Title: **Spreading the fear: The central role of CBOE VIX in global stock market uncertainty**

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Abstract: Construction of efficient portfolios is reliant on understanding the correlation between assets. If correlations change markedly during times of economic turmoil then investors are exposed to greater than desired risk levels at the most inopportune time. We examine the linkages between global stock markets using measures of market uncertainty (implied volatility). Using a sample of daily changes in G7 and BRIC implied volatility measures, over a 15-year sample period, we demonstrated that uncertainty in U.S. markets plays a pivotal role in global stock market uncertainty. "Fear is spread" across markets, as heightened uncertainty in U.S. markets is transmitted across global markets. Conversely, global markets do not appear to explain innovations in U.S. market uncertainty. We also report some evidence of market uncertainty linkages between European markets. Our results should provide some reassurance for investors in the sense that inter-dependencies do not appear to change in any meaningful way during the recession / crisis period of 2008-09.

Keywords: Market uncertainty; Investor fear; Implied volatility; VIX; Linkages

JEL Classification: G10, G14, G15

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1. Introduction

The recent past has provided surprise event outcomes such as the Brexit referendum (June 2016) and the U.S. Presidential election (November 2016). Naturally, such results led to higher levels of uncertainty in U.K. and U.S. financial markets. Additionally, measures of market uncertainty appear to have moved in unison across markets (Figure 1). This may be a result of closer economic and financial integration among leading developed countries. We investigate whether this market uncertainty linkage also holds over longer intervals, and whether there is a manifest change during periods of economic turmoil.

Modern portfolio theory relies on understanding the inter-dependency between assets held in the portfolio. If this correlation changes significantly over time, then the riskiness of the portfolio may also change. This is particularly important if correlations increase, and the portfolio becomes riskier, at the most inopportune moment such as during a crisis or in a recessionary environment. It is likely that investors do not fully appreciate the effect of this on portfolio efficiency (Page and Panariello, 2018).

The common perception is that international financial markets have become more integrated over time, and the rationale for this is manifold. In a detailed literature survey, Kearney and Lucey (2004) report that equity market returns have become more correlated, with a level of integration that is primarily determined by real economic linkages. For instance, Baele (2005) identifies trade integration and equity market development as leading contributors to market integration in Europe. Taveres (2009) finds that bilaterly trade intensity increases the correlation of returns and factors such as exchange rate volatility and asymmetry of output growth lower it.

Bekaert et al. (2011) observe that equity market openness with respect to foreign capital flows is the single most important factor in determining integration. Similarly, Lehkonen (2015) notes the importance of financial openness in addition to the institutional environment, creating differences between developed and emerging markets. Investment protection and market liquidity are the most important reasons to invest in developed markets, while economic, political, and technological progress to attract foreign investors is more important for emerging markets. Gagnon and Karolyi (2006) suggest that risk premia are determined by global factors as markets open to foreign investors and manifest in greater comovements in asset prices across markets.

While plenty of explanations exist as to why interdependencies *should* exist, the empirical evidence is not conclusive. At best, integration between financial markets, demonstrated by correlation in returns and/or volatility, appears to fluctuate over time. Eun and Shim (1989) suggest there is substantial interdependence among stock markets. They also emphasise the importance of U.S. markets as innovations in U.S. stock returns are quickly transmitted to global markets while no single foreign market explains U.S. returns. Von Furstenberg and Jeon (1989) and Koutmos and Booth (1995) note that this increased in the period of the 1987 crash. Solnik et al. (1996) show that correlations have generally increased over time, but not in the 10-years immediately prior to 1996. Baele (2005) finds interdependence is more pronounced for regional (EU) markets than for global markets. Page and Panariello (2018) identify convergence in 33 of 42 countries studied, but it is more prominent in some industries, and in stock price volatility rather than stock returns. Forbes and Rigobon (2002) find evidence of a high level of market comovements which they distinguish as interdependence rather than contagion. They argue this is because it is present in all states of the world rather than only jumping following a price shock.

Greater levels of financial market integration, demonstrated by greater correlation and increasing volatility dependence, reduces the benefits of international diversification (Kenourgios, 2014). Chua et al. (2009) document asymmetric changes in correlations for a broad range of international asset classes whereby correlations increase when prices are following and then decline when prices rise. This is exactly opposite to the desirable outcome for investors. In addition to undesirable correlation effects, integration may also create systemic vulnerability to market shocks (Gagnon and Karolyi, 2006).

However, the news is not all bad for investors seeking diversification benefits as there is also empirical evidence to suggest the upward trend in correlation across countries is either limited (in magnitude or geographic spread) or even non-existent. For instance, Bekaert and Harvey (1995) conduct a country-specific investigation and find that it is not always the case that world capital markets have become more integrated. Lehkonen (2015) finds that while integration increased slightly for emerging markets it actually decreased for developed markets during the crisis. Indeed, Bekaert et al. (2009) demonstrate that, with the exception of European markets, there is no evidence of higher return correlations across countries once adequately adjusted for risk. Similarly, Forbes and Rigobon (2002) illustrate that correlation coefficients are conditional on market volatility, and are biased upward. Once an adjustment is made for this bias there is virtually no increase in unconditional correlation during financial crisis.

Rather than focus on the relationship between market returns and realized volatility, we utilize measures of implied volatility based on major stock-market indexes. This is sensible for several reasons. First, implied volatility is a forward-looking measure that reflects expectations on future market volatility, or *market uncertainty*. Second, it contains more market information than either realised volatility or model-based volatility measures (Fleming et al., 1995; Blair et al., 2001). Finally, cross-market volatilities should better reflect market interdependence since they change more quickly than do market returns.

Several other papers have utilised implied volatility measures to study financial market integration and linkage. The importance of U.S. volatility indices (VIX) is emphasised (Nikinen and Sahlström, 2004; Ding et al., 2014; Dutta, 2018) in transmitting market uncertainty globally. Peng and Ng (2012) use a dynamic mixed copula approach to explore the interdependencies between popular equity indices (2 U.S. and 2 European) and corresponding volatility indices. Their positive result is only captured by volatility indices and not stock returns. Other studies find spillover of implied volatility from U.S. to U.K. and European markets (Nikinen and Sahlström, 2004; Jiang et al., 2012; Ding et al., 2014), to China and Brazil (Dutta, 2018), and in the term structure of implied volatility (Äijö, 2008). Jiang et al. (2012) suggest this is at least partly driven by the release of macroeconomic news. In particular, scheduled macroeconomic news resolves uncertainty leading to a decrease in implied volatility, while unscheduled news creates uncertainty and increases implied volatility.

The existing studies are limited either by adoption of limited sample length (Nikinen and Sahlström, 2004; Äijö, 2008), small group of international markets (Ding et al., 2014; Dutta, 2018), or both. Äijö (2008) also uses two indexes (DAX and STOXX) that have many overlapping constituent stocks. We seek to address these issues, utilising a lengthy sample that runs from January 2003 to June 2018, and a range of stock markets that primarily encompasses the G7 leading economies and also a more recent sample of BRICs.

We examine the relationship between implied volatility in G7 and BRICs markets using a Vector Autoregressive (VAR) model of the form suggested by Sims (1980). This allows us to estimate the relationships free from the identification restrictions that Sims (1980) highlights as being "neither essential….nor innocuous" in structural models. As implied volatility is a proxy for financial market uncertainty, we are able to gauge how this uncertainty spreads from one market to another. We expand the existing literature in several ways. First, we utilize a lengthy and updated sample period. Second, we incorporate a range of markets, including Japan, that are known to have exhibited different return and volatility characteristics to that studied previously. Finally, we investigate whether economic state (recession) has an influence on correlation among volatility indices (market uncertainty) and whether *fear is spread* around global markets any differently during recession.

Empirical results demonstrate that U.S. market uncertainty plays an important role in determining global stock market uncertainty. Using a VAR framework and Granger causality tests, we find that innovations in U.S. market uncertainty (VIX) are significantly and positively related to implied volatility in other global markets. However, this relationship is one-way and global markets do not have a significant influence on U.S. uncertainty. The results also provide evidence that innovations in uncertainty of European markets are intertwined. Examination of cross-market correlations and principal component analysis suggests that inter-dependencies of market uncertainty do not change in any significant way during recession / crisis.

Our findings may assist investors and portfolio managers in the planning and implementation of hedging and trading strategies. At a minimum, it should make investors aware of the need to monitor the risk associated with variation in the benefits of diversification. It may also aid regulatory authorities in the design of financial regulation and in determining the appropriate response regarding contagion during economic downturns.

The remainder of this paper proceeds as follows. Section 2 introduces the data and details the empirical methodology used in our study. Section 3 provides analysis and discussion of our main empirical results. Section 4 provides additional empirical tests and section 5 concludes.

2. Data and Methodology

2.1 Data

Our study focuses on the linkage in financial market uncertainty between G7 countries (and to a lesser extent between BRIC countries). From DataStream, we obtain the daily time series for a set of implied volatility measures, a common proxy for market uncertainty, available for the G7 countries[1] of U.S. (*VIX*), Canada (*VIXC*), France (*CACVOLI*), Germany (*VDAXNEW*), Japan (*VXJINDX*), and U.K. (*VFTSEIX*). Additionally, we utilize implied volatility measures for Brazil (*VXEWZVL*), China (*VXFXIVL*), India (*NIFVIXI*), and Russia (*RTSVXVL*). The sample period runs from January 2003 to June 2018, although the BRIC data is available only for a sub-section of that period starting in March 2011.

The most established and well-known of the implied volatility measures is the Chicago Board Options Exchange Volatility Index (CBOE VIX). VIX is computed[2] using the mid-quote prices of a range of call and put options on the S&P500 Index. The calculation produces a measure of constant 30-day expected volatility on the U.S. stock market. VIX is quoted in percentage points and translate, approximately, to the expected movement in the S&P500 Index over the next 30-day period, which is then annualized. For example, if the VIX is 20, the S&P500 is expected to have a range of ±5.77% (20% /√12) in the next 30-days. VIX is frequently referred to as a measure of *investor fear* (Whaley, 2000; Smales, 2014) since the largest constituent of the S&P500 Index option market are buyers of portfolio insurance.

The implied volatility measures for the other countries are calculated in a similar fashion. The measures for Brazil and China differ as they are based on ETFs that are traded in the U.S. even though the underlying stocks are listed in the respective countries. This creates complication in making valid inferences. For instance, it is possible that we find a different interaction effect than would be found using implied volatility derived from options traded in Brazil and China. In particular, we suspect that it is more likely that U.S. centric news and uncertainty will influence the two markets based on ETFs than would otherwise be the case.

Figure 1A illustrates the evolution of G7 implied volatility indices over the sample period. It is clear from the figure that there is some element of synchronisation among markets.

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[1] Data for Italy (FTSE MIB IVI) was not available. This is unfortunate given the political upheaval and financial stress emanating from the European debt crisis during the sample period.

[2] Detailed information as to the computation of VIX can be found in Whaley (2000) and at http://www.cboe.com/micro/vix/vix-index-rules-and-methodology.pdf

All Indices exhibit a sharp spike (and reach their highest levels) during the 2008 crisis, particularly in the immediate aftermath of the failure of Lehman Brothers and AIG (September 2008). This coincides with the stock market correction illustrated in Figure 1B. There are similar, although more muted, spikes in implied volatility during the European sovereign debt crisis. The Japanese index (VXJINDX) experiences a sharp jump in March 2011 resulting from the earthquake and tsunami of that month, and in the middle of 2013 during elections. While all stock markets have increased since 2009 there is wide variation in performance.

<Insert Figure 1>

Descriptive statistics are provided in Table 1. The level of implied volatility (market uncertainty) is higher on average in the BRIC countries, with Russia having the highest mean implied volatility of 37.60, and Canada the lowest at 17.57. The mean daily change in implied volatility is negative for all G7 countries and two of the BRICs, only Brazil and Russia have witnessed generally increasing market uncertainty levels over the sample period. The standard deviation of changes is lower in the BRIC countries but this may be explained by the sample starting after the financial crisis of 2008. Canada (Germany) has the most (least) volatile index. All implied volatility measures exhibit a high degree of kurtosis ("fat-tails").

<Insert Table 1>

The different trading hours and time zones among the different exchanges means that the closing prices are non-synchronous. Table 1 shows the open and closing times in coordinated universal time (UTC). This is a particular issue for Japan (and India) where there is no overlap of trading with North American markets. We attempt to tackle this by re-aligning the times series for those two countries by one-day. Whilst we must be careful in ignoring the difficulties of non-synchronous trading between Europe and North America we are more comfortable with this since the vast majority of important macroeconomic news is released during hours when both regions are trading. In addition, North American earnings announcements typically arrive before the market open (when Europe is open) or after the market close (when Europe is also closed) and so will be reflected in next day market movements on all exchanges.

<Insert Table 2>

Table 2, Panel A shows that the implied volatility measures of G7 countries are significantly correlated over the 2003 – 2018 sample period, with higher correlations for countries on the same continent (e.g. U.S. and Canada or France, German, and U.K.). This makes sense given the higher degree of economic linkages between such countries, and is also reflected in the correlation between stock market returns. There is no clear picture as to the effect of recession (Panel B) on the average correlation, with some correlations sharply increasing (e.g. U.S./Japan rises from 0.322 to 0.495), some falling (e.g. Germany/France falls from 0.828 to 0.672) and others unchanged (e.g. U.S./U.K.). Average correlation across all relationships increased slightly (not statistically significant on basis of equality test) from 0.439 to 0.467 during the recession period. Again, this is reflected in the correlation of stock market returns where the average correlation increases from 0.590 to 0.633.

It is possible that jumps in correlation are only short-lived and that an 18-month period is too long to discover this. We therefore repeat the analysis (Panel C) with a shorter crisis period of 6-months immediately following the collapse of Lehman Brothers on 15th September 2008. Again, there is some changes in correlation, but the average correlation is unchanged (and lower than that in Panel B). Forbes and Rigobon (2002) suggest that correlations are biased upward when volatility increases during such periods, so even this slight increase may be an over-estimation of the actual change in correlation. Interestingly, the correlation of realized 30-day volatility (standard deviation of returns) is much higher in general (0.844) and increases more dramatically during recession (0.946) or shorter crisis periods (0.945).

Panel D introduces BRICs countries and shows the correlation over the March 2011 – June 2018 sample period. Average correlation for G7 countries is virtually unchanged in this period (0.470). Correlation for BRICs countries is lower on average than that of G7 markets (also evident in Figure 2), particularly for Indian and Russian[3] stocks, suggesting that they may have a valuable role to play in well-diversified portfolios. The high correlation found for VIX with Brazil and Chinese markets (0.635 & 0.610 respectively) may be due to the computation of VXEWZVL and VXFXIVL measures using U.S. traded ETFs. The fact that VXEWZVL and VXFXIVL are based on U.S. ETFs limits our ability to make inferences as to the relationship between uncertainty in U.S. and Brazilian / Chinese markets.

[3] We omit Russian stocks from much of the VAR analysis in this study owing to gaps in the available data.

<Insert Figure 2>

Figure 2 illustrates the variation in correlation over time. Panel A shows that pairwise correlation (on a rolling 1-year basis) for G7 countries varies between 0.30 and 0.60 over the whole sample period while averaging 0.44 with little discernible trend. Panel B shows pairwise correlation among G7 and BRIC countries and demonstrates a clear downtrend over the period 2012 – 2018. There is also greater variation among BRICs ranging from a high of 0.53 in March 2012 to a low of 0.08 in May 2015.

2.2 Methodology

We use a relatively straight-forward[4] vector autoregressive (VAR) model to study the inter-relationships between implied volatility indices. Essentially, VAR estimates a dynamic simultaneous equation system, free of a priori structural restrictions. The only information required is a set of variables that are assumed to be intertemporally related. This choice is supported by the strong cross-market correlation identified in Table 2. The VAR model is specified:

$$\Delta IV_t = C + \sum_{j=1}^{K} A_j \Delta IV_{t-j} + \varepsilon_t \qquad (1)$$

Where ΔIV_t is a vector of first-differenced volatility indices, C and A_j are matrices for coefficients to be estimated with lag length K, and $\boldsymbol{\varepsilon}_t$ is the error term. Standard errors are based on Monte Carlo simulation given the presence of heteroskedasticity determined using the White (1980) test. Lag length is based on Akaike's information criterion (AIC) and Schwarz's criterion (SC). In our tables, we report the estimated coefficients for the first two lags only.

3. Empirical Results

3.1 G7 Markets

We start our empirical analysis by considering the inter-relationship between G7 volatility indices over our 15-year sample period (3,880 observations). Table 3 reports the estimated coefficients for a VAR model of the type specified in Eq.1. There are four salient

[4] Recent studies have utilised dynamic mixed copula (Peng and Ng, 2012), multivariate AR-GJR-GARCH-A-DCC (Kenourgious, 2014), and ARDL (Dutta, 2018) approaches. We prefer to utilise a more parsimonious approach that provides minimum but sufficient information to answer our research question.

points to note. First, each of the volatility indices has a statistically significant and negative own first-difference dynamics with positive changes in the lagged period associated with negative returns in the current period. Second, and perhaps most importantly, U.S. market uncertainty (denoted by VIX) has a well-defined positive relationship with all of the other markets for at least two lagged intervals. This is our first indication of the important role that VIX plays in determining implied volatility globally. This is further illustrated by the impulse response functions depicted in Figure 3, which also demonstrate that the information is quickly transmitted – majority within 1-day and all within 2-days. Third, VDAXEW has a significant positive relationship with other European markets (CACVOLI and VFTSEIX) which is consistent with the leading role that the German economy plays in Europe. Finally, VIXC has a significant but delayed influence on European markets.

<Insert Table 3>

<Insert Figure 3>

Variance decomposition allows us to understand the proportion of information each implied volatility index contributes in explaining changes in the other indices. Table 4 shows the output relating to the VAR specification for the whole sample period. The importance of U.S. market uncertainty is again emphasised. While innovations in VIX play a significant role in explaining variation in other volatility indices (ranging from 19% in Japan to 32% in France) none of the other markets contribute any information to VIX (none exceed 0.1%). This is consistent with the results of Eun and Shim (1989) regarding the influence of U.S. stock market returns. Information sharing between European markets is also present once more. For example, ΔVFTSEIX variance is partially explained by changes in U.S. (VIX), French (CACVOLI), and German (VDAXNEW) market uncertainty.

<Insert Table 4>

3.2 State Dependence

We examine whether the identified relationships are state dependent by considering a sub-sample of data focused on the NBER-defined U.S. recession that runs from December 2007 to June 2009 (377 observations). This period coincides with the financial crisis and incorporates the collapse of Lehman Brothers and bailout of AIG among others. Table 2 demonstrated that there was little difference in the correlations between implied volatility measures during this period. Table 5 reports the estimated coefficients for our VAR specification. The importance of VIX is still present and there is minimal difference in the magnitude (or statistical significance) of the estimated VIX coefficients. The own first-difference dynamics are also still present, but for several of the volatility indices this is less persistent, enduring for one period rather than a minimum of two. Lower persistence makes sense in an environment where news that influences market uncertainty arrives more regularly. There is also a significant positive (negative) relationship between VDAXNEW (VFTSEIX) and other volatility measures. This suggests that inter-relationships were more important during the recession period.

<Insert Table 5>

This is evaluated further using the variance decomposition shown in Table 6. In general, the other volatility indices explain a greater proportion of variation during recession. For example, over 53% of VIXC variation is explained by other indices (primarily VIX) during the recession as opposed to around 25% in the overall period. Similarly, the proportion of VXJINDX variation explained by VIX and VDAXNEW increases. Consistent with the significant relationships identified in Table 5, the proportion of variation explained by VDAXNEW and VFTSEIX in all other volatility indices has increased (by many multiples in some cases). This could be explained by the important role that Germany plays in the European economy, and the pivotal role that London plays in international finance. Even though correlations between the indices are not changing significantly (Table 2) there is clearly an increase in the proportion of variance explained by other markets. This suggests there may be greater linkages between G7 markets during recession that are not captured by correlation.

<Insert Table 6>

3.3 BRICs

Next, we investigate whether market uncertainty in BRICs plays any role in determining uncertainty elsewhere in the world. In addition to the existing Indian NIFVIXI, we are able to utilize the implied volatility measures introduced by CBOE in 2011 that are based on Brazilian and Chinese ETFs. As already mentioned, it is difficult to draw valid insights into the relationship between prevailing uncertainty in U.S. and Brazil / China but it does allow us to draw some initial insights as to the relative importance of BRICs market uncertainty in a global context. The estimated coefficients for the VAR specification using a sample period from March 2011 to June 2018 is shown in Table 7.

<Insert Table 7>

Again, we see significant negative own dynamics. Innovations in U.S. market uncertainty (VIX) continues to have a significant positive relationship with all of the other indices, and this includes BRICs. The estimated coefficient for the Indian market (NIFVIXI) is statistically significant in several cases, including for the relationship with VIX. Table 8 suggests that Indian and Japanese markets each explain around 4% of variance in ΔVIX – a much higher proportion than other volatility indices. The estimated coefficients for Brazilian (VXEWZVL) and Chinese (VXFXIVL) implied volatility also have significant and positive relationships with other indices, particularly those outside of North America.

Once again, we interpret this with caution given the underlying ETFs are traded in the U.S. rather than Brazil or China, and we have already demonstrated the importance of U.S. market uncertainty in a global context. Therefore, we are reluctant to assume that this result signifies that uncertainty in Brazilian and Chinese financial markets play a meaningful role in global uncertainty. This conclusion is supported by the variance decomposition shown in Table 8 whereby VXEWZVL and VXFXIVL explain less than 0.5% of variance in any other volatility measure (other than each other). Table 8 also demonstrates the continued influence of ΔVIX in explaining variation in the other measures (22% of variance on average) and the inter-relationship between European markets.

<Insert Table 8>

4. Additional Tests

4.1 Causality

The tests so far provide evidence as to the importance of innovations in U.S. market uncertainty in determining changes in global uncertainty, and additionally to inter-dependences between European markets. We provide further evidence using Granger (1969) causality tests. Table 9, Panel A shows the results of pair-wise tests while Panel B shows VAR/Block test results. The null hypothesis for each point in the table reads as "*y*-variable does not cause *x*-variable". For instance, the null hypothesis for 112.135 reported in the top-right is "ΔVIX does not cause ΔFTSEIX" – in this case, the null is clearly rejected.

<Insert Table 9>

The pair-wise tests support our earlier results; rejecting the null hypothesis that ΔVIX does not cause innovations in other markets and failing to reject the null that other markets do not cause changes in VIX. That is, the relationship of ΔVIX with other implied volatility measures is uni-directional. There is supporting evidence for the inter-relationship between European markets as bi-directional Granger causality is found, and this extends to the Canadian market (ΔVIXC) too. Finally, we identify bi-directional causality running from Japan to all markets (with the exception of U.S. which has a uni-directional relationship). Intuitively this makes sense given the time-zone that Japan trades in and the size of the Japanese stock market[5]. VAR/Block causality tests (Panel B) also demonstrate uni-directional causality from U.S. to other global markets, and between European markets. No causality to/from Japan is evidenced in this specification.

4.2 Principal Component Analysis

Earlier, we provided evidence to suggest that the linkage between market uncertainty measures was not affected by economic recession. An alternative way of exploring this issue is to adopt the methodology of Von Furstenberg and Jeon (1989). They use a principal component analysis to study the inter-relationship between daily stock returns in Frankfurt, London, New York, and Tokyo. They find that the explanatory power of the first principal component rose from 34% to 55% following the market crash of 1987.

<Insert Table 10>

Table 10 provides principal component analysis for the implied volatility measures (Panel A) and associated stock index returns (Panel B) in our study. For the G7 implied volatility measures we note that the explanatory power of the first principal component is 55.1% in the overall sample period, and the cumulative power of the first two components is 71.9%. As one might expect, the cumulative proportion for the initial two components in the combined G7 + BRICs setting is lower (61.0%). One might expect this given a wider range of potential influences on developing markets.

[5] With a market capitalisation of $5.7 billion the Tokyo Stock Exchange is the third largest stock exchange at the end of June 2018.

Importantly, for G7 implied volatility, the comparative numbers for the recession period are 54.6% and 72.9%, and 55.1% and 73.2% for the shorter crisis period. That is, in contrast to the results of Von Furstenberg and Jeon (1989), there is very little difference (there is a slight decline) in the explanatory power of principal components during the 2008-09 recession / crisis period. Noting that the explanatory power of the first two principal components are higher for stock index returns than for implied volatility, we find that the change in cumulative proportion is also minor during recession. Together, this suggests that there is little difference in the linkages between market uncertainty measures during recession / crisis.

5. Conclusion

Construction of efficient portfolios is reliant on understanding the correlation between assets. Diversification benefits arising from the inclusion of international stocks relies on relatively low levels of correlation between global stock markets. If correlations change markedly during times of economic turmoil then investors are exposed to greater than desired risk levels at the most inopportune time. We examine the linkages between global stock markets using measures of market uncertainty (implied volatility).

Our empirical results show that U.S. market uncertainty plays a pivotal role in global stock market uncertainty. Heightened uncertainty in U.S. markets is transmitted across global markets, and we provide the specific example of employment news where such "fear is spread". Conversely, global markets do not appear to explain innovations in U.S. market uncertainty. We also find that there is some evidence of market uncertainty linkages between European markets that are closely integrated economically and politically. We provide some reassurance for investors, and regulators, in the sense that linkages do not appear to change in any meaningful way during the recession period of 2008-09.

Further work in this area could examine the transmission process of a wide range of macroeconomic news items. For instance, the U.S. employment report is often cited as an important influence on global markets. In addition, the availability of a range of news sentiment measures may be utilised to understand how a broader set of news is reflected in market uncertainty and diffused across global markets.

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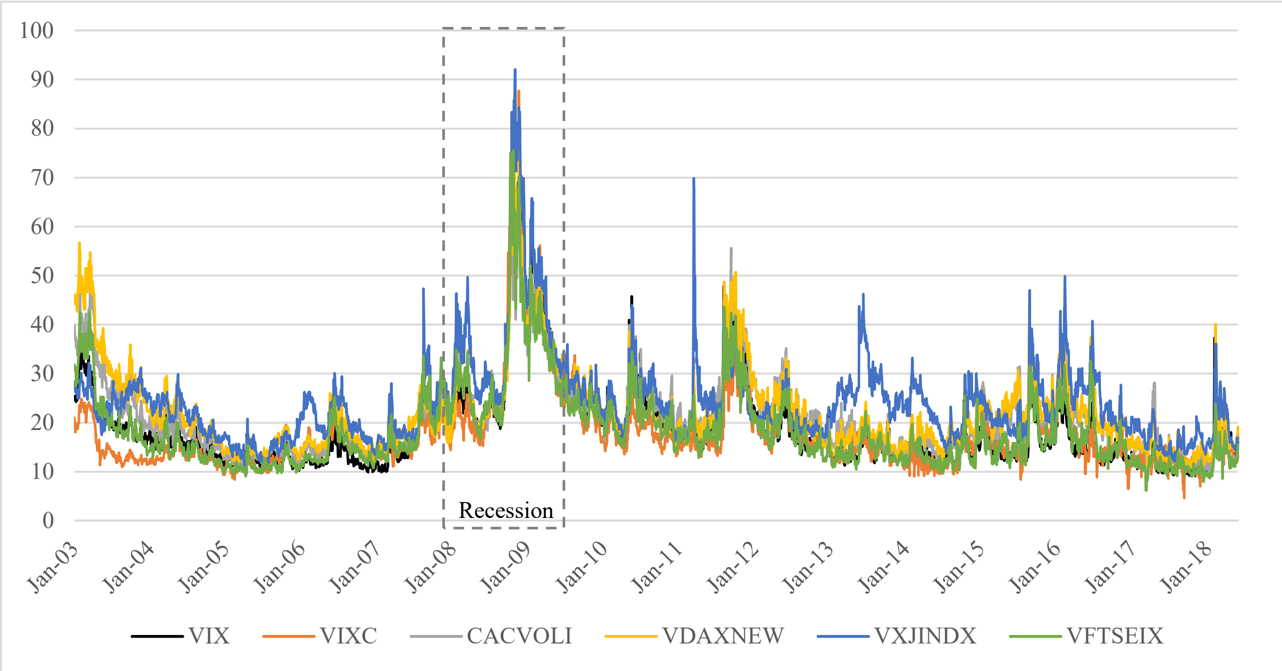

Figure 1A. G7 Volatility Indices (2003 - 2018)

Note: This figure depicts the stock market volatility indices for members of the G7. US (*VIX*), Canada (*VIXC*), France (*CACVOLI*), Germany (*VDAXNEW*), Japan (*VXJINDX*), and UK (*VFTSEIX*).

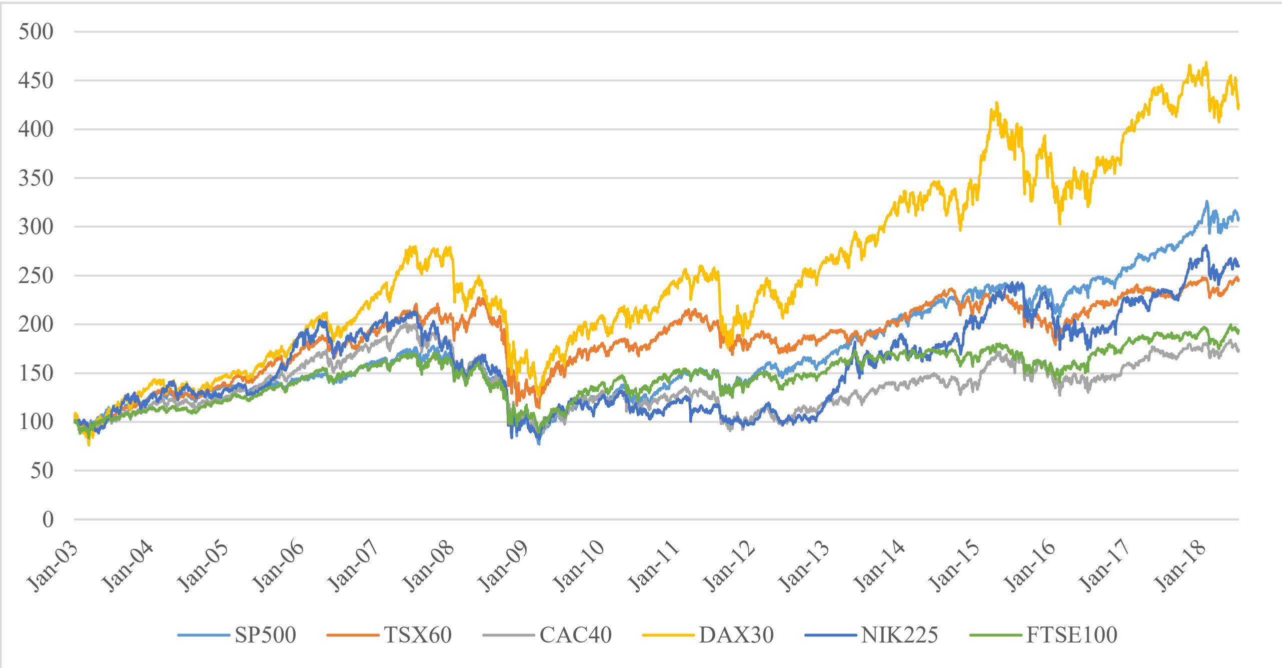

Figure 1B. G7 Stock Market Performance (2003 - 2018)

Note: This figure depicts the performance of stock market indices underlying volatility indices for G7 members. US (*SP500*), Canada (*TSX60*), France (*CAC40*), Germany (*DAX30*), Japan (*NIK225*), and UK (*FTSE100*).

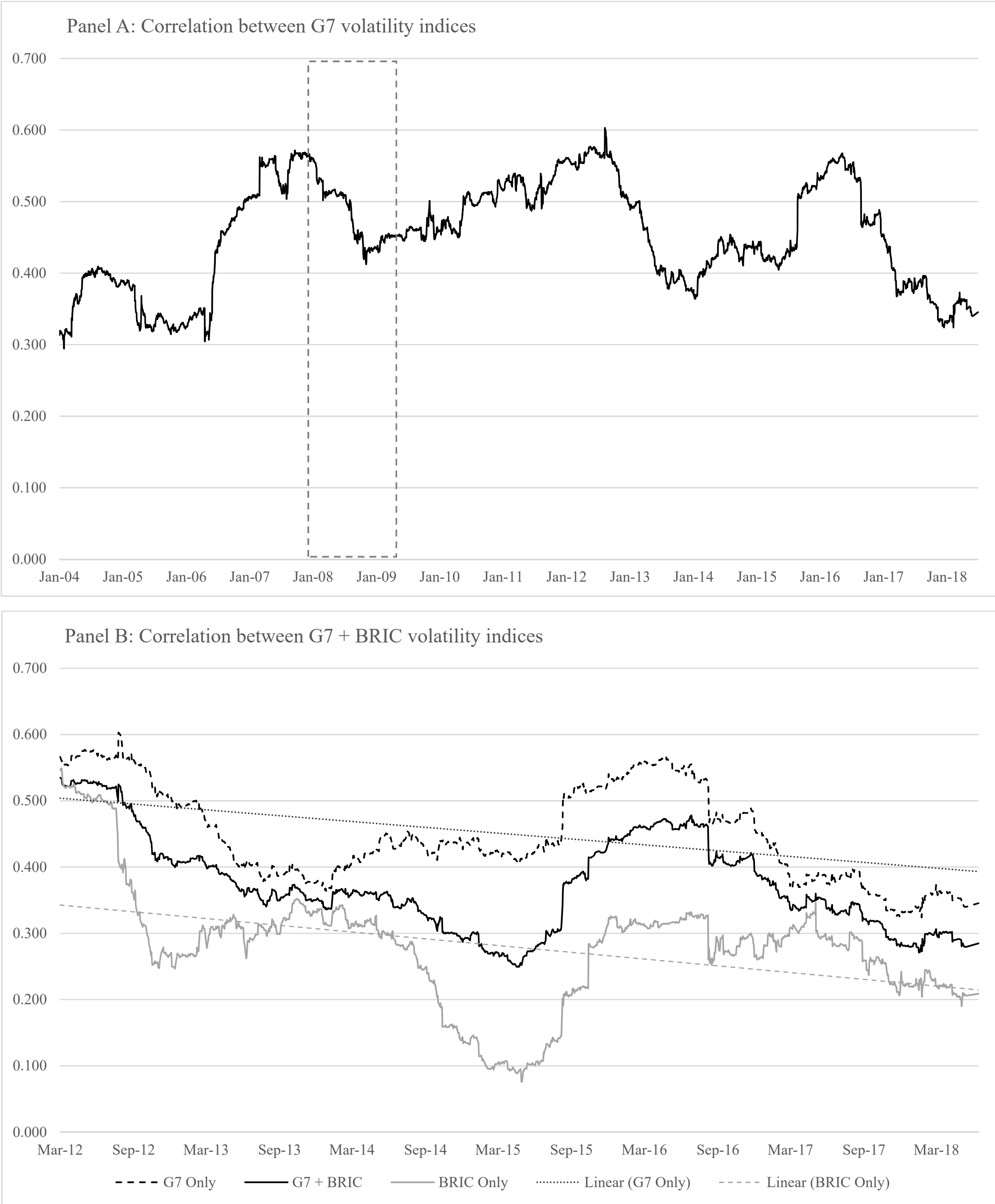

Figure 2. Correlation between G7 and BRIC volatility indices (2012 - 2018)

Note: This figure depicts the 1-year (252 trading day) moving average of the correlation between volatility indices. The correlation is computed as the average of pairwise correlations.

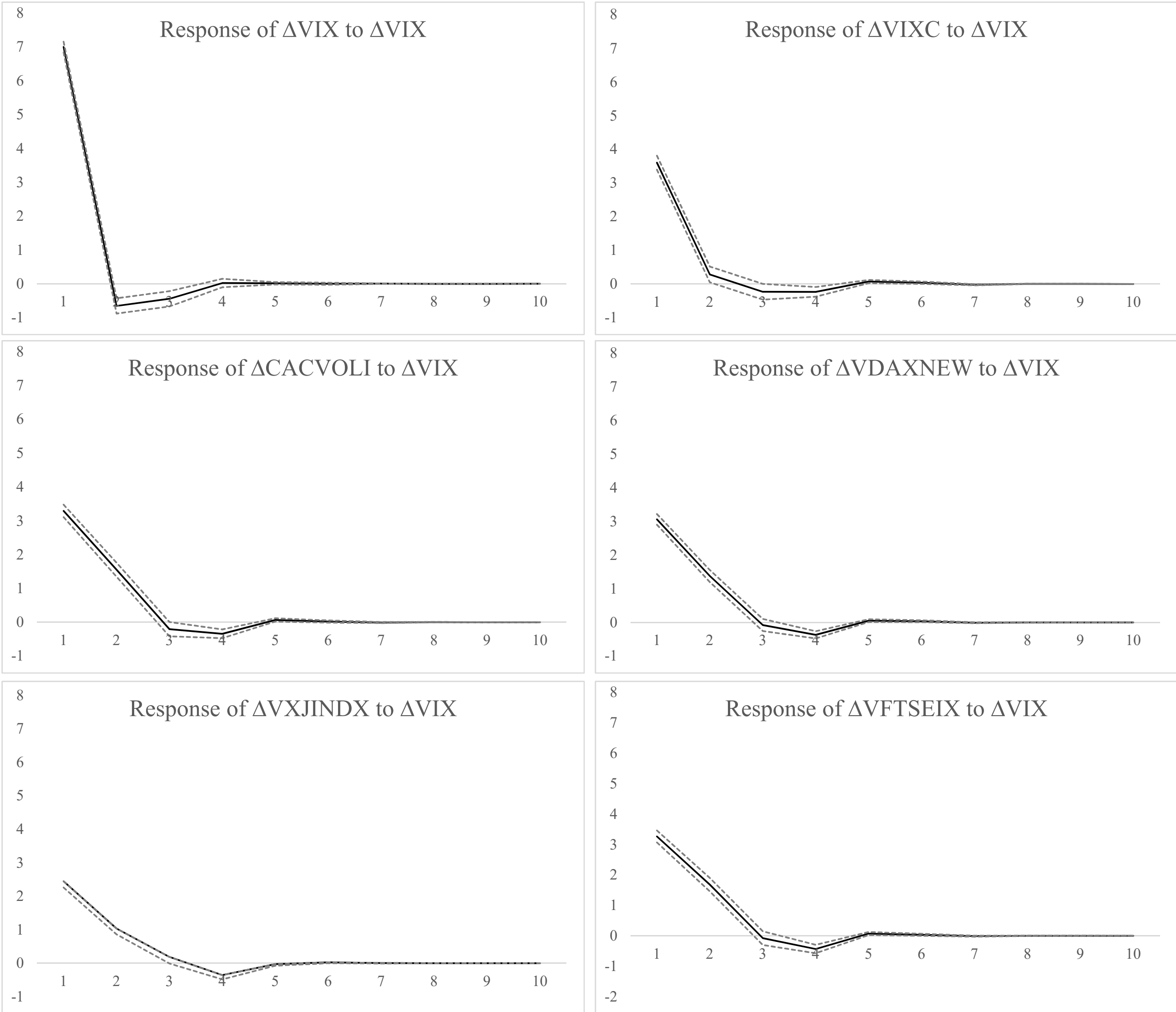

Figure 3. G7 Volatility Indices Impulse Response Function

Note: This figure depicts the impulse response of G7 volatility indices resulting from changes in VIX (ΔVIX) computed using the VAR model specified in Eq. (**1**). The response is to Cholesky 1 std.dev. Innovations ± 2 std. err. Sample period: January 2003 - June 2018.

Table 1
Descriptive Statistics

	USA	*CANADA*	*FRANCE*	*GERMANY*	*JAPAN*	*UK*	*BRAZIL*	*CHINA*	*INDIA*	*RUSSIA*
	VIX	VIXC	CACVOLI	VDAXNEW	VXJINDX	VFTSEIX	VXEWZVL	VXFXIVL	NIFVIXI	RTSVXVL
Underlying	S&P 500	S&P/TSX 60	CAC 40	DAX 30	Nikkei 225	FTSE 100	MSCI Brazil ETF	FTSE China 25 ETF	Nifty 50	MOEX
Trading Hours (UTC)	14:30 - 21:00	14:30 - 21:00	08:00 - 16:30	07:00 - 19:00	00:00 - 06:00	08:00 - 16:30	14:30 - 21:00	14:30 - 21:00	03:45 - 10:00	07:00 - 15:45
Level										
Mean	18.71	17.57	21.66	22.45	24.17	18.37	32.81	26.07	21.91	37.60
Standard Deviation	8.77	8.02	8.39	8.98	9.20	8.24	8.78	7.09	9.84	20.89
Min	9.1	4.0	9.2	11.0	11.2	6.2	16.7	15.1	10.5	15.4
Max	80.9	87.7	78.1	83.2	92.0	75.5	72.8	63.4	85.1	200.5
Change (Δ)										
Mean	-0.013	-0.009	-0.022	-0.025	-0.015	-0.021	0.003	-0.023	-0.039	0.003
Standard Deviation	7.04	7.31	6.59	5.68	6.05	6.99	5.02	5.15	5.82	6.53
Min	-35.1	-60.7	-50.5	-37.0	-32.7	-48.7	-62.0	-20.3	-47.0	-29.9
Max	76.8	63.6	53.9	41.1	55.2	44.8	32.4	36.6	49.7	91.2
Skewness	1.0	0.3	0.4	0.5	1.4	0.2	-0.4	0.9	0.4	1.8
Kurtosis	10.5	11.9	8.0	6.8	12.0	7.1	18.9	7.2	14.1	21.8
Sample Start	Jan-03	Jan-03	Jan-03	Jan-03	Jan-03	Jan-03	Mar-11	Mar-11	Mar-08	Jan-06
No. Observations	3882	3882	3882	3882	3882	3882	1815	1815	2581	2753

Note : This table presents summary data for the implied volatility indices used in this study. This includes volatility for six of the G7 countries (USA, Canada, France, Germany, Japan, UK) and the four BRICs (Brazil, Russia, India, China).
Sample Period: January 2003 - June 2018

Table 2

Correlation Analysis

Panel A: G7 (Jan'03 - Jun '18)

Implied Volatility	ΔVIX	ΔVIXC	ΔCACVOLI	ΔVDAXNEW	ΔVXJINDX
ΔVIXC	**0.530**				
ΔCACVOLI	**0.452**	**0.359**			
ΔVDAXNEW	**0.489**	**0.387**	**0.828**		
ΔVXJINDX	**0.322**	**0.213**	**0.222**	**0.242**	
ΔVFTSEIX	**0.438**	**0.371**	**0.748**	**0.769**	**0.220**
		Average: 0.439			

Stock Returns	SP500	TSX60	CAC40	DAX30	NIK225
TSX60	**0.730**				
CAC40	**0.587**	**0.544**			
DAX30	**0.605**	**0.522**	**0.916**		
NIK225	**0.509**	**0.396**	**0.401**	**0.405**	
FTSE100	**0.562**	**0.562**	**0.891**	**0.831**	**0.388**
		Average: 0.590			

Realized Volatility	σ_{SP500}	σ_{TSX60}	σ_{CAC40}	σ_{DAX30}	σ_{NIK225}
σ_{TSX60}	**0.930**				
σ_{CAC40}	**0.888**	**0.827**			
σ_{DAX30}	**0.857**	**0.790**	**0.953**		
σ_{NIK225}	**0.758**	**0.759**	**0.731**	**0.707**	
$\sigma_{FTSE100}$	**0.930**	**0.885**	**0.952**	**0.908**	**0.781**
			Average: 0.844		

Panel B: G7 Recession (Dec '07 - Jun '09)

Implied Volatility	ΔVIX	ΔVIXC	ΔCACVOLI	ΔVDAXNEW	ΔVXJINDX
ΔVIXC	**0.681**				
ΔCACVOLI	**0.349**	**0.339**			
ΔVDAXNEW	**0.460**	**0.439**	**0.672**		
ΔVXJINDX	**0.495**	**0.403**	**0.271**	**0.320**	
ΔVFTSEIX	**0.452**	**0.439**	**0.611**	**0.799**	**0.279**
		Average: 0.467			

Stock Returns	SP500	TSX60	CAC40	DAX30	NIK225
TSX60	**0.747**				
CAC40	**0.572**	**0.582**			
DAX30	**0.628**	**0.564**	**0.918**		
NIK225	**0.621**	**0.450**	**0.473**	**0.512**	
FTSE100	**0.547**	**0.588**	**0.945**	**0.876**	**0.472**
		Average: 0.633			

Realized Volatility	σ_{SP500}	σ_{TSX60}	σ_{CAC40}	σ_{DAX30}	σ_{NIK225}
σ_{TSX60}	**0.975**				
σ_{CAC40}	**0.951**	**0.957**			
σ_{DAX30}	**0.944**	**0.947**	**0.973**		
σ_{NIK225}	**0.904**	**0.902**	**0.934**	**0.943**	
$\sigma_{FTSE100}$	**0.946**	**0.935**	**0.988**	**0.951**	**0.936**
			Average: 0.946		

Panel C: G7 Crisis (15 Sep '08 - 15 Mar '09)

Implied Volatility	ΔVIX	ΔVIXC	ΔCACVOLI	ΔVDAXNEW	ΔVXJINDX
ΔVIXC	**0.742**				
ΔCACVOLI	**0.425**	**0.381**			
ΔVDAXNEW	**0.505**	**0.407**	**0.600**		
ΔVXJINDX	**0.554**	**0.432**	**0.294**	**0.235**	
ΔVFTSEIX	**0.474**	**0.378**	**0.512**	**0.667**	**0.213**
		Average: 0.455			

Stock Returns	SP500	TSX60	CAC40	DAX30	NIK225
TSX60	**0.745**				
CAC40	**0.575**	**0.562**			
DAX30	**0.657**	**0.547**	**0.904**		
NIK225	**0.640**	**0.435**	**0.460**	**0.526**	
FTSE100	**0.556**	**0.578**	**0.951**	**0.878**	**0.476**
		Average: 0.633			

Realized Volatility	σ_{SP500}	σ_{TSX60}	σ_{CAC40}	σ_{DAX30}	σ_{NIK225}
σ_{TSX60}	**0.980**				
σ_{CAC40}	**0.970**	**0.956**			
σ_{DAX30}	**0.967**	**0.935**	**0.948**		
σ_{NIK225}	**0.924**	**0.917**	**0.914**	**0.945**	
$\sigma_{FTSE100}$	**0.953**	**0.935**	**0.989**	**0.924**	**0.914**
			Average: 0.945		

Panel D: G7 + BRICs (Mar' 11 - Jun '18)

Implied Volatility	ΔVIX	ΔVIXC	ΔCACVOLI	ΔVDAXNEW	ΔVXJINDX	ΔVFTSEIX	ΔVXEWZVL	ΔVXFXIVL	ΔNIFVIXI
ΔVIXC	**0.548**								
ΔCACVOLI	**0.504**	**0.390**							
ΔVDAXNEW	**0.520**	**0.405**	**0.883**						
ΔVXJINDX	**0.349**	**0.180**	**0.261**	**0.272**					
ΔVFTSEIX	**0.489**	**0.378**	**0.804**	**0.812**	**0.249**				
ΔVXEWZVL	**0.635**	**0.465**	**0.472**	**0.485**	**0.241**	**0.486**			
ΔVXFXIVL	**0.610**	**0.450**	**0.457**	**0.488**	**0.257**	**0.456**	**0.654**		
ΔNIFVIXI	**0.138**	*0.064*	0.042	*0.059*	**0.240**	*0.054*	**0.138**	**0.087**	
ΔRTSVXVL	**0.268**	**0.279**	**0.347**	**0.369**	**0.090**	**0.354**	**0.305**	**0.278**	-0.009
				Average (all): 0.362 Average (G7): 0.470					

Note : This table presents Spearman Rank-Order correlation for the daily change in implied volatility indices, in addition to stock returns and realized volatility of the associated underlying stock indices. This includes six members of the G7 (US - *VIX* , Canada - *VIXC* , France - *CACVOLI* , German - *VDAXNEW* , Japan - *VXJINDX* , UK - *VFTSEIX*) and the four BRICs nations (Brazil - *VXEWZVL* , China - *VXFXIVL* , India - *NIFVIXI* , Russia - *RTSVXVL*). The daily changes are aligned to account for different time zones and exchange hours. Panel A shows the correlation matrix for G7 members only and covers the whole sample period from Jan 2003 - Jun 2018. Panel B shows the correlation matrix for G7 members during the recession of Dec 2007 - June 2009. Panel C shows the correlation G7 correlation matrix in the 6-month crisis period starting with the failure of Lehman Brothers on 15 September 2008. Panel D shows the correlation matrix for G7 and BRIC countries over the period following introduction of implied volatility indices in BRICs (Mar 2011 - Jun 2018). Realized volatility is the rolling 30-day standard deviation of daily log returns. **Bold** font indicates significant at the 1% level and *italic* font indicates significant at 5% level.

Table 3
VAR: Inter-relationship between G7 volatility indices

	ΔVIX		ΔVIXC		ΔCACVOLI		ΔVDAXNEW		ΔVXJINDX		ΔVFTSEIX	
Constant	-0.013		-0.012		-0.022		-0.023		-0.007		-0.018	
	(0.112)		(0.112)		(0.099)		(0.087)		(0.087)		(0.105)	
ΔVIX(-1)	-0.192	***	0.215	***	0.252	***	0.204	***	0.082	***	0.255	***
	(0.021)		(0.021)		(0.019)		(0.016)		(0.016)		(0.020)	
ΔVIX(-2)	-0.108	***	0.073	***	0.078	***	0.081	***	0.030	***	0.104	***
	(0.023)		(0.022)		(0.020)		(0.017)		(0.017)		(0.021)	
ΔVIXC(-1)	0.028		-0.366	***	0.022		0.021		0.015		0.060	***
	(0.019)		(0.019)		(0.017)		(0.015)		(0.015)		(0.018)	
ΔVIXC(-2)	0.021		-0.133	***	0.039	**	0.033	**	0.008		0.043	**
	(0.019)		(0.019)		(0.017)		(0.015)		(0.015)		(0.018)	
ΔCACVOLI(-1)	-0.035		-0.039		-0.361	***	0.016		0.029		-0.012	
	(0.033)		(0.033)		(0.029)		(0.026)		(0.026)		(0.031)	
ΔCACVOLI(-2)	-0.034		-0.017		-0.170	***	-0.034		-0.028		-0.050	
	(0.033)		(0.033)		(0.029)		(0.025)		(0.026)		(0.031)	
ΔVDAXNEW(-1)	0.045		0.074	*	0.080	**	-0.180	***	0.043		0.068	**
	(0.041)		(0.041)		(0.036)		(0.032)		(0.038)		(0.032)	
ΔVDAXNEW(-2)	0.017		0.076	*	0.065	*	-0.055	*	0.061		0.028	
	(0.041)		(0.040)		(0.036)		(0.031)		(0.038)		(0.031)	
ΔVXJINDX(-1)	0.003		-0.008		-0.009		-0.020		-0.197	***	-0.012	
	(0.021)		(0.021)		(0.019)		(0.017)		(0.017)		(0.020)	
ΔVXJINDX(-2)	0.052	*	-0.024		0.003		-0.003		-0.059	***	0.001	
	(0.022)		(0.020)		(0.018)		(0.015)		(0.015)		(0.019)	
ΔVFTSEIX(-1)	0.004		0.003		0.021		-0.056	***	0.027		-0.322	***
	(0.027)		(0.027)		(0.024)		(0.021)		(0.021)		(0.025)	
ΔVFTSEIX(-2)	0.030		-0.089	***	-0.017		-0.032		0.027		-0.132	***
	(0.027)		(0.027)		(0.024)		(0.021)		(0.021)		(0.025)	
Adj. R^2	0.048		0.108		0.166		0.157		0.009		0.174	
F-Statistic	17.313		40.253		65.601		61.015		41.095		69.315	
Log-Likelihood	-13047		-13020		-12572		-12041		-12053		-12785	
Akiaike AIC	6.692		6.704		6.428		6.142		6.431		6.536	
No. Observations	3880		3880		3880		3880		3880		3880	

Note: This table reports the estimated coefficients for the VAR model specified in Eq. (1). The endogenous variables are the daily changes in volatility indices for the US (*VIX*), Canada (*VIXC*), France (*CACVOLI*), Germany (*VDAXNEW*), Japan (*VXJINDX*), and UK (*VFTSEIX*). Lag selection is on the basis of AIC and SC with only the first two lags reported. Standard errors are reported in parentheses. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level respectively.
Sample Period: January 2003 - June 2018

Table 4
Variance decomposition for G7 volatility indices

Period	S.E.	ΔVIX	ΔVIXC	ΔCACVOLI	ΔVDAXNEW	ΔVXJINDX	ΔVFTSEIX
Δ*VIX*							
1	6.997	100.000	0.000	0.000	0.000	0.000	0.000
2	7.031	99.902	0.058	0.001	0.037	0.001	0.000
3	7.049	99.776	0.063	0.003	0.039	0.096	0.023
4	7.051	99.743	0.072	0.003	0.045	0.104	0.033
5	7.051	99.743	0.072	0.004	0.045	0.104	0.033
Δ*VIXC*							
1	6.948	26.896	73.104	0.000	0.000	0.000	0.000
2	7.284	24.620	75.282	0.004	0.091	0.003	0.000
3	7.302	24.599	74.911	0.067	0.095	0.037	0.291
4	7.318	24.596	74.763	0.084	0.095	0.040	0.423
5	7.319	24.596	74.760	0.084	0.095	0.040	0.425
Δ*CACVOLI*							
1	6.190	28.289	0.888	70.822	0.000	0.000	0.000
2	6.575	30.658	0.789	68.371	0.161	0.004	0.017
3	6.588	30.641	0.857	68.266	0.169	0.005	0.063
4	6.605	30.751	0.876	68.099	0.179	0.022	0.073
5	6.605	30.755	0.875	68.095	0.179	0.022	0.073
Δ*VDAXNEW*							
1	5.398	32.202	0.846	37.192	29.761	0.000	0.000
2	5.659	35.231	0.769	35.456	28.335	0.045	0.164
3	5.670	35.115	0.810	35.634	28.231	0.046	0.163
4	5.686	35.333	0.818	35.528	28.082	0.056	0.183
5	5.686	35.336	0.819	35.523	28.081	0.056	0.186
Δ*VXJINDX*							
1	6.020	18.818	0.040	2.363	1.034	77.746	0.000
2	6.041	19.328	0.086	2.151	0.882	77.520	0.033
3	6.050	19.372	0.094	2.255	0.892	77.349	0.039
4	6.060	19.647	0.094	2.250	0.892	77.075	0.043
5	6.060	19.647	0.096	2.252	0.892	77.070	0.043
Δ*VFTSEIX*							
1	6.540	24.899	1.318	27.635	6.445	0.138	39.566
2	6.973	27.699	1.194	26.526	6.021	0.161	38.399
3	6.979	27.666	1.196	26.567	6.041	0.161	38.369
4	7.000	27.888	1.202	26.496	6.006	0.173	38.236
5	7.001	27.892	1.202	26.495	6.006	0.173	38.232

Note: This table reports the variance decomposition for the VAR model specified in Eq. (1). The variables are the daily changes in volatility indices for the US (*VIX*), Canada (*VIXC*), France (*CACVOLI*), Germany (*VDAXNEW*), Japan (*VXJINDX*), and UK (*VFTSEIX*).
Sample Period: January 2003 - June 2018

Table 5

VAR: Inter-relationship between G7 volatility indices during 2007-09 recession

	ΔVIX		ΔVIXC		ΔCACVOLI		ΔVDAXNEW		ΔVXJINDX		ΔVFTSEIX	
Constant	0.054		0.149		0.070		0.128		0.065		-0.026	
	(0.363)		(0.420)		(0.383)		(0.290)		(0.295)		(0.335)	
ΔVIX(-1)	-0.259	***	0.122	**	0.361	***	0.345	***	0.384	***	0.239	***
	(0.081)		(0.064)		(0.085)		(0.065)		(0.066)		(0.074)	
ΔVIX(-2)	-0.169	***	0.105	*	0.291	***	0.156	***	0.144	***	0.185	***
	(0.085)		(0.060)		(0.089)		(0.068)		(0.069)		(0.078)	
ΔVIXC(-1)	0.073		-0.316	***	0.065		0.055		0.067		0.115	*
	(0.065)		(0.076)		(0.069)		(0.052)		(0.053)		(0.060)	
ΔVIXC(-2)	0.106		-0.117		-0.005		0.049		-0.015		0.099	*
	(0.065)		(0.076)		(0.069)		(0.052)		(0.053)		(0.060)	
ΔCACVOLI(-1)	-0.079		-0.094		-0.489	***	-0.007		-0.008		-0.107	
	(0.064)		(0.075)		(0.068)		(0.052)		(0.052)		(0.059)	
ΔCACVOLI(-2)	-0.097		-0.108		-0.250	***	-0.075		-0.151	***	-0.081	
	(0.065)		(0.075)		(0.068)		(0.052)		(0.053)		(0.060)	
ΔVDAXNEW(-1)	0.257	**	0.150		0.308	***	0.052		0.165	**	0.409	***
	(0.109)		(0.126)		(0.115)		(0.087)		(0.089)		(0.101)	
ΔVDAXNEW(-2)	-0.100		-0.040		0.044		-0.058		0.089		0.007	
	(0.107)		(0.124)		(0.113)		(0.086)		(0.087)		(0.099)	
ΔVXJINDX(-1)	-0.026		-0.042		0.013		-0.065		-0.323	***	-0.080	
	(0.068)		(0.079)		(0.072)		(0.055)		(0.056)		(0.063)	
ΔVXJINDX(-2)	-0.022		-0.072		0.055		-0.024		-0.073		0.045	
	(0.063)		(0.073)		(0.067)		(0.050)		(0.051)		(0.058)	
ΔVFTSEIX(-1)	-0.174	**	-0.072		-0.159	*	-0.250	***	-0.028		-0.561	***
	(0.080)		(0.093)		(0.085)		(0.064)		(0.065)		(0.074)	
ΔVFTSEIX(-2)	0.073		-0.009		-0.115		0.034		0.065		-0.134	*
	(0.082)		(0.095)		(0.087)		(0.066)		(0.067)		(0.076)	
Adj. R^2	0.063		0.062		0.189		0.153		0.293		184.000	
F-Statistic	3.100		3.058		8.298		6.654		13.958		8.069	
Log-Likelihood	-1264		-1320		-1285		-1180		-1186		-1234	
Akiaike AIC	6.775		7.070		6.884		6.327		6.361		6.614	
No. Observations	377		377		377		377		377		377	

Note: This table reports the estimated coefficients for the VAR model specified in Eq. (1) for the 2007-09 recession period only. The endogenous variables are the daily changes in volatility indices for the US (*VIX*), Canada (*VIXC*), France (*CACVOLI*), Germany (*VDAXNEW*), Japan (*VXJINDX*), and UK (*VFTSEIX*). Lag selection is on the basis of AIC and SC with only the first two lags reported. Standard errors are reported in parentheses.

***, **, and * indicate statistical significance at the 1%, 5%, and 10% level respectively.

Sample Period: December 2007 - June 2009

Table 6
Variance decomposition for G7 volatility indices during 2007 - 09 recession

Period	S.E.	ΔVIX	ΔVIXC	ΔCACVOLI	ΔVDAXNEW	ΔVXJINDX	ΔVFTSEIX
ΔVIX							
1	7.042	100.000	0.000	0.000	0.000	0.000	0.000
2	7.265	97.871	0.234	0.150	0.554	0.050	1.142
3	7.370	95.900	0.353	0.514	1.133	0.053	2.046
4	7.385	95.546	0.515	0.691	1.152	0.057	2.039
5	7.389	95.460	0.520	0.690	1.150	0.065	2.114
ΔVIXC							
1	8.157	53.669	46.331	0.000	0.000	0.000	0.000
2	8.460	51.753	47.592	0.268	0.168	0.076	0.144
3	8.511	51.476	47.077	0.638	0.477	0.185	0.146
4	8.549	51.279	46.808	0.955	0.477	0.235	0.247
5	8.553	51.297	46.781	0.956	0.476	0.236	0.255
ΔCACVOLI							
1	7.434	21.596	0.450	77.955	0.000	0.000	0.000
2	8.202	22.276	0.409	75.557	1.007	0.003	0.747
3	8.241	22.068	0.515	75.195	1.200	0.025	0.996
4	8.375	22.941	0.619	73.376	1.170	0.124	1.770
5	8.379	22.925	0.627	73.372	1.172	0.127	1.777
ΔVDAXNEW							
1	5.629	36.103	0.781	17.798	45.318	0.000	0.000
2	6.110	40.817	0.696	15.717	39.027	0.391	3.352
3	6.147	40.324	0.745	16.137	38.561	0.389	3.844
4	6.212	41.443	0.730	15.812	37.781	0.427	3.807
5	6.213	41.436	0.732	15.815	37.775	0.437	3.807
ΔVXJINDX							
1	5.723	25.055	0.711	2.007	5.498	66.729	0.000
2	6.753	25.045	0.677	1.443	3.985	68.816	0.035
3	6.852	24.923	0.717	3.065	4.386	66.853	0.055
4	6.902	25.177	0.817	3.200	4.835	65.883	0.088
5	6.907	25.144	0.820	3.209	4.852	65.790	0.186
ΔVFTSEIX							
1	6.497	29.290	1.284	9.584	12.443	0.055	47.344
2	7.173	27.354	1.271	9.513	10.254	0.554	51.054
3	7.217	27.297	1.290	9.520	10.483	0.881	50.528
4	7.303	28.229	1.275	9.342	10.250	1.092	49.811
5	7.306	28.206	1.274	9.364	10.245	1.105	49.806

Note: This table reports the variance decomposition for the VAR model specified in Eq. (1), and apply to the sample period covering the NBER-defined recession. The variables are the daily changes in volatility indices for the US (*VIX*), Canada (*VIXC*), France (*CACVOLI*), Germany (*VDAXNEW*), Japan (*VXJINDX*), and UK (*VFTSEIX*).
Sample Period: December 2007 - June 2009

Table 7
VAR: Inter-relationship between G7 and BRIC volatility indices

	ΔVIX	ΔVIXC	ΔCACVOLI	ΔVDAXNEW	ΔVXJINDX	ΔVFTSEIX	ΔVXEWZVL	ΔVXFXIVL	ΔNIFVIXI
Constant	-0.033	-0.014	-0.022	-0.019	-0.065	-0.022	0.008	-0.016	-0.041
	(0.182)	(0.192)	(0.155)	(0.137)	(0.126)	(0.174)	(0.117)	(0.120)	(0.113)
ΔVIX(-1)	-0.107***	0.202***	0.322***	0.254***	0.267**	0.356***	0.085***	0.047**	0.158***
	(0.035)	(0.037)	(0.030)	(0.027)	(0.024)	(0.034)	(0.023)	(0.023)	(0.022)
ΔVIX(-2)	-0.052	0.067*	0.051	0.052*	0.097***	0.072**	0.068***	0.036	-0.012
	(0.038)	(0.040)	(0.032)	(0.028)	(0.026)	(0.036)	(0.024)	(0.025)	(0.023)
ΔVIXC(-1)	0.033	-0.416***	0.014	0.017	-0.014	0.070***	0.000	0.005	-0.014
	(0.025)	(0.026)	(0.021)	(0.019)	(0.017)	(0.024)	(0.016)	(0.016)	(0.015)
ΔVIXC(-2)	0.029	-0.147***	0.039*	0.032*	0.001	0.049**	-0.005	-0.014	-0.010
	(0.025)	(0.026)	(0.021)	(0.019)	(0.017)	(0.024)	(0.016)	(0.016)	(0.016)
ΔCACVOLI(-1)	-0.057	-0.079	-0.320***	0.049	0.021	0.028	0.010	-0.073*	-0.040
	(0.057)	(0.060)	(0.048)	(0.043)	(0.039)	(0.054)	(0.037)	(0.038)	(0.035)
ΔCACVOLI(-2)	-0.072	-0.060	-0.181***	-0.052	0.021	-0.096*	-0.073**	-0.082*	-0.091*
	(0.057)	(0.060)	(0.048)	(0.042)	(0.039)	(0.054)	(0.036)	(0.037)	(0.051)
ΔVDAXNEW(-1)	0.037	0.122*	0.033	-0.216***	0.080*	-0.021	-0.036	0.019	0.021
	(0.068)	(0.072)	(0.058)	(0.051)	(0.047)	(0.065)	(0.044)	(0.045)	(0.042)
ΔVDAXNEW(-2)	0.103	0.158**	0.088	-0.028	-0.002	0.052	0.027	0.005	0.067
	(0.067)	(0.071)	(0.057)	(0.050)	(0.046)	(0.064)	(0.043)	(0.044)	(0.042)
ΔVXJINDX(-1)	0.036	0.017	0.016	-0.008	-0.262***	0.024	0.013	0.032	-0.037*
	(0.036)	(0.038)	(0.030)	(0.027)	(0.025)	(0.034)	(0.023)	(0.024)	(0.022)
ΔVXJINDX(-2)	-0.062**	-0.009	-0.008	-0.022	-0.054**	-0.024	-0.015	-0.029	-0.005
	(0.033)	(0.035)	(0.028)	(0.025)	(0.023)	(0.031)	(0.021)	(0.022)	(0.020)
ΔVFTSEIX(-1)	0.018	-0.014***	0.019	-0.044	0.008	-0.319***	0.003	0.036	-0.021
	(0.039)	(0.041)	(0.033)	(0.029)	(0.027)	(0.037)	(0.025)	(0.026)	(0.024)
ΔVFTSEIX(-2)	-0.007	-0.166***	-0.050	-0.074**	-0.013	-0.155***	0.002	0.051	-0.007
	(0.039)	(0.041)	(0.033)	(0.029)	(0.027)	(0.037)	(0.025)	(0.026)	(0.024)
ΔVXEWZVL(-1)	0.017	0.183	0.156***	0.090**	0.055*	0.163***	-0.074**	0.042	0.112***
	(0.048)	(0.051)	(0.041)	(0.036)	(0.034)	(0.046)	(0.031)	(0.032)	(0.030)
ΔVXEWZVL(-2)	0.062	0.061	0.060	0.148***	0.002	0.088*	0.058*	0.041	0.057*
	(0.049)	(0.051)	(0.041)	(0.037)	(0.033)	(0.046)	(0.031)	(0.032)	(0.030)
ΔVXFXIVL(-1)	0.064	-0.049	0.007	0.005	0.153***	0.018	-0.006	-0.109***	0.078**
	(0.053)	(0.056)	(0.045)	(0.040)	(0.037)	(0.050)	(0.034)	(0.035)	(0.033)
ΔVXFXIVL(-2)	-0.060	0.042	0.000	0.029	0.064*	0.057	-0.053	-0.034	-0.023
	(0.053)	(0.056)	(0.045)	(0.040)	(0.036)	(0.050)	(0.034)	(0.035)	(0.033)
ΔNIFVIXI(-1)	-0.089**	0.048	-0.078**	-0.099***	-0.002	-0.119***	-0.052**	-0.013	-0.056**
	(0.041)	(0.043)	(0.035)	(0.031)	(0.028)	(0.039)	(0.026)	(0.027)	(0.025)
ΔNIFVIXI(-2)	-0.054	0.016	0.020	0.020	-0.021	-0.018	-0.012	-0.015	-0.048*
	(0.041)	(0.043)	(0.035)	(0.030)	(0.028)	(0.039)	(0.026)	(0.027)	(0.025)
Adj. R^2	0.009	0.136	0.120	0.109	0.244	0.151	0.012	0.007	0.077
F-Statistic	1.888	16.862	14.763	13.339	33.402	18.894	2.182	1.708	9.365
Log-Likelihood	-6274	-6368	-5981	-5753	-5600	-6186	-5475	-5523	-5411
Akiaike AIC	6.946	7.050	6.623	6.371	6.202	6.849	6.064	6.118	5.993
No. Observations	1810	1810	1810	1810	1810	1810	1810	1810	1810

Note: This table reports the estimated coefficients for the VAR model specified in Eq. (1). The endogenous variables are the daily changes in volatility indices for the US (*VIX*), Canada (*VIXC*), France (*CACVOLI*), Germany (*VDAXNEW*), Japan (*VXJINDX*), UK (*VFTSEIX*), Brazil (*VXEWZVL*), China (*VXFXIVL*), and India (*NIFVIXI*). Lag selection is on the basis of AIC and SC with only the first two lags reported. Standard errors are reported in parentheses.
***, **, and * indicate statistical significance at the 1%, 5%, and 10% level respectively.
Sample Period: March 2011 - June 2018

Table 8

Variance decomposition for G7 and BRIC volatility indices

Period	S.E.	ΔVIX	ΔVIXC	ΔCACVOLI	ΔVDAXNEW	ΔVXJINDX	ΔVFTSEIX	ΔVXEWZVL	ΔVXFXIVL	ΔNIFVIXI
Δ*VIX*										
1	7.428	100.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	7.773	91.677	0.106	0.006	0.056	3.961	0.011	0.010	0.004	4.169
3	7.798	91.178	0.108	0.011	0.088	3.946	0.027	0.047	0.141	4.455
Δ*VIXC*										
1	8.051	18.092	81.908	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	8.745	15.619	81.014	0.005	0.165	0.622	0.001	0.542	0.068	1.964
3	8.791	15.454	80.186	0.110	0.164	0.718	0.700	0.536	0.151	1.981
Δ*CACVOLI*										
1	6.229	24.620	0.803	74.577	0.000	0.000	0.000	0.000	0.000	0.000
2	6.982	26.029	0.640	63.880	0.040	4.092	0.020	0.077	0.018	5.204
3	7.028	25.714	0.788	63.193	0.103	4.112	0.110	0.736	0.028	5.216
Δ*VDAXNEW*										
1	5.469	25.937	0.812	46.225	27.027	0.000	0.000	0.000	0.000	0.000
2	6.114	27.649	0.656	38.113	22.806	5.295	0.101	0.254	0.034	5.093
3	6.163	27.214	0.717	38.018	22.450	5.214	0.163	0.965	0.100	5.159
Δ*VXJINDX*										
1	6.046	20.648	0.000	0.759	0.223	78.370	0.000	0.000	0.000	0.000
2	6.167	20.487	0.016	0.786	0.247	76.552	0.002	0.289	0.091	1.530
3	6.179	20.422	0.026	0.875	0.286	76.235	0.002	0.360	0.170	1.624
Δ*VFTSEIX*										
1	6.990	18.795	1.108	30.255	5.602	0.007	44.233	0.000	0.000	0.000
2	7.954	22.415	1.012	25.233	4.809	4.617	37.563	0.146	0.018	4.187
3	8.009	22.152	0.999	25.245	4.804	4.603	37.095	0.735	0.105	4.260
Δ*VXEWZVL*										
1	4.843	30.161	0.392	1.639	0.370	0.066	0.274	67.099	0.000	0.000
2	5.015	28.637	0.369	1.586	0.403	2.018	0.256	63.007	0.035	3.688
3	5.038	28.557	0.380	1.852	0.439	2.007	0.257	62.548	0.136	3.824
Δ*VXFXIVL*										
1	4.761	39.683	0.442	1.289	0.646	0.653	0.083	5.542	51.661	0.000
2	5.141	34.064	0.380	1.285	0.583	7.321	0.159	4.753	45.308	6.148
3	5.155	34.029	0.443	1.361	0.581	7.320	0.255	4.778	45.081	6.152
Δ*NIFVIXI*										
1	4.981	6.085	0.039	0.098	0.009	4.808	0.019	0.519	0.174	88.250
2	5.010	6.019	0.350	0.226	0.130	4.756	0.031	0.749	0.489	87.251
3	5.039	5.950	0.476	0.292	0.204	4.702	0.094	0.742	1.020	86.520

Note: This table reports the variance decomposition for the VAR model specified in Eq. (1). The variables are the daily changes in volatility indices for the US (*VIX*), Canada (*VIXC*), France (*CACVOLI*), Germany (*VDAXNEW*), Japan (*VXJINDX*), UK (*VFTSEIX*), Brazil (*VXEWZVL*), China (*VXFXIVL*), and India (*NIFVIXI*).

Sample Period: March 2011 - June 2018

Table 9

Granger causality test results

Panel A: Pair-wise	ΔVIX	ΔVIXC	ΔCACVOLI	ΔVDAXNEW	ΔVXJINDX	ΔVFTSEIX
Δ*VIX*		33.397 ***	104.380 ***	86.268 ***	31.523 ***	112.135 ***
		(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Δ*VIXC*	1.653		21.536 ***	16.454 ***	2.612 **	29.666 ***
	(0.143)		(0.000)	(0.000)	(0.023)	(0.000)
Δ*CACVOLI*	0.977	8.617 ***		6.230 ***	3.851 ***	10.512 ***
	(0.430)	(0.000)		(0.000)	(0.002)	(0.000)
Δ*VDAXNEW*	1.348	12.054 ***	13.925 ***		2.913 **	14.513 ***
	(0.241)	(0.000)	(0.000)		(0.013)	(0.000)
Δ*VXJINDX*	0.755	28.014 ***	93.137 ***	99.390 ***		101.068 ***
	(0.390)	(0.000)	(0.000)	(0.000)		(0.000)
Δ*VFTSEIX*	1.415	9.727 ***	10.128 ***	3.318 ***	3.300 ***	
	(0.216)	(0.000)	(0.000)	(0.005)	(0.006)	

Panel B: VAR / Block	ΔVIX	ΔVIXC	ΔCACVOLI	ΔVDAXNEW	ΔVXJINDX	ΔVFTSEIX
Δ*VIX*		29.502 ***	114.563 ***	91.088 ***	120.863 ***	111.261 ***
		(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Δ*VIXC*	2.274		3.448	3.020	0.753	9.826 ***
	(0.321)		(0.178)	(0.221)	(0.686)	(0.007)
Δ*CACVOLI*	2.012	2.114		4.176	0.431	4.502
	(0.366)	(0.348)		(0.124)	(0.806)	(0.105)
Δ*VDAXNEW*	2.380	2.432	6.551 **		3.044	0.923
	(0.304)	(0.296)	(0.038)		(0.218)	(0.630)
Δ*VXJINDX*	5.631 *	0.338	0.450	0.823		1.390
	(0.060)	(0.845)	(0.798)	(0.663)		(0.499)
Δ*VFTSEIX*	0.301	3.318	17.023 ***	7.223 **	0.411	
	(0.860)	(0.190)	(0.000)	(0.027)	(0.814)	
Total	22.535	138.153 ***	251.934 ***	231.864 ***	589.756 ***	312.999 ***
	(0.127)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)

Note: This table presents test results for Granger causality tests. Panel A presents *F* -statistics for pairwise causality between variables, with *p* -values in parentheses. Panel B presents results for VAR Granger causality / block exogeneity Wald Tests of causality between variables, where the values in parentheses are *p* -values for Wald tests with a χ^2 distribution. The variables are implied volatility indices for the US (*VIX*), Canada (*VIXC*), France (*CACVOLI*), Germany (*VDAXNEW*), Japan (*VXJINDX*), and UK (*VFTSEIX*). Lag selection is on the basis of AIC.

***, **, and * indicate statistical significance at the 1%, 5%, and 10% level respectively.

Table 10

Principal Component Analysis

Panel A: Implied Volatility	G7 (*All: Jan '03 - June '18*)			G7 (*Recession: Dec '07 - Jun '09*)			G7 (*Crisis: Sep '08 - Mar '09*)			G7 + BRICs (*Mar '11 - Jun '18*)		
N	Eigen Value	Proportion	Cumulative Proportion	Eigen Value	Proportion	Cumulative Proportion	Eigen Value	Proportion	Cumulative Proportion	Eigen Value	Proportion	Cumulative Proportion
1	3.305	0.551	0.551	3.275	0.546	0.546	3.309	0.551	0.551	4.235	0.471	0.471
2	1.010	0.168	0.719	1.098	0.183	0.729	1.087	0.181	0.732	1.258	0.140	0.610
3	0.777	0.130	0.849	0.651	0.109	0.837	0.594	0.099	0.831	0.945	0.105	0.715
4	0.453	0.076	0.924	0.444	0.074	0.911	0.475	0.079	0.910	0.744	0.083	0.798
5	0.285	0.048	0.972	0.275	0.046	0.957	0.315	0.053	0.962	0.665	0.074	0.872
6	0.170	0.028	1.000	0.258	0.043	1.000	0.223	0.037	1.000	0.422	0.047	0.919
7										0.324	0.036	0.955
8										0.274	0.031	0.985
9										0.132	0.015	1.000

Panel B: Stock Returns	G7 (*All: Jan '03 - June '18*)			G7 (*Recession: Dec '07 - Jun '09*)			G7 (*Crisis: Sep '08 - Mar '09*)		
N	Eigen Value	Proportion	Cumulative Proportion	Eigen Value	Proportion	Cumulative Proportion	Eigen Value	Proportion	Cumulative Proportion
1	4.008	0.668	0.668	4.200	0.700	0.700	4.201	0.700	0.700
2	0.871	0.145	0.813	0.856	0.143	0.843	0.853	0.142	0.843
3	0.626	0.104	0.918	0.559	0.093	0.936	0.572	0.095	0.938
4	0.270	0.045	0.962	0.234	0.039	0.975	0.232	0.039	0.977
5	0.156	0.026	0.988	0.104	0.017	0.992	0.095	0.016	0.993
6	0.070	0.012	1.000	0.046	0.008	1.000	0.045	0.008	1.000

Note: This table reports principal component analysis for the daily changes in implied volatility and stock market indices for the US (*VIX*), Canada (*VIXC*), France (*CACVOLI*), Germany (*VDAXNEW*), Japan (*VXJINDX*), UK (*VFTSEIX*), Brazil (*VXEWZVL*), China (*VXFXIVL*), and India (*NIFVIXI*).

Sample Period: January 2003 - June 2018