots & \psi_{v_2\leftarrow s_N}^{(H)} \\ \vdots & \vdots & \ddots & \vdots \\ \psi_{v_N\leftarrow s_1}^{(H)} & \psi_{v_N\leftarrow s_2}^{(H)} & \dots & \psi_{v_N\leftarrow s_N}^{(H)} \end{bmatrix}, \mathbf{B}_{i\leftarrow j}^{(H)} = \begin{bmatrix} \psi_{v_1\leftarrow k_1}^{(H)} & \psi_{v_1\leftarrow k_2}^{(H)} & \dots & \psi_{v_1\leftarrow k_N}^{(H)} \\ \psi_{v_2\leftarrow k_1}^{(H)} & \psi_{v_2\leftarrow k_2}^{(H)} & \dots & \psi_{v_2\leftarrow k_N}^{(H)} \\ \vdots & \vdots & \ddots & \vdots \\ \psi_{v_N\leftarrow k_1}^{(H)} & \psi_{v_N\leftarrow k_2}^{(H)} & \dots & \psi_{v_N\leftarrow k_N}^{(H)} \end{bmatrix}$$

The remaining blocks are defined analogously. As in the previous sub-section, the within- and between-moment spillover from volatility risk premium to volatility risk premium is given by:

$$M_{v\leftarrow v}^{(H)} = \frac{1}{m} trace\left(\boldsymbol{B}_{v\leftarrow v}^{(H)}\right); S_{v\leftarrow v}^{(H)} = \frac{1}{m}\boldsymbol{u}_{\boldsymbol{m}}'\boldsymbol{B}_{v\leftarrow v}^{(H)}\boldsymbol{u}_{\boldsymbol{m}} - M_{v\leftarrow v}^{(H)} \tag{13}$$

The within- and between-moment spillover from skewness risk premium to volatility risk premium is defined as:

$$M_{v\leftarrow s}^{(H)} = \frac{1}{m} trace\left(\boldsymbol{B}_{v\leftarrow s}^{(H)}\right); S_{v\leftarrow s}^{(H)} = \frac{1}{m}\boldsymbol{u}_{\boldsymbol{m}}'\boldsymbol{B}_{v\leftarrow s}^{(H)}\boldsymbol{u}_{\boldsymbol{m}} - M_{v\leftarrow s}^{(H)} \tag{14}$$

Finally, the within- and between-moment spillover from kurtosis risk premium to volatility risk premium is computed as:

$$M_{v\leftarrow k}^{(H)} = \frac{1}{m} trace\left(\boldsymbol{B}_{v\leftarrow k}^{(H)}\right); S_{v\leftarrow k}^{(H)} = \frac{1}{m}\boldsymbol{u}_{\boldsymbol{m}}'\boldsymbol{B}_{v\leftarrow k}^{(H)}\boldsymbol{u}_{\boldsymbol{m}} - M_{v\leftarrow k}^{(H)} \tag{15}$$

The remaining blocks are defined analogously.

Appendix B. Data construction

We follow the model-free methodology of Bakshi, Kapadia and Madan (2003) in computing the risk-neutral moments, namely, implied variance, skewness and kurtosis. The studies of Breedon and Litzenberger (1978) and Bakshi and Madan (2000) show that risk-neutral distributions can be recovered from a set of option prices and any payoff function with bounded expectation can be spanned by a continuum of out-the-money calls and puts. The replication of any twice-differentiable payoff $F(S)$ function of any underlying price process S_t at period t and maturity T is given by (Carr and Madan, 2001; Bakshi, Kapadia and Madan 2003):

$$\begin{aligned} F(S) &= F(S_0) + (S - S_0)\, F_S(S_0) \\ &+ \int_{S_0}^{\infty} F_{SS}(K) Max\,(S - K, 0)\, dK + \int_{0}^{S_0} F_{SS}(K) Max\,(K - S, 0)\, dK \end{aligned} \tag{16}$$

Applying the expectation operator $E^Q\{.\}$, to F_S, under the risk-neutral probability Q such as:

$$\begin{aligned} E^Q\left\{e^{-r(T-t)}F(S)\right\} &= \left(F(S_0) - F_S(S_0)S_0\right) e^{-r(T-t)} + F_S(S_0)S_t \\ &+ \int_{S_0}^{\infty} F_{SS}(K)C(T,t,K)dK + \int_{0}^{S_0} F_{SS}(K)P(T,t,K)dK \end{aligned} \tag{17}$$

where F_S and F_{SS} are the first and second derivatives of the contingent claim payoff function; $C(T,t,K)$ and $P(T,t,K)$ are the call and put options with strike price K and time to maturity $T-t$. Setting the square, cubic and quartic contract payoffs to $F(S) = log(S_T/S_t)^2$, $F(S) = log(S_T/S_t)^3$ and $F(S) = log(S_T/S_t)^4$, respectively, allows us to derive risk-neutral moments using the previous equation. Performing standard differentiation steps and setting $S_0 = S_t$, Bakshi, Kapadia and Madan (2003) derive the fair payoff values by computing the discounted risk-neutral expectation $E^Q\left\{e^{-r(T-t)}F(S)\right\}$ for the square payoff $V(T,t) = E^Q\left\{e^{-r(T-t)}log(S_T/S_t)^2\right\}$, cubic payoff

$W(T,t) = E^Q\left\{e^{-r(T-t)}log(S_T/S_t)^3\right\}$ and quartic payoff $X(T,t) = E^Q\left\{e^{-r(T-t)}log(S_T/S_t)^4\right\}$ as:

$$V(T,t) = \int_{S_t}^{\infty} \frac{2\left(1 - log(\frac{K}{S_t})\right)}{K^2} C(T,t,K)dK + \int_0^{S_t} \frac{2\left(1 + log(\frac{S_t}{K})\right)}{K^2} P(T,t,K)dK \tag{18}$$

$$\begin{aligned} W(T,t) = &\int_{S_t}^{\infty} \frac{6\left(log(\frac{K}{S_t})\right) - 3\left(log(\frac{K}{S_t})\right)^2}{K^2} C(T,t,K)dK \\ - &\int_0^{S_t} \frac{6\left(log(\frac{S_t}{K})\right) + 3\left(log(\frac{S_t}{K})\right)^2}{K^2} P(T,t,K)dK \end{aligned} \tag{19}$$

$$\begin{aligned} X(T,t) = &\int_{S_t}^{\infty} \frac{12\left(log(\frac{K}{S_t})\right)^2 - 4\left(log(\frac{K}{S_t})\right)^3}{K^2} C(T,t,K)dK \\ + &\int_0^{S_t} \frac{12\left(log(\frac{S_t}{K})\right)^2 + 4\left(log(\frac{S_t}{K})\right)^3}{K^2} P(T,t,K)dK \end{aligned} \tag{20}$$

The model-free risk-neutral volatility $v(T,t)$, risk-neutral skewness $s(T,t)$ and risk-neutral kurtosis $k(T,t)$ can then be extracted from a collection of out-the-money option contracts at period t with maturity T. These risk-neutral moments are defined as follows:

$$v(T,t) = \left[e^{r(T-t)}V(T-t) - \mu(T,t)^2\right]^{\frac{1}{2}} \tag{21}$$

$$s(T,t) = \frac{e^{r(T-t)}W(T-t) - 3\mu(T,t)e^{r(T-t)}V(T-t) + 2\mu(T,t)^3}{\left[e^{r(T-t)}V(T-t) - \mu(T,t)^2\right]^{\frac{3}{2}}} \tag{22}$$

$$\begin{aligned} k(T,t) = &\frac{e^{r(T-t)}X(T-t) - 4\mu(T,t)e^{r(T-t)}W(T-t) + 6\mu(T,t)^2e^{r(T-t)}V(T-t)}{\left[e^{r(T-t)}V(T-t) - \mu(T,t)^2\right]^2} \\ - &\frac{3\mu(T,t)^4}{\left[e^{r(T-t)}V(T-t) - \mu(T,t)^2\right]^2} \end{aligned} \tag{23}$$

Using the martingale property, the mean μ of the risk-neutral distribution is computed from a Taylor expansion as follows:

$$\mu(t,T) = e^{r(T-t)} - 1 - e^{r(T-t)}\left(\frac{V(T-t)}{2!} + \frac{W(T-t)}{3!} + \frac{X(T-t)}{4!}\right) \tag{24}$$

Knowing the risk-neutral and realized moments (Amaya, Christoffersen, Jacobs and Vasquez, 2015), we can finally estimate the risk premium moments as the difference between them (Bollerslev, Tauchen and Zhou, 2009).