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

Author: Smales, L.A., UWA Business School, University of Western Australia, Perth, Australia

Initial Version: 10-March-2019

This Version: 29-March-2021

Abstract: 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 20-year sample period, we demonstrate 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. While there is a clear increase in inter-dependence during crisis periods, we observe a disparity in the way that inter-dependencies change during the two major economic crises in our sample period; the GFC (2007-2009) and COVID-pandemic (2020).   the additional importance of US news largely drives the result during the GFC, while the effect is more widespread (particularly within European markets) during COVID.

Keywords: Market uncertainty; Implied volatility; VIX; Linkages; COVID

JEL Classification: G10, G14, G15

1. Introduction

In addition to the global COVID pandemic, 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 financial markets. Additionally, measures of market uncertainty appear to have moved in unison across G7 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 bilateral 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 2001 to December 2020, incorporating the COVID-pandemic, and a range of stock markets that primarily encompasses the G7 leading economies and also a more recent sample of BRICS countries.

We examine the relationship between implied volatility 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 (crisis / recession) has an influence on correlation among volatility indices (market uncertainty) and whether *fear is spread* around global markets any differently during crisis periods. Our sample period incorporates two major economic crises – the global financial crisis of 2007-09 and the COVID pandemic of 2020.

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. We observe a disparity in the way that inter-dependencies change during the two major economic crises in our sample period; the GFC (2007-2009) and COVID-pandemic (2020). In both cases, there is evidence of greater inter-dependency between G7 markets. However, the additional importance of US news largely drives the result during the GFC, while the effect is more widespread (particularly within European markets) during COVID.

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 introduces additional tests using the sample of BRICS countries 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 BRICS 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*), Italy (*IVIMIB*), Japan (*VXJINDX*), and U.K. (*VFTSEIX*). Additionally, we utilize implied volatility measures for Brazil (*VXEWZVL*), China (*VXFXIVL*), India (*NIFVIXI*), Russia (*RTSVXVL*), and South Africa (*JSAIVI*). The sample period runs from January 2001 to December 2020, 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.

[1] Data is only available from October 2010 – December 2019 for *VIXC*, and from April 2010 – December 2020 for *IVIMIB*. As a result, both implied volatility measures are absent from our primary analysis.

[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

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. All Indices exhibit a sharp spike (and reach their highest levels) during the global financial crisis (GFC) of 2008-09, particularly in the immediate aftermath of the failure of Lehman Brothers and AIG (September 2008), and the start of the COVID pandemic in 2020. This coincides with the major stock market corrections illustrated in Figure 1B. VIX peaked at 82.69 on 16th March 2020 and established 5 of the Top 10 values during that week. This compares to a peak of 80.86 during the GFC. 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 average of implied volatility (market uncertainty) is highest in Italy. This is consistent with the political upheaval, and dramatic COVID-related impact, observed in Italy during our sample period. In contrast, the level of implied volatility is lowest in Canada although this excludes the COVID period (UK and USA have the next lowest). The mean daily change in implied volatility is negative for all G7 countries aside from Italy. The standard deviation of changes is lowest (highest) in Germany (Canada). All implied volatility measures exhibit a high degree of kurtosis ("fat-tails"). The level of implied volatility (market uncertainty) is higher on average in the BRIC countries, with Russia having the highest mean implied volatility of 37.6.

<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 2001 – 2020 sample period, with higher correlations between European countries (e.g. the average correlation for France, German, Italy and U.K. is 0.62). This makes sense given the higher degree of economic linkages between such countries, and is also reflected in the correlation between stock market returns.

We disaggregate the data to study the effect of recession and financial crisis on correlations. First, we consider all periods that fall within a NBER-defined recession. This relates to U.S. recessions but we note that it also coincides with global economic slowdowns. This indicates three periods of recession; the dot-com crash related slowdown (April 2001 – November 2001), the global financial crisis (January 2008 – June 2009), and the COVID pandemic (March 2020 – December 2020). Although some correlations are relatively unchanged (e.g. U.S./Japan goes from 0.402 to 0.401), several correlations increase sharply (e.g. Germany/Italy rises from 0.62 to 0.75), and the average correlation increased from 0.395 to 0.507. The magnitude of the increase is reflected in realized volatility (0.807 to 0.893) but less so in stock returns (0.604 to 0.643).

We disaggregate the data further so as to gain an understanding of the two major economic crises occurring during our sample period – one a financial-led crisis (GFC) and the other a health-led crisis (COVID). This time, we designate the crisis periods using the TED spread which is a commonly used indicator of credit (or liquidity) risk. The crisis period is indicated by a TED spread of 0.65 (this is equal to the spread high prior to crisis) or greater for 2 consecutive days. This indicates the GFC period as 15 May 2007 – 15 May 2009 and COVID crisis as 17 March 2020 – 27 April 2020. 17th March 2020 coincides with the E.U. barring most travellers and the imposition of lockdowns in South America. We also repeat our analysis with the NBER-defined recession indicators for each period and observe qualitatively similar results.

The results for the GFC period (Panel C) are similar to that for all recession periods (Panel B). However, the results for the COVID-pandemic suggest that all correlations were higher (with the exception of Japan) and the average rose to 0.600 (from 0.395 for the whole sample). The average among European countries rises to 0.826. The sharper impact on correlations during COVID may relate to a) the magnitude of the economic impact being greater than during the GFC, and b) the effect was simultaneous across countries rather than spread over a longer period as credit conditions deteriorated in one market and then another.

<Insert Figure 2>

Figure 2 illustrates the variation in correlation over time. 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 0.45 with little discernible trend. Again, correlation is shown to increase during periods of economic instability.

2.2 Methodology

We use a relatively straight-forward[3] 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 $\%\Delta IV_t$ is a vector of daily percentage-changed 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 1-2 lags only.

[3] 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.

3. Empirical Results

3.1 G7 Markets

We start our empirical analysis by considering the inter-relationship between G7 volatility indices over our 20-year sample period (4,998 observations). Table 3 reports the estimated coefficients for a VAR model of the type specified in Eq.1. There are three salient 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. Finally, 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. Owing to their shorter sample period, VIXC and IVIMIB are not included in this analysis. Instead, after incorporating the two additional indices, we repeat the analysis and report the qualitatively similar results in Appendix A.

<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 16% in France to 34% in Germany) 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[4].

<Insert Table 4>

3.2 State Dependence – Economic Crisis

We examine whether the identified relationships are state dependent by considering sub-samples of data focused on the GFC (17 May 2007 – 17 May 2009) and COVID (17 March 2020 – 30 December 2020) crises[5]. The GFC period has 500 observations while the COVID period as 201. Table 2 demonstrated that there was an increase in the correlations between implied volatility measures during crisis periods, particularly in the case of COVID.

Table 5 reports the estimated coefficients for our VAR specification, with the GFC period in Panel A and the COVID period in Panel B. The importance of VIX for other markets is present in both sub-periods and the magnitude of the coefficients has increased (the average was 0.19 in the overall sample, and rises to 0.43 and 0.38 in the GFC and COVID periods respectively). The own first-difference dynamics are also still present, but the magnitude is greater (the average rising to 0.36 during GFC and 0.47 during COVID as opposed to 0.23 overall), and the effect is less persistent in enduring for one period rather than two or more. Lower persistence makes sense in an environment where news that influences market uncertainty arrives more regularly.

<Insert Table 5>

This is evaluated further using the variance decomposition shown in Table 6. Here we find a clear difference between the two sub-periods. During the GFC, VIX explains at least 5% more of the variation in three of the indices and 3% in the other. No notable increases are found for any other measure. In contrast, during COVID, the influence of VIX increase for just 1 index (CACVOLI), while the variance share attributable to European indices increases for three countries. This could be explained by COVID-related news in Europe having global

[4] Qualitatively similar results are shown in Appendix B and C for variance decomposition after the inclusion of *VIXC* and *IVIMIB*.

[5] We obtain qualitatively similar results using the NBER-defined recessionary periods running from January 2008 – June 2009 and March 2020 – December 2020.

implications as the virus spread, while the GFC-related events of global importance were primarily US-centric.

<Insert Table 6>

3.3 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 some inter-dependences between European markets. We provide further evidence using Granger (1969) causality tests. Table 7, 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 92.86 reported in the top-right is "%ΔVIX does not cause %ΔFTSEIX" – in this case, the null is clearly rejected.

<Insert Table 7>

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 more supporting evidence for the inter-relationship between European markets as bi-directional Granger causality is found. VAR/Block causality tests (Panel B) also demonstrate uni-directional causality from U.S. to other global markets, and between European markets.

3.4 Principal Component Analysis

Earlier, we provided evidence to suggest that the linkage between market uncertainty measures was impacted by economic crisis. 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 8>

Table 8 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 56.8% in the overall sample period, and the cumulative power of the first two components is 74.4%. When VIXC and IVIMIB are added to the sample (last 3 columns), the cumulative proportion for the initial two components is lower (63.8%) which one might expect given a wider range of potential influences on additional markets.

For implied volatility (Panel A), the comparative numbers increase during both the GFC and COVID. This is largely attributable to an additional 5% applying to the first principal component. The change is in the same direction, but of a smaller magnitude, for stock returns (Panel B). Both results are consistent with those of Von Furstenberg and Jeon (1989) in that the explanatory power of principal components increases during periods of economic crisis.

4. Additional Tests - BRICS

Having focused on the developed markets of the G7, we complete our empirical analysis by investigating whether similar relationships exist in emerging BRICS markets. In particular, we are interested in whether US market uncertainty also influences BRICS markets, and whether BRICS play any role in determining uncertainty elsewhere in the world.

In addition to the Indian (NIFVIXI), and South African (JSAIVI), indices we are able to utilize the implied volatility measures introduced by CBOE in 2011 that are based on Brazilian (VXEWZVL) and Chinese (VXFXIVL) ETFs. We do not include Russian (RTSVXVL) implied volatility as its availability ends early in the sample period. As already mentioned, it is potentially 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 December 2019 (when VIXC ends) is shown in Table 9.

<Insert Table 9>

Again, we see (Panel A) that innovations in U.S. market uncertainty (VIX) have a significant positive relationship with all of the other indices, and this includes BRICS. That is, the importance of VIX is truly global. We also see significant own dynamics once again. The estimated coefficient for the Indian market (NIFVIXI) is statistically significant in several cases, including for the relationship with German (VDAXNEW), Italian (IVIMIB), and UK (VFTSEIX) markets. However, Table 10 shows that the Indian market explains a low level of variance (2% or less) for each European market.

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 2.2% of variance in any other volatility measure (other than for each other). Table 10 also demonstrates the continued influence of VIX in explaining variation in the other markets (22% of variance on average) and the inter-relationship between European markets.

<Insert Table 10>

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, “spreading the fear”. Conversely, global markets do not appear to explain innovations in U.S. market uncertainty. We also find that there is some evidence of linkages between European markets that are closely integrated economically and politically.

We demonstrate a differential effect stemming from each of the two economic crises occurring in our sample period. In both cases, there is greater inter-dependency between G7 markets. However, in the case of the GFC it is largely the additional importance of US news that drives the result, while during COVID the effect is more widespread (particularly within European markets). This result is important for investors, and regulators, seeking to understand the linkages between financial markets, particularly during crisis periods.

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.

<Insert Appendix A>

<Insert Appendix B>

<Insert Appendix C>

References

1. Äijö, J., 2008, Implied volatility term structure linkages between VDAX, VSMI and VSTOXX volatility indices, *Global Finance Journal*, 18, 290–302

2. Baele, L., 2005, Volatility spillover effects in European equity markets, *Journal of Financial and Quantitative Analysis*, 40, 373-401

3. Bekaert, G., and C.R. Harvey, 1995, Time-varying world market integration, *Journal of Finance*, 50, 403-444

4. Bekaert, G., R.J. Hodrick, and X. Zhang, 2009, International stock return comovements, *Journal of Finance*, 64, 2591-2626

5. Bekaert, G., C.R. Harvey, C.T. Lundbald, and S. Siegel, 2011, What segments equity markets? *Review of Financial Studies*, 24, 3841-3890

6. Blair, B., S. Poon, S., and S. Taylor, 2001, Forecasting S&P 100 volatility: The incremental information content of implied volatilities and high-frequency index returns, *Journal of Econometrics*, 105, 5–26

7. Chua, D.B., M. Kritzman, and S. Page, 2009, The myth of diversification, *Journal of Portfolio Management*, 36, 26-35

8. Ding, L., Y. Huang, and X. Pu, 2014, Volatility linkage across global equity markets, *Global Finance Journal*, 25, 71-89

9. Dutta, A., 2018, Implied volatility linkages between the U.S. and emerging equity markets: A note, *Global Finance Journal*, 35, 138-146

10. Eun, C.S., and S. Shim, 1989, International transmission of stock market movements, *Journal of Financial and Quantitative Analysis*, 24, 241-256

11. Fleming, J., B. Ostdiek, B., and R. Whaley, 1995, Predicting stock market volatility: A new measure, *Journal of Futures Markets*, 15, 265-302

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

13. Gagnon, L., and G.A. Karolyi, 2006, Price and volatility transmission across borders, *Financial Markets, Institutions and Instruments*, 15, 107–158

14. Granger, J. W. J., 1969, Investigating causal relationships by econometric models and cross-spectral analysis, *Econometrica*, 37, 424– 438

15. Jiang, G.J., E. Konstantinidi, and G. Skiadopoulos, 2012, Volatility spillovers and the effect of news announcements, *Journal of Banking & Finance*, 36, 2260-2273

16. Kearney, C., and B.M. Lucey, 2004, International equity market integration: Theory, evidence and implications, *International Review of Financial Analysis*, 13, 571-583

17. Kenourgios, D., 2014, On Financial Contagion and Implied Market Volatility, *International Review of Financial Analysis*, 34, 21-30

18. Koutmos, G., and G.G. Booth, 1995, Asymmetric volatility transmission in international stock markets, *Journal of International Money and Finance*, 14, 747-762

19. Lehkonen, H., 2015, Stock market integration and the global financial crisis, *Review of Finance*, 19, 2039-2094

20. Nikkinen, J., and P. Sahlström. 2004, International transmission of uncertainty implicit in stock index option prices, *Global Finance Journal*, 15, 1-15

21. Page, S., and R.A. Panariello, 2018, When diversification fails, *Financial Analysts Journal*, 74, Forthcoming

22. Peng, Y., and W.L. Ng, 2012, Analysing financial contagion and asymmetric market dependence with volatility indices via copulas, *Annals of Finance*, 8, 49-74

23. Simpson, M.W., and S. Ramchander, 2004, An examination of the impact of macroeconomic news on the spot and futures Treasuries markets, *Journal of Futures Markets*, 24, 453-478

24. Sims, C.A., 1980, Macroeconomics and Reality, *Econometrica*, 48, 1-48

25. Smales, L.A., 2014, News sentiment and the investor fear gauge, *Finance Research Letters*, 11, 122-130

26. Solnik, B., C. Boucrelle, and Y.L. Fur, 1996, International market correlation and volatility, *Financial Analysts Journal*, September, 52, 17-34

27. Tavares, J., 2009, Economic integration and the comovement of stock returns, *Economic Letters*, 103, 65-67

28. Von Furstenberg, G., and B.N. Jeon, 1989, International stock price movements: Links and messages, *Brookings Papers on Economic Activity*, 1, 125-167

29. Whaley, R.E., 2000, The investor fear gauge, *Journal of Portfolio Management*, 26, 12-17

30. White, H., 1980, A heteroskedasticity-consistent covariance matrix estimator and a direct test for heteroskedasticity, *Econometrica*, 48, 817– 838

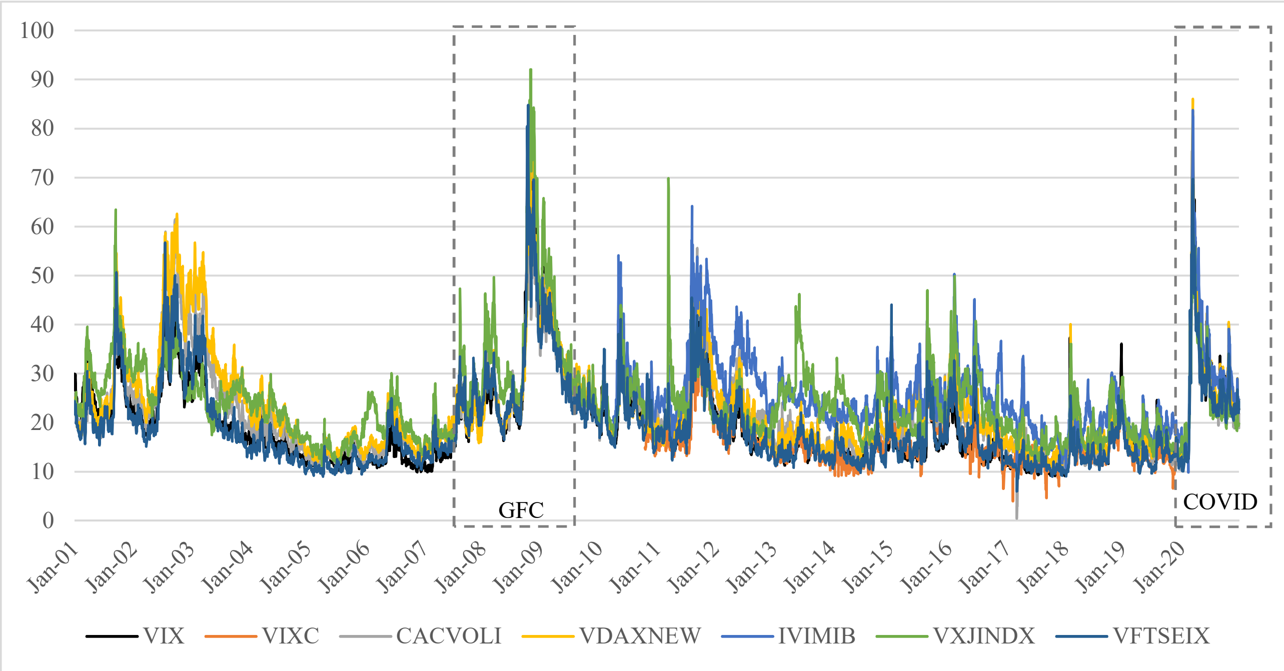

Figure 1A. G7 Volatility Indices (2001 - 2020)

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

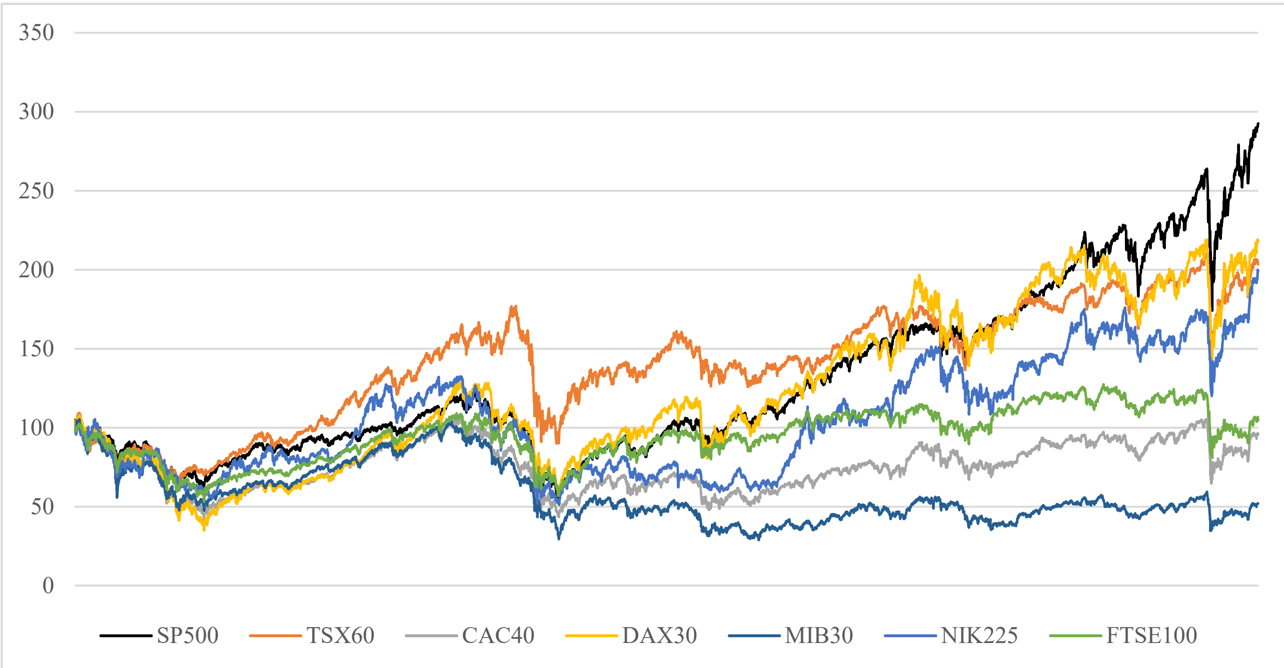

Figure 1B. G7 Stock Market Performance (2001 - 2020)

Note: This figure depicts the performance of stock market indices underlying volatility indices for G7 members. US (*SP500*), Canada (*TSX60*), France (*CAC40*), Germany (*DAX30*), Italy (*MIB30*), Japan (*NIK225*), and UK (*FTSE100*).

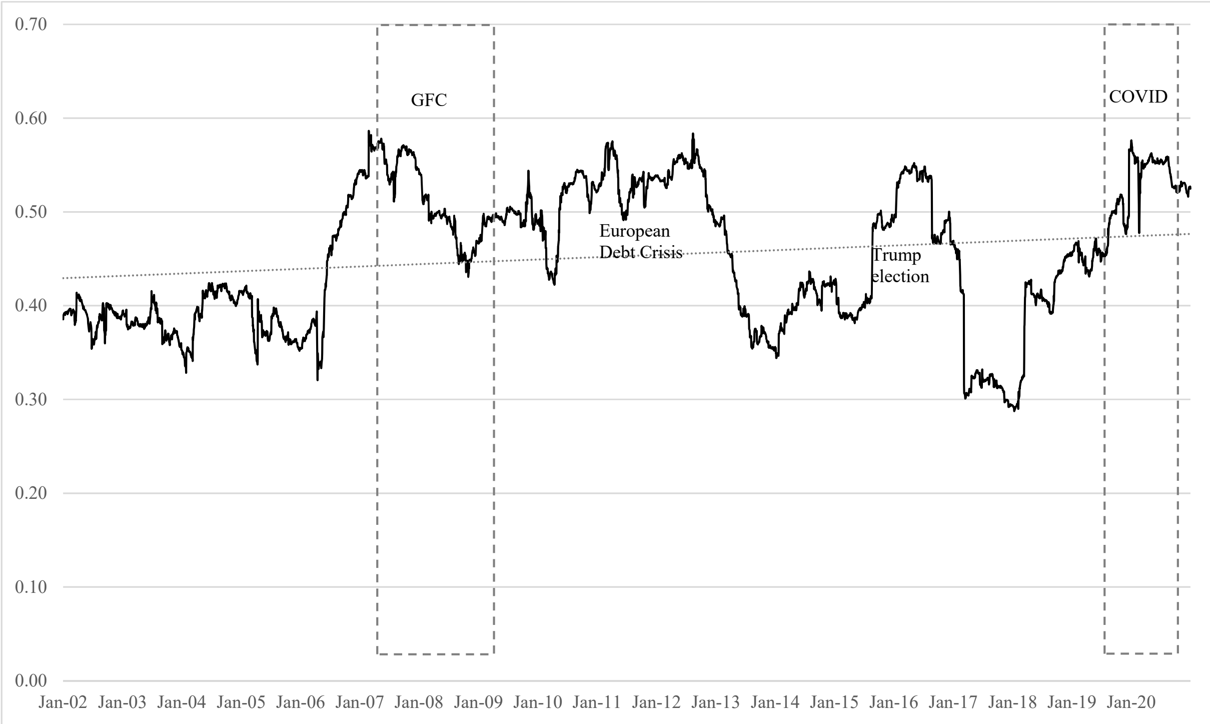

Figure 2. Correlation between G7 implied volatility indices (2002 - 2020)

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

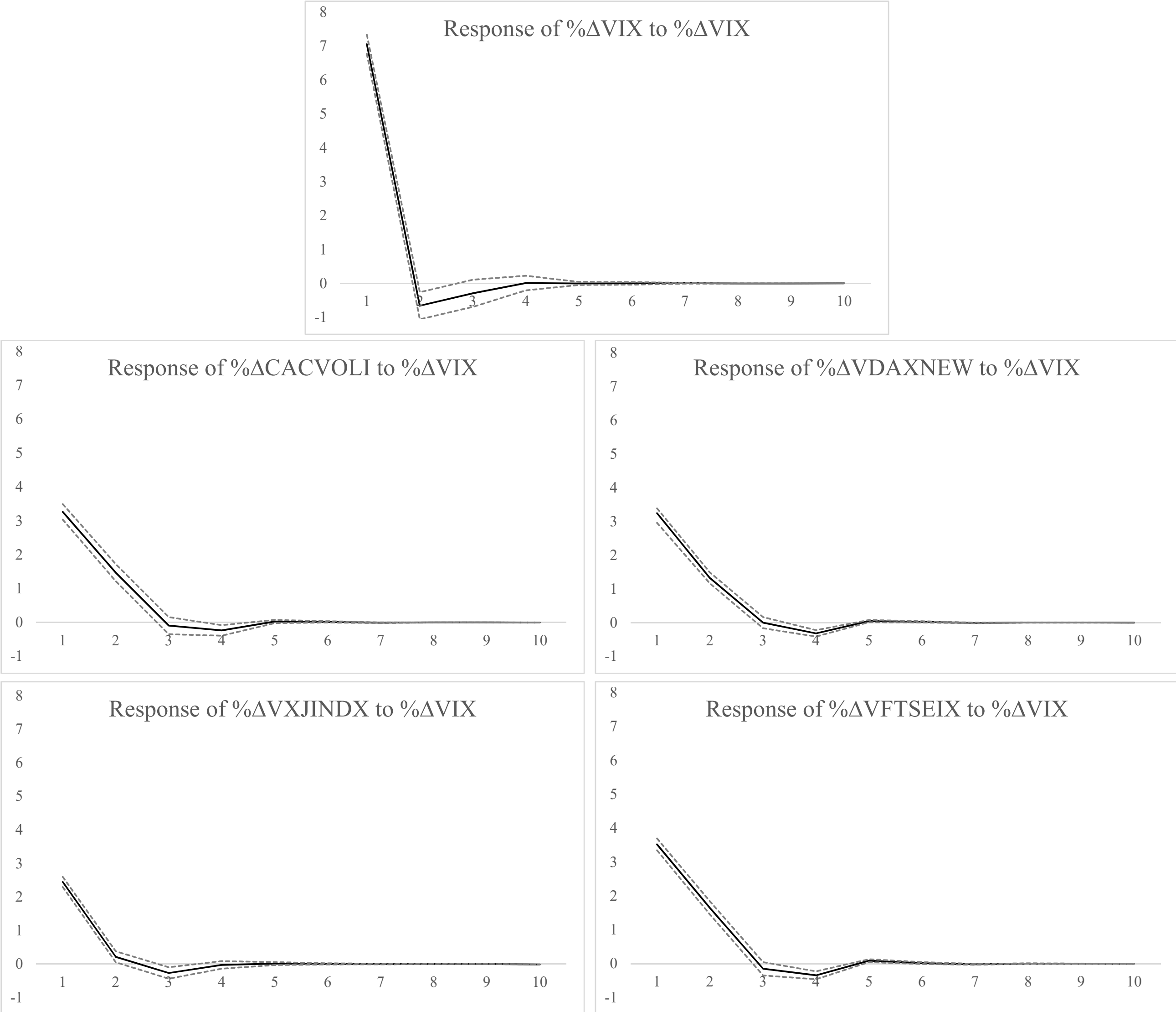

Figure 3. G7 Volatility Indices Impulse Response Function

Note: This figure depicts the impulse response of G7 volatility indices resulting from changes in VIX ($\%\Delta VIX$) computed using the VAR model specified in Eq. (**1**). The response is to Cholesky 1 std.dev. Innovations ± 2 std. err. Sample period: January 2001 - December 2020.

Table 1
Descriptive Statistics

	USA	*CANADA*	*FRANCE*	*GERMANY*	*ITALY*	*JAPAN*	*UK*	*BRAZIL*	*CHINA*	*INDIA*	*RUSSIA*	*SOUTH AFRICA*
	VIX	VIXC	CACVOLI	VDAXNEW	IVIMIB	VXJINDX	VFTSEIX	VXEWZVL	VXFXIVL	NIFVIXI	RTSVXVL	JSAIVI
Underlying	S&P 500	S&P/TSX 60	CAC 40	DAX 30	MIB30	Nikkei 225	FTSE 100	MSCI Brazil ETF	FTSE China 25 ETF	Nifty 50	MOEX	JSETOP40
Trading Hours (UTC)	14:30 - 21:00	14:30 - 21:00	08:00 - 16:30	07:00 - 19:00	07:00 - 16:30	00:00 - 06:00	08:00 - 16:30	14:30 - 21:00	14:30 - 21:00	03:45 - 10:00	07:00 - 15:45	07:00 - 15:00
Level												
Mean	19.84	15.62	22.30	23.45	26.03	24.46	19.41	35.02	25.78	21.62	37.63	21.72
Standard Deviation	9.07	4.45	9.18	10.01	8.11	9.04	8.87	11.65	6.92	9.84	20.94	6.66
Min	9.1	4.0	0.4	11.0	9.9	11.2	6.0	16.7	15.1	10.5	15.4	10.6
Max	82.7	36.7	83.6	86.0	83.8	92.0	84.8	144.4	69.3	85.1	200.5	58.0
Change (%Δ)												
Mean	-0.007	-0.007	-0.006	-0.004	0.003	-0.001	-0.004	0.012	-0.009	-0.018	0.003	0.015
Standard Deviation	7.14	9.49	8.96	5.84	6.02	6.06	7.03	5.22	5.57	5.75	6.55	3.29
Min	-35.1	-110.2	-354.0	-37.0	-61.7	-32.7	-73.8	-62.0	-28.8	-47.0	-29.9	-34.6
Max	76.8	111.4	192.3	41.1	62.0	55.2	54.0	33.1	36.6	49.7	91.2	39.3
Skewness	1.1	0.3	-9.6	0.7	-0.1	1.3	0.4	0.2	0.9	0.4	1.8	1.3
Kurtosis	9.8	31.2	54.1	6.5	16.5	10.8	9.7	14.9	7.4	13.2	21.7	27.5
Sample Start	Jan-01	Oct-10	Jan-01	Jan-01	Apr-10	Jan-01	Jan-01	Mar-11	Mar-11	Mar-08	Jan-06	May-07
Sample End	Dec-20	Dec-19	Dec-20	Dec-20	Dec-20	Dec-20	Dec-20	Dec-20	Dec-20	Dec-20	Dec-16	Dec-20
No. Observations	5000	2294	5000	5000	2688	5000	5000	2447	2447	3208	2730	3411

Note : This table presents summary data for the implied volatility indices used in this study. This includes volatility for the G7 countries (USA, Canada, France, Germany, Italy, Japan, UK) and the five BRICS (Brazil, Russia, India, China, and South Africa).
Sample Period: January 2001 - December 2020

Table 2

Correlation Analysis

Panel A: G7 (Jan'01 - Dec '20)

Implied Volatility	%ΔVIX	%ΔVIXC	%ΔCACVOLI	%ΔVDAXNEW	%ΔIVIMIB	%ΔVXJINDX
%ΔVIXC	**0.360**					
%ΔCACVOLI	**0.347**	**0.173**				
%ΔVDAXNEW	**0.526**	**0.289**	**0.598**			
%ΔIVIMIB	**0.343**	**0.198**	**0.535**	**0.621**		
%ΔVXJINDX	**0.402**	**0.166**	**0.197**	**0.295**	**0.223**	
%ΔVFTSEIX	**0.471**	**0.286**	**0.606**	**0.793**	**0.588**	**0.274**
				Average: 0.395		

Stock Returns	SP500	TSX60	CAC40	DAX30	MIB30	NIK225
TSX60	**0.761**					
CAC40	**0.592**	**0.556**				
DAX30	**0.619**	**0.552**	**0.907**			
MIB30	**0.556**	**0.529**	**0.887**	**0.829**		
NIK225	**0.456**	**0.346**	**0.368**	**0.381**	**0.358**	
FTSE100	**0.565**	**0.567**	**0.892**	**0.822**	**0.798**	**0.343**
			Average: 0.604			

Realized Volatility	σ_{SP500}	σ_{TSX60}	σ_{CAC40}	σ_{DAX30}	σ_{MIB30}	σ_{NIK225}
σ_{TSX60}	**0.922**					
σ_{CAC40}	**0.872**	**0.791**				
σ_{DAX30}	**0.834**	**0.742**	**0.953**			
σ_{MIB30}	**0.792**	**0.732**	**0.896**	**0.829**		
σ_{NIK225}	**0.714**	**0.705**	**0.694**	**0.662**	**0.641**	
$\sigma_{FTSE100}$	**0.911**	**0.842**	**0.949**	**0.907**	**0.837**	**0.731**
				Average: 0.807		

Panel B: G7 Recession

Implied Volatility	%ΔVIX	%ΔVIXC	%ΔCACVOLI	%ΔVDAXNEW	%ΔIVIMIB	%ΔVXJINDX
%ΔVIXC						
%ΔCACVOLI	**0.396**					
%ΔVDAXNEW	**0.504**		**0.648**			
%ΔIVIMIB	**0.392**		**0.564**	**0.749**		
%ΔVXJINDX	**0.401**		**0.269**	**0.332**	**0.252**	
%ΔVFTSEIX	**0.498**		**0.641**	**0.882**	**0.727**	**0.351**
				Average: 0.507		

Stock Returns	SP500	TSX60	CAC40	DAX30	MIB30	NIK225
TSX60	**0.796**					
CAC40	**0.595**	**0.617**				
DAX30	**0.634**	**0.608**	**0.921**			
MIB30	**0.574**	**0.605**	**0.916**	**0.872**		
NIK225	**0.500**	**0.367**	**0.402**	**0.446**	**0.404**	
FTSE100	**0.583**	**0.628**	**0.929**	**0.868**	**0.862**	**0.388**
			Average: 0.643			

Realized Volatility	σ_{SP500}	σ_{TSX60}	σ_{CAC40}	σ_{DAX30}	σ_{MIB30}	σ_{NIK225}
σ_{TSX60}	**0.978**					
σ_{CAC40}	**0.928**	**0.902**				
σ_{DAX30}	**0.888**	**0.852**	**0.967**			
σ_{MIB30}	**0.909**	**0.880**	**0.947**	**0.946**		
σ_{NIK225}	**0.802**	**0.781**	**0.841**	**0.838**	**0.757**	
$\sigma_{FTSE100}$	**0.939**	**0.909**	**0.975**	**0.935**	**0.935**	**0.846**
				Average: 0.893		

Panel C: G7 GFC (15 May '07 - 15 May '09)

Implied Volatility	%ΔVIX	%ΔVIXC	%ΔCACVOLI	%ΔVDAXNEW	%ΔIVIMIB	%ΔVXJINDX
%ΔVIXC						
%ΔCACVOLI	**0.408**					
%ΔVDAXNEW	**0.473**		**0.697**			
%ΔIVIMIB						
%ΔVXJINDX	**0.460**		**0.256**	**0.255**		
%ΔVFTSEIX	**0.500**		**0.682**	**0.843**		**0.275**
				Average: 0.485		

Stock Returns	SP500	TSX60	CAC40	DAX30	MIB30	NIK225
TSX60	**0.767**					
CAC40	**0.585**	**0.563**				
DAX30	**0.633**	**0.543**	**0.913**			
MIB30	**0.546**	**0.533**	**0.928**	**0.855**		
NIK225	**0.607**	**0.424**	**0.441**	**0.467**	**0.437**	
FTSE100	**0.562**	**0.566**	**0.943**	**0.870**	**0.876**	**0.436**
			Average: 0.643			

Realized Volatility	σ_{SP500}	σ_{TSX60}	σ_{CAC40}	σ_{DAX30}	σ_{MIB30}	σ_{NIK225}
σ_{TSX60}	**0.978**					
σ_{CAC40}	**0.959**	**0.936**				
σ_{DAX30}	**0.936**	**0.912**	**0.963**			
σ_{MIB30}	**0.958**	**0.927**	**0.961**	**0.952**		
σ_{NIK225}	**0.878**	**0.854**	**0.911**	**0.920**	**0.886**	
$\sigma_{FTSE100}$	**0.951**	**0.920**	**0.981**	**0.922**	**0.947**	**0.899**
				Average: 0.931		

Panel D: G7 COVID-19 Pandemic (17 Mar '20 - 27 Apr '20)

Implied Volatility	%ΔVIX	%ΔVIXC	%ΔCACVOLI	%ΔVDAXNEW	%ΔIVIMIB	%ΔVXJINDX
%ΔVIXC						
%ΔCACVOLI	**0.729**					
%ΔVDAXNEW	**0.643**		**0.826**			
%ΔIVIMIB	**0.665**		**0.759**	**0.845**		
%ΔVXJINDX	*0.395*		0.255	0.263	0.173	
%ΔVFTSEIX	**0.558**		**0.783**	**0.952**	**0.789**	**0.361**
				Average: 0.600		

Stock Returns	SP500	TSX60	CAC40	DAX30	MIB30	NIK225
TSX60	**0.896**					
CAC40	**0.744**	**0.852**				
DAX30	**0.759**	**0.864**	**0.962**			
MIB30	**0.763**	**0.838**	**0.900**	**0.925**		
NIK225	0.259	0.151	0.196	0.317	0.272	
FTSE100	**0.749**	**0.889**	**0.937**	**0.926**	**0.898**	0.172
			Average: 0.679			

Realized Volatility	σ_{SP500}	σ_{TSX60}	σ_{CAC40}	σ_{DAX30}	σ_{MIB30}	σ_{NIK225}
σ_{TSX60}	**0.995**					
σ_{CAC40}	**0.984**	**0.994**				
σ_{DAX30}	**0.981**	**0.991**	**0.998**			
σ_{MIB30}	**0.938**	**0.947**	**0.969**	**0.967**		
σ_{NIK225}	**0.927**	**0.933**	**0.906**	**0.906**	**0.898**	
$\sigma_{FTSE100}$	**0.979**	**0.993**	**0.994**	**0.993**	**0.950**	**0.937**
				Average: 0.961		

Note : This table presents Pearson (pairwise) correlation for the daily percentage change in implied volatility indices, in addition to stock returns and realized volatility of the associated underlying stock indices. This includes members of the G7: US - *VIX* , Canada - *VIXC* , France - *CACVOLI* , German - *VDAXNEW* , Italy - IVIMIB, Japan - *VXJINDX* , UK - *VFTSEIX* . 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 2001 - Dec 2020. Panel B shows the correlation matrix for G7 members during NBER-defined recession periods only. Panel C shows the correlation G7 correlation matrix in the period of the global financial crisis indicated by TED spread greater than 0.65 for at least 2 consecutive days. Panel D shows the correlation for the COVID-19 pandemic again indicated by high levels of the TED spread. 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		%ΔCACVOLI		%ΔVDAXNEW		%ΔVXJINDX		%ΔVFTSEIX	
Constant	-0.003		-0.005		0.002		-0.002		0.004	
	(0.098)		(0.117)		(0.008)		(0.085)		(0.091)	
%ΔVIX(-1)	-0.183	***	0.220	***	0.205	***	0.091	***	0.262	***
	(0.018)		(0.021)		(0.014)		(0.016)		(0.017)	
%ΔVIX(-2)	-0.082	***	0.082	***	0.106	***	0.046	***	0.103	***
	(0.018)		(0.022)		(0.014)		(0.016)		(0.017)	
%ΔCACVOLI(-1)	-0.006		-0.389	***	-0.010		-0.009		0.018	
	(0.015)		(0.018)		(0.012)		(0.013)		(0.001)	
%ΔCACVOLI(-2)	0.003		-0.059	***	-0.020		0.000		-0.012	
	(0.015)		(0.018)		(0.012)		(0.013)		(0.014)	
%ΔVDAXNEW(-1)	0.010		0.104	***	-0.208	***	0.014		0.114	***
	(0.030)		(0.036)		(0.023)		(0.026)		(0.028)	
%ΔVDAXNEW(-2)	-0.022		0.003		-0.088	***	0.010		0.028	
	(0.030)		(0.036)		(0.023)		(0.026)		(0.031)	
%ΔVXJINDX(-1)	-0.023		-0.040	*	-0.030	*	-0.220	***	-0.031	*
	(0.019)		(0.022)		(0.015)		(0.015)		(0.018)	
%ΔVXJINDX(-2)	-0.026		0.008		0.003		-0.049	***	0.011	
	(0.019)		(0.021)		(0.014)		(0.014)		(0.017)	
%ΔVFTSEIX(-1)	-0.010		0.041		-0.019		0.016		-0.181	***
	(0.025)		(0.030)		(0.020)		(0.019)		(0.024)	
%ΔVFTSEIX(-2)	0.030		-0.017		-0.008		0.004		-0.173	***
	(0.027)		(0.024)		(0.020)		(0.019)		(0.023)	
Adj. R^2	0.012		0.120		0.086		0.207		0.101	
F-Statistic	6.27		69.23		48.16		131.43		57.28	
Akiaike AIC	6.75		7.10		6.28		6.21		6.63	
No. Observations	4998		4998		4998		4998		4998	

Note: This table reports the estimated coefficients for the VAR model specified in Eq. (1). The endogenous variables are the daily percentage changes in implied volatility indices for the US (*VIX*), France (*CACVOLI*), Germany (*VDAXNEW*), Japan (*VXJINDX*), and UK (*VFTSEIX*). Lag selection is on the basis of AIC 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 2001 - December 2020

Table 4
Variance decomposition for G7 volatility indices

Period	S.E.	%ΔVIX	%ΔCACVOLI	%ΔVDAXNEW	%ΔVXJINDX	%ΔVFTSEIX
%ΔVIX						
1	7.056	**100.000**	0.000	0.000	0.000	0.000
2	7.089	**99.950**	0.000	0.019	0.028	0.003
3	7.099	**99.818**	0.013	0.019	0.105	0.045
4	7.100	**99.792**	0.018	0.026	0.116	0.048
5	7.100	**99.791**	0.018	0.026	0.116	0.049
%ΔCACVOLI						
1	8.402	**15.087**	**84.913**	0.000	0.000	0.000
2	8.943	**16.017**	**83.459**	0.444	0.048	0.031
3	8.962	**15.959**	**83.289**	0.608	0.057	0.087
4	8.967	**16.010**	**83.197**	0.625	0.066	0.101
5	8.967	**16.011**	**83.196**	0.625	0.067	0.101
%ΔVDAXNEW						
1	5.577	**33.904**	**16.743**	**49.353**	0.000	0.000
2	5.818	**36.307**	**16.340**	**47.212**	0.125	0.016
3	5.826	**36.207**	**16.478**	**47.158**	0.139	0.018
4	5.839	**36.339**	**16.504**	**46.975**	0.151	0.031
5	5.839	**36.342**	**16.505**	**46.971**	0.151	0.031
%ΔVXJINDX						
1	6.049	**19.756**	1.441	1.951	**76.705**	0.147
2	6.056	**19.841**	1.477	1.948	**76.563**	0.171
3	6.062	**19.995**	1.475	1.952	**76.408**	0.171
4	6.062	**19.996**	1.475	1.952	**76.405**	0.172
5	6.062	**19.996**	1.475	1.952	**76.404**	0.173
%ΔVFTSEIX						
1	6.664	**27.939**	**20.269**	**16.696**	0.110	**34.986**
2	6.983	**30.993**	**19.220**	**16.690**	0.181	**32.917**
3	7.016	**30.741**	**19.268**	**16.556**	0.187	**33.249**
4	7.035	**30.819**	**19.269**	**16.484**	0.203	**33.225**
5	7.036	**30.825**	**19.265**	**16.488**	0.203	**33.219**

Note: This table reports the variance decomposition for the VAR model specified in Eq. (1). The variables are the daily percentage changes in implied volatility indices for the US (*VIX*), France (*CACVOLI*), Germany (*VDAXNEW*), Japan (*VXJINDX*), and UK (*VFTSEIX*). **Bold** text indicates more than 10% of variance explained by variable.
Sample Period: January 2001 - December 2020

Table 5

VAR: Inter-relationship between G7 volatility indices during financial crisis

Panel A: GFC	%ΔVIX		%ΔCACVOLI		%ΔVDAXNEW		%ΔVXJINDX		%ΔVFTSEIX	
Constant	0.238		0.053		0.042		0.027		0.063	
	(0.339)		(0.319)		(0.248)		(0.271)		(0.276)	
%ΔVIX(-1)	-0.236	***	0.476	***	0.388	***	0.455	***	0.415	***
	(0.059)		(0.056)		(0.044)		(0.048)		(0.048)	
%ΔCACVOLI(-1)	-0.064		-0.573	***	-0.012		-0.002		-0.030	
	(0.070)		(0.066)		(0.051)		(0.056)		(0.057)	
%ΔVDAXNEW(-1)	0.182		-0.033		-0.290	***	0.026		0.012	
	(0.118)		(0.086)		(0.111)		(0.094)		(0.096)	
%ΔVXJINDX(-1)	-0.055		-0.065		-0.080	*	-0.349	***	-0.075	
	(0.060)		(0.057)		(0.044)		(0.005)		(0.049)	
%ΔVFTSEIX(-1)	-0.066		-0.077		-0.215	***	0.099		-0.326	***
	(0.104)		(0.098)		(0.076)		(0.083)		(0.085)	
Adj. R^2	0.056		0.210		0.154		0.315		0.185	
F -Statistic	2.49		7.64		5.55		12.49		5.45	
No. Observations	500		500		500		500		500	
Panel B: COVID	%ΔVIX		%ΔCACVOLI		%ΔVDAXNEW		%ΔVXJINDX		%ΔVFTSEIX	
Constant	-0.634		-0.818		-0.621		-0.329		-0.535	
	(0.493)		(0.524)		(0.421)		(0.371)		(0.426)	
%ΔVIX(-1)	-0.215	**	0.342	***	0.398	***	0.309	***	0.474	***
	(0.087)		(0.092)		(0.074)		(0.065)		(0.075)	
%ΔCACVOLI(-1)	0.004		-0.722	***	-0.027		0.065		-0.115	
	(0.110)		(0.117)		(0.094)		(0.083)		(0.010)	
%ΔVDAXNEW(-1)	0.319	**	0.189		-0.436	**	-0.232		-0.200	
	(0.251)		(0.267)		(0.214)		(0.188)		(0.217)	
%ΔVXJINDX(-1)	-0.166		-0.129		-0.134		-0.467	***	-0.106	
	(0.100)		(0.109)		(0.088)		(0.076)		(0.088)	
%ΔVFTSEIX(-1)	-0.215		0.256		0.172		0.037		-0.518	***
	(0.239)		(0.253)		(0.203)		(0.206)		(0.179)	
Adj. R^2	0.117		0.263		0.179		0.410		0.224	
F -Statistic	2.33		4.58		3.19		7.96		3.90	
No. Observations	201		201		201		201		201	

Note: This table reports the estimated coefficients for the VAR model specified in Eq. (1) for periods of *financial crisis only*. The endogenous variables are the daily percentage changes in implied volatility indices for the US (*VIX*), France (*CACVOLI*), Germany (*VDAXNEW*), Japan (*VXJINDX*), and UK (*VFTSEIX*). Panel A reports the estimated coefficients for the *global financial crisis* period (May 2007 - May 2009) and Panel B reports the estimates for the *COVID pandemic* period (March 2020 - December 2020). Lag selection is on the basis of AIC with only the first lag reported. Standard errors are reported in parentheses.

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

Sample Period: May 2007 - May 2009 and March 2020 - December 2020

Table 6

Panel A: Variance decomposition for G7 volatility indices during GFC

Period	S.E.	%ΔVIX	%ΔCACVOLI	%ΔVDAXNEW	%ΔVXJINDX	%ΔVFTSEIX
Δ*VIX*						
1	7.558	100.000	0.000	0.000	0.000	0.000
2	7.779	99.371	0.042	0.322	0.189	0.076
3	7.832	98.554	0.048	1.057	0.188	0.154
Δ*CACVOLI*						
1	7.110	**27.187**	72.813	0.000	0.000	0.000
2	8.046	**27.775**	70.916	0.969	0.242	0.098
3	8.090	**27.578**	70.812	1.235	0.266	0.109
Δ*VDAXNEW*						
1	5.537	*36.122*	21.209	42.669	0.000	0.000
2	6.006	*40.262*	19.868	37.692	0.801	1.377
3	6.023	*40.032*	19.972	37.811	0.808	1.378
Δ*VXJINDX*						
1	7.222	**25.914**	2.475	2.812	68.597	0.202
2	7.358	**25.029**	4.283	2.796	67.549	0.343
3	7.388	**24.835**	4.417	3.139	67.132	0.476
Δ*VFTSEIX*						
1	6.149	**38.018**	18.623	14.495	0.386	28.478
2	6.642	**39.360**	18.705	13.918	1.019	26.998
3	6.671	**39.206**	18.572	13.820	1.048	27.355

Panel B: Variance decomposition for G7 volatility indices during COVID

Period	S.E.	%ΔVIX	%ΔCACVOLI	%ΔVDAXNEW	%ΔVXJINDX	%ΔVFTSEIX
Δ*VIX*						
1	7.018	100.000	0.000	0.000	0.000	0.000
2	7.178	98.206	0.008	0.118	1.010	0.658
3	7.363	95.711	1.741	0.848	1.038	0.662
Δ*CACVOLI*						
1	7.615	**24.789**	75.211	0.000	0.000	0.000
2	8.592	**20.581**	72.877	2.505	*3.479*	0.558
3	8.711	**20.741**	71.421	2.679	*3.511*	1.648
Δ*VDAXNEW*						
1	6.115	33.541	**29.378**	37.080	0.000	0.000
2	6.512	35.423	**28.146**	34.690	1.371	0.370
3	6.606	35.404	**27.365**	33.739	1.335	2.157
Δ*VXJINDX*						
1	6.738	*23.384*	**9.163**	1.460	62.785	*3.207*
2	6.854	*24.574*	**9.611**	1.417	60.872	*3.525*
3	6.894	*24.345*	**9.998**	1.466	60.528	*3.662*
Δ*VFTSEIX*						
1	6.270	27.457	**31.293**	**28.367**	0.009	12.873
2	6.797	30.371	**31.881**	**25.563**	1.185	10.999
3	6.879	30.335	**31.492**	**24.975**	1.172	12.025

Note: This table reports the variance decomposition for the VAR model specified in Eq. (1), and apply to the sample period covering the GFC and COVID pandemic. The variables are the daily percentage changes in implied volatility indices for the US (*VIX*), France (*CACVOLI*), Germany (*VDAXNEW*), Japan (*VXJINDX*), and UK (*VFTSEIX*). Increases of 5% or more relative to the overall sample period are indicated by **bold**, and 3%-5% by *italics* .

Sample Period: May 2007 - May 2009 and March 2020 - December 2020

Table 7
Granger causality test results

Panel A: Pair-wise	%ΔVIX	%ΔCACVOLI	%ΔVDAXNEW	%ΔVXJINDX	%ΔVFTSEIX
%ΔVIX		90.29 ***	83.13 ***	215.21 ***	92.86 ***
		(0.000)	(0.000)	(0.000)	(0.000)
%ΔCACVOLI	0.682		4.458 ***	56.12 ***	2.544 **
	(0.665)		(0.000)	(0.000)	(0.018)
%ΔVDAXNEW	0.945	45.215 ***		117.49 **	6.988 ***
	(0.461)	(0.000)		(0.000)	(0.000)
%ΔVXJINDX	0.502	4.715 ***	0.724		1.444
	(0.807)	(0.000)	(0.630)		(0.193)
%ΔVFTSEIX	1.415	35.613 ***	3.318 ***	102.18 ***	
	(0.216)	(0.000)	(0.005)	(0.000)	

Panel B: VAR / Block	%ΔVIX	%ΔCACVOLI	%ΔVDAXNEW	%ΔVXJINDX	%ΔVFTSEIX
%ΔVIX		267.50 ***	496.82 ***	542.11 ***	530.52 ***
		(0.000)	(0.000)	(0.000)	(0.000)
%ΔCACVOLI	0.358		5.210	0.665	6.151
	(0.986)		(0.285)	(0.956)	(0.188)
%ΔVDAXNEW	2.274	14.658 ***		14.363 ***	21.422 ***
	(0.686)	(0.006)		(0.006)	(0.000)
%ΔVXJINDX	8.902 *	5.009	12.624 **		4.108
	(0.064)	(0.286)	(0.013)		(0.392)
%ΔVFTSEIX	6.175	6.520	3.468	10.673 **	
	(0.187)	(0.164)	(0.483)	(0.031)	
Total	18.273	566.76 ***	520.99 ***	1355.25 ***	587.32 ***
	(0.308)	(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*), 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 8

Principal Component Analysis

Panel A: Implied Volatility	*All: Jan '01 - Dec '20*			*GFC: May '07 - May '09*			*COVID: Mar '20 - Dec '20*			*Oct '10 - Dec '19*		
N	Eigen Value	Proportion	Cumulative Proportion	Eigen Value	Proportion	Cumulative Proportion	Eigen Value	Proportion	Cumulative Proportion	Eigen Value	Proportion	Cumulative Proportion
1	2.837	0.568	0.568	3.056	0.611	0.611	3.091	0.618	0.618	3.447	0.493	0.493
2	0.880	0.176	0.744	0.910	0.182	0.793	0.886	0.177	0.795	1.018	0.146	0.638
3	0.659	0.132	0.875	0.535	0.107	0.900	0.624	0.125	0.920	0.852	0.122	0.760
4	0.418	0.084	0.959	0.342	0.068	0.969	0.337	0.067	0.987	0.622	0.089	0.849
5	0.205	0.041	1.000	0.156	0.031	1.000	0.063	0.013	1.000	0.439	0.063	0.911
6										0.416	0.059	0.971
7										0.245	0.029	1.000
Panel B: Stock Returns	*All: Jan '01 - Dec '20*			*GFC: May '07 - May '09*			*COVID: Mar '20 - Dec '20*			*Oct '10 - Dec '19*		
N	Eigen Value	Proportion	Cumulative Proportion	Eigen Value	Proportion	Cumulative Proportion	Eigen Value	Proportion	Cumulative Proportion	Eigen Value	Proportion	Cumulative Proportion
1	3.350	0.670	0.670	3.489	0.698	0.698	3.645	0.729	0.729	4.624	0.661	0.661
2	0.893	0.179	0.849	0.891	0.178	0.876	0.741	0.148	0.877	0.932	0.133	0.794
3	0.509	0.102	0.951	0.445	0.089	0.965	0.442	0.089	0.966	0.784	0.112	0.906
4	0.174	0.035	0.986	0.126	0.025	0.990	0.123	0.025	0.990	0.247	0.035	0.941
5	0.073	0.015	1.000	0.049	0.010	1.000	0.050	0.010	1.000	0.197	0.028	0.969
6										0.152	0.022	0.991
7										0.062	0.009	1.000

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

Sample Period: January 2001 - December 2020

Table 9

Inter-relationship between G7 and BRIC volatility indices

Panel A: VAR	%ΔVIX	%ΔVIXC	%ΔCACVOLI	%ΔVDAXNEW	%ΔIVIMIB	%ΔVXJINDX	%ΔVFTSEIX	%ΔVXEWZVL	%ΔVXFXIVL	%ΔNIFVIXI	%ΔJSAIVI
Constant	-0.039	0.002	-0.039	-0.035	-0.021	-0.061	-0.026	-0.010	-0.024	-0.034	-0.027
	(0.166)	(0.185)	(0.223)	(0.125)	(0.112)	(0.113)	(0.154)	(0.105)	(0.110)	(0.103)	(0.062)
%ΔVIX(-1)	-0.113 ***	0.237 ***	0.321 ***	0.253 ***	0.195 ***	0.274 ***	0.355 ***	0.051 **	0.054 **	0.144 ***	0.053 ***
	(0.033)	(0.036)	(0.044)	(0.025)	(0.022)	(0.022)	(0.030)	(0.021)	(0.022)	(0.020)	(0.012)
%ΔVIXC(-1)	0.026	-0.534 ***	0.010	0.011	0.018	-0.014	0.022	0.006	-0.004	-0.004	0.005
	(0.022)	(0.024)	(0.029)	(0.016)	(0.015)	(0.015)	(0.020)	(0.014)	(0.014)	(0.013)	(0.008)
%ΔCACVOLI(-1)	0.007	-0.010	-0.432 ***	-0.012	0.028 *	-0.007	0.029	-0.006	-0.004	-0.002	0.008
	(0.022)	(0.024)	(0.029)	(0.016)	(0.015)	(0.015)	(0.020)	(0.014)	(0.014)	(0.014)	(0.008)
%ΔVDAXNEW(-1)	0.047	0.007	0.110	-0.190 ***	0.089 ***	0.080 **	-0.165 ***	-0.021	0.014	-0.048	-0.021
	(0.051)	(0.056)	(0.068)	(0.038)	(0.034)	(0.034)	(0.047)	(0.032)	(0.034)	(0.031)	(0.019)
%ΔIVIMIB(-1)	-0.035	0.086 *	0.078	0.026	-0.240 ***	0.041	0.060	0.008	0.002	-0.034	-0.004
	(0.045)	(0.050)	(0.060)	(0.033)	(0.030)	(0.030)	(0.041)	(0.028)	(0.030)	(0.028)	(0.017)
%ΔVXJINDX(-1)	0.021	-0.033	-0.015	-0.042 *	-0.058 **	-0.310 ***	-0.017	-0.010	0.012	-0.046 **	-0.007
	(0.034)	(0.037)	(0.045)	(0.025)	(0.023)	(0.023)	(0.031)	(0.021)	(0.022)	(0.021)	(0.013)
%ΔVFTSEIX(-1)	-0.015	0.022	0.004	-0.037	0.000	0.040	-0.192 ***	0.017	-0.005	0.028	-0.006
	(0.041)	(0.045)	(0.055)	(0.031)	(0.027)	(0.028)	(0.038)	(0.026)	(0.027)	(0.025)	(0.015)
%ΔVXEWZVL(-1)	0.007	0.178 ***	-0.047	0.059 *	0.095 ***	0.016	0.034	-0.072 ***	0.034	0.084 ***	0.036 **
	(0.044)	(0.049)	(0.059)	(0.033)	(0.030)	(0.030)	(0.041)	(0.028)	(0.029)	(0.027)	(0.016)
%ΔVXFXIVL(-1)	0.027	-0.083	0.066	0.015	-0.026	0.126 ***	0.018	-0.018	-0.135 ***	-0.019	0.005
	(0.049)	(0.054)	(0.065)	(0.036)	(0.033)	(0.033)	(0.045)	(0.031)	(0.032)	(0.030)	(0.018)
%ΔNIFVIXI(-1)	-0.046	0.045	-0.076	-0.061 **	-0.063 **	-0.008	-0.079 **	-0.026	0.019	-0.043 *	0.006
	(0.037)	(0.041)	(0.050)	(0.028)	(0.025)	(0.025)	(0.034)	(0.024)	(0.025)	(0.023)	(0.014)
%ΔJSAIVI(-1)	-0.018	-0.038	-0.081	-0.056	-0.086 **	-0.069 *	-0.079	-0.069 *	0.013	-0.061	-0.099 ***
	(0.060)	(0.066)	(0.080)	(0.045)	(0.040)	(0.041)	(0.055)	(0.038)	(0.040)	(0.037)	(0.022)
Adj. R^2	0.032	0.196	0.173	0.114	0.134	0.266	0.138	0.005	0.012	0.062	0.063
F-Statistic	1.627	13.111	11.407	7.360	8.649	18.943	8.950	1.246	1.584	4.304	4.320
No. Observations	2185	2185	2185	2185	2185	2185	2185	2185	2185	2185	
Panel B: Correlation	**%ΔVIX**	**%ΔVIXC**	**%ΔCACVOLI**	**%ΔVDAXNEW**	**%ΔIVIMIB**	**%ΔVXJINDX**	**%ΔVFTSEIX**	**%ΔVXEWZVL**	**%ΔVXFXIVL**	**%ΔNIFVIXI**	**%ΔJSAIVI**
%ΔVIXC	**0.360**										
%ΔCACVOLI	**0.347**	**0.173**									
%ΔVDAXNEW	**0.526**	**0.290**	**0.598**								
%ΔIVIMIB	**0.344**	**0.198**	**0.535**	**0.621**							
%ΔVXJINDX	**0.402**	**0.166**	**0.197**	**0.295**	**0.223**						
%ΔVFTSEIX	**0.471**	**0.286**	**0.606**	**0.793**	**0.588**	**0.274**					
%ΔVXEWZVL	**0.586**	**0.250**	**0.272**	**0.454**	**0.311**	**0.284**	**0.409**				
%ΔVXFXIVL	**0.667**	**0.315**	**0.303**	**0.524**	**0.355**	**0.333**	**0.469**	**0.605**			
%ΔNIFVIXI	**0.171**	**0.146**	**0.163**	**0.289**	**0.330**	**0.074**	**0.275**	**0.234**	**0.270**		
%ΔRTSVXVL	**0.214**	**0.232**	**0.332**	**0.360**	**0.357**	**0.078**	**0.312**	**0.300**	**0.269**	**0.223**	
%ΔJSAIVI	**0.190**	**0.109**	**0.197**	**0.307**	**0.241**	**0.082**	**0.283**	**0.168**	**0.190**	**0.159**	**0.233**

Average (all): 0.321 Average (G7): 0.360 Average (BRICS): 0.265

Note: Panel A 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*), Italy (*IVIMIB*), Japan (*VXJINDX*), UK (*VFTSEIX*), Brazil (*VXEWZVL*), China (*VXFXIVL*), India (*NIFVIXI*), and South Africa (*JSAIVI*). Lag selection is on the basis of AIC with only the first lag reported. Standard errors are reported in parentheses. Panel B presents Pearson (pairwise) correlation for the daily change in implied volatility indices with **bold** text indicating statistical significance at the 1% level.

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

Sample Period: March 2011 - December 2019

Table 10
Variance decomposition for G7 and BRIC volatility indices

Period	S.E.	%ΔVIX	%ΔVIXC	%ΔCACVOLI	%ΔVDAXNEW	%ΔIVIMIB	%ΔVXJINDX	%ΔVFTSEIX	%ΔVXEWZVL	%ΔVXFXIVL	%ΔNIFVIXI	%ΔJSAIVI
%ΔVIX												
1	7.770	**100.000**	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	7.806	**99.767**	0.068	0.003	0.018	0.036	0.013	0.008	0.003	0.009	0.070	0.004
3	7.826	**99.379**	0.069	0.003	0.019	0.080	0.193	0.036	0.004	0.057	0.143	0.017
%ΔVIXC												
1	8.642	**17.521**	**82.479**	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	9.621	**14.263**	**84.847**	0.055	0.071	0.133	0.042	0.013	0.437	0.083	0.043	0.012
3	9.659	**14.150**	**84.458**	0.270	0.073	0.155	0.145	0.105	0.462	0.105	0.054	0.021
%ΔCACVOLI												
1	10.431	**11.659**	0.317	**88.024**	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	11.230	**11.802**	0.281	**87.470**	0.213	0.048	0.006	0.000	0.017	0.026	0.095	0.041
3	11.274	**11.721**	0.379	**86.802**	0.308	0.049	0.046	0.013	0.349	0.026	0.116	0.191
%ΔVDAXNEW												
1	5.826	**32.221**	0.935	**13.993**	**52.851**	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	6.097	**34.112**	0.860	**13.797**	**50.561**	0.004	0.173	0.074	0.142	0.001	0.208	0.068
3	6.140	**33.638**	0.865	**14.081**	**50.165**	0.112	0.171	0.122	0.498	0.009	0.220	0.118
%ΔIVIMIB												
1	5.228	**13.815**	0.624	**24.239**	**8.014**	**53.308**	0.000	0.000	0.000	0.000	0.000	0.000
2	5.568	**19.429**	0.577	**21.506**	**7.079**	**50.130**	0.417	0.001	0.345	0.058	0.270	0.187
3	5.610	**19.157**	0.752	**21.745**	**6.974**	**49.369**	0.477	0.072	0.468	0.404	0.270	0.311
%ΔVXJINDX												
1	6.125	**21.936**	0.004	0.827	1.928	0.851	**73.697**	0.080	0.103	0.469	0.004	0.099
2	6.149	**22.137**	0.004	0.869	1.952	0.845	**73.235**	0.154	0.181	0.467	0.058	0.098
3	6.165	**22.033**	0.032	0.864	1.996	0.902	**73.162**	0.160	0.217	0.468	0.059	0.107
%ΔVFTSEIX												
1	7.173	**28.128**	1.264	**20.695**	**16.704**	0.181	0.054	**32.975**	0.000	0.000	0.000	0.000
2	7.581	**30.809**	1.136	**19.122**	**17.627**	0.186	0.096	**30.685**	0.027	0.000	0.227	0.086
3	7.702	**29.913**	1.100	**19.403**	**17.079**	0.189	0.113	**31.216**	0.467	0.064	0.223	0.232
%ΔVXEWZVL												
1	4.921	**31.490**	0.337	0.452	1.505	0.133	0.007	0.102	**65.974**	0.000	0.000	0.000
2	4.942	**31.253**	0.334	0.482	1.568	0.132	0.035	0.107	**65.846**	0.031	0.061	0.152
3	4.950	**31.167**	0.356	0.483	1.605	0.133	0.056	0.114	**65.663**	0.049	0.065	0.310
%ΔVXFXIVL												
1	5.161	**45.461**	0.543	0.572	2.244	0.262	1.209	0.083	4.456	**45.170**	0.000	0.000
2	5.184	**45.089**	0.553	0.576	2.225	0.260	1.199	0.086	4.418	**45.564**	0.027	0.005
3	5.200	**44.882**	0.626	0.595	2.277	0.347	1.305	0.158	4.394	**45.281**	0.075	0.061
%ΔNIFVIXI												
1	4.825	**5.145**	0.278	0.529	2.367	1.616	1.315	0.257	0.516	0.773	**87.203**	0.000
2	4.968	**9.082**	0.274	0.587	2.436	1.639	1.543	0.289	0.851	0.768	**82.413**	0.118
3	4.998	**8.977**	0.451	0.666	2.419	1.626	1.525	0.427	0.934	0.995	**81.859**	0.120
%ΔJSAIVI												
1	2.907	**2.884**	0.312	0.649	1.591	0.076	0.281	0.325	0.010	0.450	0.052	**93.371**
2	2.959	**4.878**	0.309	0.628	1.711	0.077	0.298	0.327	0.268	0.434	0.055	**91.014**
3	3.008	**5.120**	0.299	0.628	1.675	0.084	0.308	0.330	0.410	0.436	0.185	**90.524**

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*), Italy (*IVIMIB*), Japan (*VXJINDX*), UK (*VFTSEIX*), Brazil (*VXEWZVL*), China (*VXFXIVL*), India (*NIFVIXI*), and South Africa (*JSAIVI*).
Sample Period: March 2011 - June 2018

Appendix A

VAR: Inter-relationship between G7 volatility indices - including Canada and Italy

	%ΔVIX		%ΔVIXC		%ΔCACVOLI		%ΔVDAXNEW		%ΔIVIMIB		%ΔVXJINDX		%ΔVFTSEIX	
Constant	-0.023		-0.002		-0.025		-0.011		-0.006		-0.018		-0.014	
	(0.161)		(0.179)		(0.221)		(0.124)		(0.110)		(0.118)		(0.153)	
%ΔVIX(-1)	-0.090	***	0.245	***	0.291	***	0.258	***	0.205	***	0.307	***	0.338	***
	(0.026)		(0.029)		(0.036)		(0.020)		(0.018)		(0.019)		(0.025)	
%ΔVIXC(-1)	0.024		-0.511	***	0.034		0.020		0.155		0.001		0.034	*
	(0.020)		(0.022)		(0.028)		(0.016)		(0.014)		(0.015)		(0.020)	
%ΔCACVOLI(-1)	0.011		-0.020		-0.388	***	-0.007		0.027	*	-0.006		0.033	*
	(0.021)		(0.023)		(0.028)		(0.016)		(0.014)		(0.015)		(0.020)	
%ΔVDAXNEW(-1)	0.048		0.010		0.111	*	-0.175	***	0.069	**	0.030		0.164	***
	(0.047)		(0.052)		(0.065)		(0.036)		(0.032)		(0.035)		(0.045)	
%ΔIVIMIB(-1)	(0.048)		0.049		0.050		0.002		-0.256	***	0.036		0.027	
	(0.042)		(0.047)		(0.058)		(0.032)		(0.029)		(0.030)		(0.040)	
%ΔVXJINDX(-1)	0.043		-0.039		0.012		-0.008		-0.034		-0.196	***	0.014	
	(0.030)		(0.033)		(0.041)		(0.023)		(0.022)		(0.022)		(0.028)	
%ΔVFTSEIX(-1)	-0.020		0.053		0.011		-0.028		-0.005		0.045		-0.155	***
	(0.037)		(0.041)		(0.051)		(0.028)		(0.025)		(0.027)		(0.035)	
Adj. R^2	0.011		0.181		0.118		0.079		0.115		0.214		0.102	
F-Statistic	3.87		37.12		22.92		15.13		22.17		45.41		19.73	
Akiaike AIC	6.94		7.15		7.57		6.40		6.17		6.31		6.83	
No. Observations	2290		2290		2290		2290		2290		2290		2290	

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

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

Sample Period: October 2010 - December 2019

Appendix B

Variance decomposition for G7 volatility indices - including Canada and Italy

Period	S.E.	%ΔVIX	%ΔVIXC	%ΔCACVOLI	%ΔVDAXNEW	%ΔIVIMIB	%ΔVXJINDX	%ΔVFTSEIX
%ΔVIX								
1	7.751	**100.000**	0.000	0.000	0.000	0.000	0.000	0.000
2	7.778	**99.777**	0.056	0.004	0.020	0.045	0.086	0.012
3	7.781	**99.571**	0.066	0.009	0.027	0.062	0.232	0.033
%ΔVIXC								
1	8.592	**17.539**	**82.462**	0.000	0.000	0.000	0.000	0.000
2	9.465	**14.602**	**85.002**	0.051	0.109	0.134	0.044	0.059
3	9.507	**14.455**	**84.764**	0.308	0.073	0.182	0.099	0.120
%ΔCACVOLI								
1	10.599	**11.955**	0.464	**87.581**	0.000	0.000	0.000	0.000
2	11.258	**12.341**	0.417	**86.924**	0.280	0.033	0.003	0.002
3	11.082	**12.448**	0.348	**86.708**	0.366	0.091	0.032	0.007
%ΔVDAXNEW								
1	5.911	**32.584**	0.993	**14.213**	**52.210**	0.000	0.000	0.000
2	6.145	**34.935**	0.921	**13.945**	**50.155**	0.000	0.006	0.038
3	6.128	**34.714**	0.893	**14.446**	**49.733**	0.117	0.018	0.078
%ΔIVIMIB								
1	5.270	**13.846**	0.692	**23.247**	8.630	**53.585**	0.000	0.000
2	5.589	**19.872**	0.639	**20.707**	7.677	**50.946**	0.157	0.001
3	5.597	**19.727**	0.829	**21.906**	7.193	**50.046**	0.249	0.051
%ΔVXJINDX								
1	6.375	**21.333**	0.034	0.992	2.382	0.956	**74.200**	0.103
2	6.390	**21.549**	0.068	1.010	2.390	0.968	**73.886**	0.129
3	6.386	**21.280**	0.054	1.040	2.280	0.942	**74.236**	0.168
%ΔVFTSEIX								
1	7.266	**27.762**	1.318	**20.574**	**15.844**	0.251	0.060	**34.189**
2	7.633	**30.589**	1.197	**19.208**	**16.739**	0.267	0.056	**31.944**
3	7.719	**30.010**	1.172	**19.586**	**16.369**	0.270	0.063	**32.529**

Note: This table reports the variance decomposition for the VAR model specified in Eq. (1). The variables are the daily percentage changes in implied volatility indices for the US (*VIX*), Canada (*VIXC*), France (*CACVOLI*), Germany (*VDAXNEW*), Italy (*IVIMIB*), Japan (*VXJINDX*), and UK (*VFTSEIX*). **Bold** text indicates more than 10% of variance explained by variable.
Sample Period: October 2010 - December 2019

Appendix C

Panel A - VAR: Inter-relationship between G7 volatility indices during COVID - including Italy

	%ΔVIX	%ΔCACVOLI	%ΔVDAXNEW	%ΔIVIMIB	%ΔVXJINDX	%ΔVFTSEIX
Constant	-0.640	-0.776	-0.592	-0.409	-0.303	-0.521
	(0.496)	(0.523)	(0.421)	(0.356)	(0.369)	(0.430)
%ΔVIX(-1)	-0.181 **	0.369 ***	0.411 ***	0.348 ***	0.324 ***	0.484 ***
	(0.090)	(0.095)	(0.077)	(0.065)	(0.067)	(0.078)
%ΔCACVOLI(-1)	-0.015	-0.739 ***	-0.039	0.050	0.046	-0.126
	(0.110)	(0.118)	(0.095)	(0.080)	(0.084)	(0.097)
%ΔVDAXNEW(-1)	0.220	0.175	-0.392 *	0.046	-0.214	-0.174
	(0.266)	(0.281)	(0.225)	(0.191)	(0.198)	(0.231)
%ΔIVIMIB(-1)	-0.008	-0.070	-0.126	-0.560 ***	-0.112	-0.094
	(0.157)	(0.166)	(0.134)	(0.113)	(0.118)	(0.137)
%ΔVXJINDX(-1)	-0.178	-0.257 **	-0.096	-0.138 *	-0.439 ***	-0.083
	(0.110)	(0.111)	(0.089)	(0.076)	(0.079)	(0.091)
%ΔVFTSEIX(-1)	-0.128	0.323	0.224	0.220	0.007	-0.586 ***
	(0.252)	(0.266)	(0.214)	(0.181)	(0.219)	(0.188)
Adj. R^2	0.109	0.268	0.185	0.357	0.414	0.215
F -Statistic	2.03	4.06	2.89	5.65	6.91	3.28
No. Observations	201	201	201	201	201	201

Panel B - Variance decomposition for G7 volatility indices during COVID - including Italy

Period	%ΔVIX	%ΔCACVOLI	%ΔVDAXNEW	%ΔIVIMIB	%ΔVXJINDX	%ΔVFTSEIX
%ΔVIX						
1	100.000	0.000	0.000	0.000	0.000	0.000
2	98.084	0.032	0.225	0.117	1.396	0.146
3	94.080	1.921	*2.198*	0.250	1.402	0.149
%ΔCACVOLI						
1	**22.863**	77.137	0.000	0.000	0.000	0.000
2	**18.719**	75.261	*3.123*	0.142	*2.110*	0.646
3	**18.471**	72.608	*3.003*	1.030	*2.416*	*2.472*
%ΔVDAXNEW						
1	33.339	**27.783**	38.878	0.000	0.000	0.000
2	35.740	**26.972**	35.796	0.389	0.546	0.557
3	34.678	**25.713**	34.194	1.367	0.537	*3.511*
%ΔIVIMIB						
1	*18.108*	17.045	**23.214**	41.633	0.000	0.000
2	**26.651**	12.703	**17.832**	40.841	1.325	0.649
3	**26.531**	11.745	**16.483**	38.719	2.122	*4.401*
%ΔVXJINDX						
1	21.123	**6.749**	1.676	2.608	64.174	*3.670*
2	22.617	**7.825**	1.642	*3.582*	60.753	*3.583*
3	21.692	**8.015**	2.297	*3.587*	60.544	*3.866*
%ΔVFTSEIX						
1	26.072	**30.474**	**30.473**	0.507	0.008	12.467
2	31.038	**31.093**	**26.579**	0.731	0.359	10.199
3	30.187	**30.401**	**25.838**	1.076	0.678	11.820

Note: Panel A reports the estimated coefficients for the VAR model specified in Eq. (1) for the COVID pandemic period only (March 2020 - December 2020). The endogenous variables are the daily percentage changes in implied volatility indices for the US (*VIX*), France (*CACVOLI*), Germany (*VDAXNEW*), Italy (*IVIMIB*), Japan (*VXJINDX*), and UK (*VFTSEIX*). Lag selection is on the basis of AIC with only the first lag reported. Standard errors are reported in parentheses. Panel B reports the variance decomposition for the model shown in Panel A. Increases of 5% or more relative to the overall sample period are indicated by **bold**, and 3%-5% by *italics*.

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

Sample Period: March 2020 - December 2020