Not Everyone is a Follower: The Behaviour of Interest Rate and Equity Markets within Major Economies relative to the US

Diana Tunaru
University of Kent,
Kent Business School,
Park Wood, Canterbury, CT2 7FS UK
d.tunaru@kent.ac.uk

Frank J. Fabozzi
EDHEC Business School
Contact author: fabozzi321@aol.com
EDHEC Risk Institute North American postal address
858 Tower View Circle, New Hope, PA 18938 USA

Abstract

Using a multi-factor continuous-time model we study the impact of the global financial crisis on the information transmission mechanism between interest rate and equity markets in the US and each of the four major economies (UK, Japan, Germany and Canada). The exchange of information through the return channel shows that the equity markets communicate differently with the short- and long-term interest markets: the linkages between the equity and money-markets follow similar patterns across all four major economies, while the feedbacks between the returns on equity and bond markets suggest country-specific relationships with the US The level of interdependence is higher between the equity and long-term bond markets, while within the money-markets context there is evidence of the flight-to-quality phenomenon.

Keywords: Global financial crisis, Level effects, Return feedbacks, Spillover effects

JEL: F37, G15, G01

1. Introduction

Despite the regularity of the financial crises, it is still difficult to control the spread of a crisis and to contain its consequences to the market where the shock has originated. Post-examination of such events can always bring important insights about the dynamic evolution of a crisis with great implications for policy makers and regulators on one hand, and international investors and portfolio managers on the other hand. The global financial crisis of 2007-2009 (hereafter GFC) had evolved in a complex fashion (Longstaff, 2010), involving different asset classes from fixed income (the subprime mortgage crisis of 2007) to equity markets (the collapse of Lehman Brothers in September 2008). It highlighted not only the importance of the country of origin (the US) in the financial global network, but also the implications of a crisis in one type of market to the other asset classes. In this paper we assess the impact of the GFC on the levels of market-integration within both domestic and international contexts.

In the aftermath of the GFC, the research on spillover effects has been revived with numerous studies exploring various transmission channels and developing new methods to model the dynamics of a crisis (Diebold and Yilmaz, 2009; Longstaff, 2010; Diebold and Yilmaz, 2012; Claeys and Vasicek, 2014; Finta et al., 2017). Most spillovers studies keep the domestic and the international transmission channels in isolation with fewer studies (e.g. Andersen et al., 2007; Christiansen, 2010; Ehrmann et al., 2011) combining simultaneously equity and bond returns in a discrete time econometric framework.

We investigate the impact of the GFC on the return feedback and correlations between the US and each of the four major economies, namely the UK, Germany, Japan and Canada. The continuous-time framework of Chan, Karolyi, Longstaff and Sanders (1992) (CKLS) was generalised to two and three factors in Nowman (2003) by including feedback effects in the conditional mean. More recently, Tunaru (2017) has modelled the term structure of interest rates for the UK using a four-factor CKLS framework. It is this four-factor dynamic model that we employ for a simultaneous analysis of the equity and bond markets between the two economies. Hence, we can analyse a more complex network of transmission channels including internal channels (domestic) and external (international) channels.

The continuous time specification that we use considers the level-effect parameter γ which measures the degree of dependence of the local volatility on the level of the state variable. In the context of equity markets the level-effect parameter is directly linked to what Black (1976) introduced as the leverage effect while trying to explain the negative empirical relationship observed between equity prices and volatility during periods of crisis. For a long time in the literature, this market anomaly was justified by the existence of high financial leverage. In a more recent empirical study, Danielsson et al. (2009) have shown that asset-market volatility is determined endogenously by multiple factors like leverage levels, feedback effects and market conditions. As a result of new hostile market conditions - the global crisis of 2008, the market participants responded through the fight-or-flight mechanism. In these turbulent times their aggregate behaviour results in inefficient or irrational markets, supporting the adaptive market hypothesis (AMH) (see Lo, 2012). The AMH assists a particular behaviour pattern called flight-to-safety, as investors adapt to new reality by rapidly reducing their equity holdings and consequently increasing pressure on prices of safer assets. Our analysis of the price discovery channel between different asset classes provides evidence of flight-to safety as there are positive feedback between equity returns and long-term yields across all major economies.

Despite the high degree of global integration among the major economies, their relationship with the US can still be country-specific due to differences in the structure of their financial systems, in the state of their economies and in the monetary policy decisions implemented following the GFC in order to mitigate its impact. Given the evidence that changes in the short-term interest rates as a monetary policy tool leads to adjustments in the return on other developed stock markets (see Hayo et al., 2010), we consider separately the short- and long-term segments of the bond markets. This allows us to explore if there are any differences in the way information is communicated between the stock markets and the specific maturity segment of the bond markets.

Our multi-factor CKLS model enables us to measure the return spillovers and detect any signs of contagion through the correlations coefficients between different pairs of asset classes. In our comparative analysis we found that the equity markets around the world became more integrated than the bond or money markets. More specifically, inside the bond and money markets the transmission channels present a lower degree of interconnectedness and there is evidence of decoupling effects of some major economies from the US - the market where the crisis originated.

The severity of the GFC and its snow-ball effect due to increased economic and financial integration prompted many central banks to act in a similar manner by lowering the short-term interest rates and also by adopting non-conventional monetary policies such as quantitative easing (QE) programmes. By modelling simultaneously, the stock and the money markets we can investigate whether the monetary policy influences the stock markets via short-term rates and observe the degree of convergence of those monetary policies across major economies by examining the transmission channel between various international money markets.

The rest of this paper is organised as follows. Section 2 reviews the current empirical evidence on information transmission between financial markets in general, and equity and bond markets in particular. Section 3 presents the data and some preliminary analysis while Section 4 describes the modelling approach. Our empirical results are presented and discussed in Section 5. The last section provides the final conclusions.

2. The Information Transmission Mechanism between Financial Markets

Developed stock markets have been thoroughly analysed with respect to spillover effects. Although the existence of return and volatility spillovers is widely acclaimed, a common feature of the findings points to the dominant role of the US stock market as a source of spillovers. For example, Hamao et al. (1990), Koutmos and Booth (1995) and Bae et al. (2003) found significant evidence of linkages between various developed stock markets with a clear global direction: the US stock market is the main exporter of volatility. Using univariate GARCH models, Base and Karolyi (1994) and Karolyi and Stulz (1996) also confirmed the influence of the US as a central "world" market on markets in other countries. The dynamics of these causal relationships seem to intensify especially after negative shocks mostly associated with a financial crisis.

Hartman et al. (2004) apply a nonparametric measure to evaluate the extreme linkages between stock and government bond markets for the G-5 countries. Based on weekly data over the 1987-1999 period they conclude that the extreme losses are generally much higher in the stock markets relative to government bond markets and find evidence for the flight-to-quality phenomenon. Both emerging and developed bond markets were analysed by Dungey et al. (2006) who applied a latent factor model to bond spread data for 12 countries in order to test for a contagion channel and showed that, despite increased volatility being experienced considerably more by the emerging markets in their study, the contagion effects were proportionately of similar magnitude for both emerging and developed markets.

Ehrmann and Fratzscher (2005) found significant international bond market linkages between the US and the euro area. Andersen et al. (2007) use high-frequency data over a relatively short period (1998-2002) to analyse the domestic contemporaneous relationship between equity and bond markets and the euro-dollar exchange rate. Connolly et al. (2007) investigated how the stock-bond returns relationship in the US, the UK and Germany varies with the changes in implied volatility from the US stock index option market. On days with large changes (positive or negative) in implied volatility, the stock-bond correlations were found to be negative, while for days with little changes in implied volatility the relationship is negative. Bond and equity volatilities have been analysed simultaneously by Christiansen (2010) who decomposed individual European bond/equity variances into global, regional and local bond/equity effects in order to measure the impact of the introduction of the euro in 2000 on spillover effects.

The idea of considering as many transmission channels as possible was followed and empirically investigated by Ehrmann et al. (2011) who analysed simultaneously the linkages between three asset classes both domestically and internationally for the US and the euro area. Their structural multifactor model includes seven asset prices as the endogenous variables: short-term interest rates, bond yields and equity returns, in both economies and their exchange rate. Their results show that the strongest shock transmission takes place within asset classes. Another key result suggests that the direct transmission of shocks in the bond markets is substantially increased by indirect transmission channels through other asset classes. For example, the equity markets in the US also influence the other two markets in the Eurozone, the short-term interest rates and bond yields, respectively.

The spillovers literature refers to the concept of contagion, which may occur during a financial crisis when markets seem to move together in a much closer manner when compared to an otherwise calm period. Under different forms of overreaction, noise trading and/or speculation, contagion may explain why changes in stock prices in one market spread across world markets beyond the level of propagation implied by economic fundamentals (Lin et al., 1994). Forbes and Rigobon (2002) challenged the accuracy of the tests for the presence of contagion based on correlation coefficients that were influenced by stock market volatility. They argued that the estimates of the correlation coefficients could be biased due to heteroscedasticity and therefore the previous association of a financial crisis with the phenomenon of contagion became questionable. When a correction for this bias was applied, the results changed and no longer evidenced the contagion effect. A simultaneous analysis of stock and bond markets was conducted by who introduced the concept of cross-asset contagion by recognizing evidence of contagion between stocks and bonds when there is "a significant increase of the correlation coefficient in a crisis period compared to a benchmark period resulting in a positive correlation level" Baur and Lucey (2009, p341). Their findings suggest that flights are occurring frequently during crises and if they happen simultaneously in different countries this could be interpreted as cross-country contagion.

More recently, Claeys and Vasicek (2014) used the factor-augmented VAR (FAVAR) model to measure the linkages between the government bond spreads of 16 EU countries during the 2000-2012 period. They found evidence of short periods of contagion between 2010 and 2011, defined by the International Monetary Fund and EU bailout-interventions for Greece and Ireland. However, they conclude that contagion is a rather rare phenomenon and the strongest linkages are the result of a larger shocks rather than of contagion.

Cheung et al. (2010) introduced the term of *fear* spillovers for which the best indicator is the TED spreads (i.e., the difference between the interest rates on interbank loans and on short-term US Treasury bills). In this context, the credit risk becomes another channel of transmission of information that seems to have changed the correlation among international markets during the recent global financial crisis. The authors use a trivariate VAR model and a Granger causality test to examine the return and volatility spillovers between the TED spread, the returns for the S&P500 stock index and other global stock markets such as the UK, Hong Kong, Japan, Australia, Russia and China. While the dominant role of the US increased during the crisis, the TED spread was also found to Granger cause the S&P500. These results may explain the spillover effects into other global stock markets.

Focusing on the US, Ding and Pu (2012) examined closely connected financial sectors in the US under different economic conditions. Stock, corporate bond and credit derivatives markets are considered for exploring both the static and dynamic structure of information spillovers and identifying factors that may influence any linkage across these markets. Based on a VAR estimation model and daily data over the period 2004-2009, the empirical results indicate a more intensified and timely information-transmission among these markets during the 2007-2009 crisis. While both volatility and liquidity factors influence separately the linkages between the markets, during the crisis when both factors are exogenously included in the model, it is only the volatility channel that is significant in all the three sub-periods analysed and that has a strong impact on all three financial markets. Furthermore, Ding and Pu (2012) found evidence that the credit derivatives and the stock markets swap the leading role in sending shock signals once a systemic crisis exists. Before the crisis, the surprise information is absorbed first by the credit derivatives market that quickly affects the stock market. However, during the crisis the stock market becomes more independent and plays a dominant role with investors taking more into account the signals from the equity markets rather than from the bond and the credit derivative markets. Similar evidence was found by Diebold and Yilmaz (2012) who developed a spillover index to measure the magnitude of the volatility spillovers (total and directional) across the US stock, bond, foreign exchange and commodities markets within a generalized VAR framework over the period 1999-2010. While the bond markets react rather slowly, the US equity market plays the most important role during all seven phases of the crisis, with net positive volatility spillovers from the stock market to the other markets exceeding 6% immediately after the collapse of Lehman Brothers in September 2008.

3. Data

We examine the interaction of the equity and interest rate markets for four country-pairs US-UK, US-Japan, US-Germany and US-Canada. The equity markets under discussion, are represented by local currency indices: Standard and Poor's 500 (S&P500), Financial Times-Stock Exchange 100 Share (FTSE100), NIKKEI 500, DAX30 and SP/TSX, respectively. All daily closing prices for the five stock indices are extracted from Thomson Reuters Datastream and the daily close-to-close returns are the continuously compounded returns, computed as $R(t) = \ln(p_t / p_{t-1})$, where p_t is the market total return index (dividend included) at time t.

The short-term interest rates are represented by one-month yields on government securities provided by the Treasury bills for the US, UK and Canada, while for Japan and Germany the FIBOR and Gensaki one-month rates, respectively. The long-term interest rates are represented by the 10-year yields of government benchmark bonds. The analysis distinguishes between the pre- and post-crisis period, demarked by the third quarter of 2007 as the starting point of the GFC. The full-sample data series cover the period from 2 July 2001 to 31 July 2014 and their summary statistics are presented in Table 1.

The descriptive statistics on the stock indices show that the time series with the highest variability and volatility are the Canadian and German stock indices, SP/TSX and DAX30, respectively. Between the two subperiods the volatility increases only for the S&P500 and DAX30. Before the GFC all the skewness measures are positive for all indices, however after the crisis the FTSE100 and SP/TSX series have a negative skewness. The most volatile 10-year yields before the crisis are those of Canada and Japan, while after the crisis, the volatility of the 10-year interest rates increases dramatically more than three times for the UK and Germany; in contrast the volatility decreases for the Japanese bond rates. The money-markets portray an interesting picture regarding the volatility of the analysed one-month rates.

The GFC has a significant impact on the UK and Germany's money markets where the volatility increases more than two times, it remains stable for Japan and it decreases only for the US suggesting that the monetary policies implemented by the FED have been more effective and more time-efficient than those in the other major money-markets.

Table1. Descriptive Statistics for Daily Stock Price Indices, Long-Term Interest Rates and Short-Term Interest Rates

	Period 2001-2007					Period 2007-2014				
Stock Indices	S&P500	FTSE100	NIKKEI500	DAX30	SP/TSX	S&P500	FTSE100	NIKKEI500	DAX30	SP/TSX
Mean	1,149.38	4,998.76	1,108.53	4,648.32	9,135.46	1,332.60	5,707.22	969.13	6,897.58	12,418.59
Maximum	1,539.12	6,732.40	1,588.53	8,066.18	14,161.00	1,988.07	6,878.49	1,530.42	10,028.71	15,524.82
Minimum	776.76	3,287.00	698.49	2,203.97	5,689.43	679.28	3,512.09	633.48	3,677.07	7,527.44
Std. Dev.	165.41	787.25	237.65	1,222.08	2,214.02	281.66	746.64	219.34	1,374.54	1,511.88
Skewness	0.07	0.23	0.40	0.50	0.58	0.24	-0.65	0.67	0.25	-0.78
Kurtosis	2.64	2.08	2.03	2.75	2.13	2.67	2.95	2.09	2.71	3.72
Jarque-Bera	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10Y Bond Yields	US10Y	UK10Y	JAP10Y	GER10Y	CAD10Y	US10Y	UK10Y	JAP10Y	GER10Y	CAD10Y
Mean	4.45	4.67	4.08	1.39	4.63	2.93	3.26	1.11	2.66	2.890
Maximum	5.43	5.52	5.27	1.99	5.80	5.19	5.54	1.96	4.67	4.71
Minimum	3.10	3.86	3.02	0.43	3.73	1.40	1.38	0.44	1.12	1.58
Std. Dev.	0.44	0.32	0.51	0.31	0.50	0.83	1.01	0.34	1.02	0.75
Skewness	-0.11	0.04	0.24	-0.72	0.37	0.16	0.12	0.06	0.21	0.13
Kurtosis	2.64	2.39	2.57	3.58	2.11	2.26	2.07	2.03	1.76	2.10
Jarque-Bera	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1M Interest Rates	US1M	UK1M	JAP1M	GER1M	CAD1M	US1M	UK1M	JAP1M	GER1M	CAD1M
Mean	2.56	4.32	0.07	2.76	2.87	0.51	1.34	0.19	1.36	1.15
Maximum	5.27	5.82	0.62	4.53	4.24	5.13	5.91	0.64	5.20	4.35
Minimum	0.74	3.25	0.00	2.02	0.97	0.00	0.18	0.03	0.09	0.08
Std. Dev.	1.51	0.55	0.16	0.68	0.75	1.08	1.92	0.19	1.59	1.02
Skewness	0.54	0.18	2.22	0.53	0.59	2.55	1.57	1.40	1.21	1.74
Kurtosis	1.75	2.21	6.68	2.04	2.02	8.59	3.59	3.13	2.85	5.23
Jarque-Bera	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

This table reports the summary statistics for the five countries across three asset classes. Equity Indices, 10-year government yields and one-month interest rates. The sample period is from July 2001 to July 2014. We divide the data into two sub-periods, 2001-2007 and 2007-2014, respectively.

We provide the time series plots of the equity indices in Figure 1. The stock markets considered in this empirical investigation exhibit the highest degree of co-movement in comparison with the other asset classes analysed, namely the 10-year government bonds and one-month government securities. Despite the gravity of this crisis, the stock markets followed a global trend of steady recovery reaching historical record high levels. Only the NIKKEI 500 time series follows a more particular path towards its recovery, with values still below the pre-crisis levels. Three major negative shocks seem to have impacted the paths of all stock market indices more or less at the same time. First, the cumulative effect of two events, the burst of the dot.com bubble and the terrorist attack in 2001 in the US, reached maximum effects in 2002. Second, the spread of the 2007 subprime mortgage crisis in the US culminated with the announcement of the collapse of Lehman Brothers in September 2008. The third negative shock is represented by the European sovereign debt crisis in 2011 that transferred also into the stock markets, however with lower impact relative to the global financial crisis in the US.

The graphs of the five time-series for the 10-year government bond yields illustrated in Figure 2 show the particularities of each national bond market, with the Canadian and Japanese long-term bond markets evolving along more individual paths. Two common features can be observed across all time-series analysed. The stock market downturn in 2002 impacted almost instantly all the other major bond markets around the world. Likewise, the clear event of the GFC in September 2008 led to a sharp decline in long-term interest rates. Another common reaction of the world bond markets, except Japan, is observed in 2011 as a result of the European sovereign debt crisis. After 2012 only the US, the UK and the Canadian bond markets show signs of recovering, with the 10-year bond yields remaining stable above 2%.

The one-month interest rates time series in Figure 3 exhibits the most diversity in their evolution. The differences and similarities in their paths over the sample period July 2001- July 2014 are clearly illustrated in Figure 3. In the pre-crisis period the short-term interest rates for the US and Germany evolved along a similar path, however with the German one-month FIBOR slightly lagging behind with a prolonged downturn in 2002 and a delayed start of the recovery in 2006 following the real-estate bubble in the US. The rest of the one-month interest rates have a slightly more particular evolution, with the UK and Canadian rates showing recovering as early as 2003 and 2004, respectively, while the Japanese rates reacted in jumps with an unprecedented increase in 2006. The ignition of the crisis in the summer of 2007 in the subprime mortgage market in the US had an immediate effect on the US one-month Treasury bills, as well as on the Canadian one-month securities. The other short-term interest rates series responded initially with a period of high volatility until September 2008 when a major decline is observed. Beyond 2008, the money markets around the world behaved in a similar manner with short-term rates just above the zero level, with only Canadian short-term rates close to 1%.

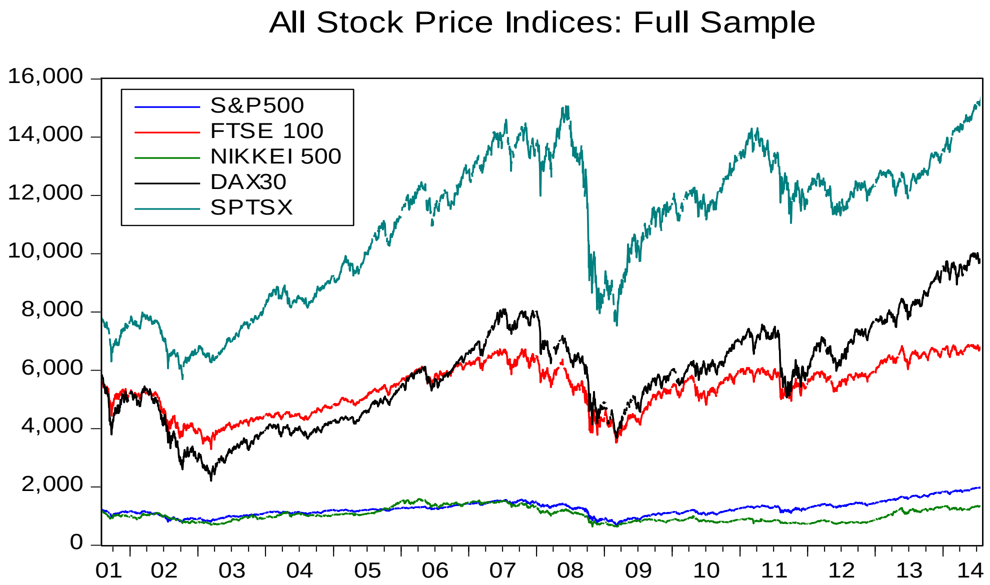

Figure 1. The time-series of stock price indices for all five countries during 2001-2014.

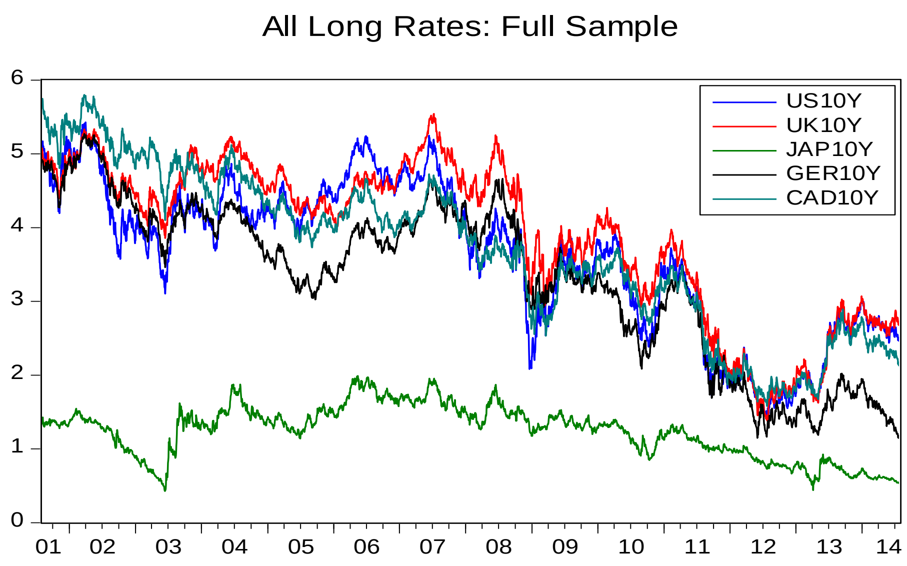

Figure 2. The time-series of long-term yields for all five countries during 2001-2014.

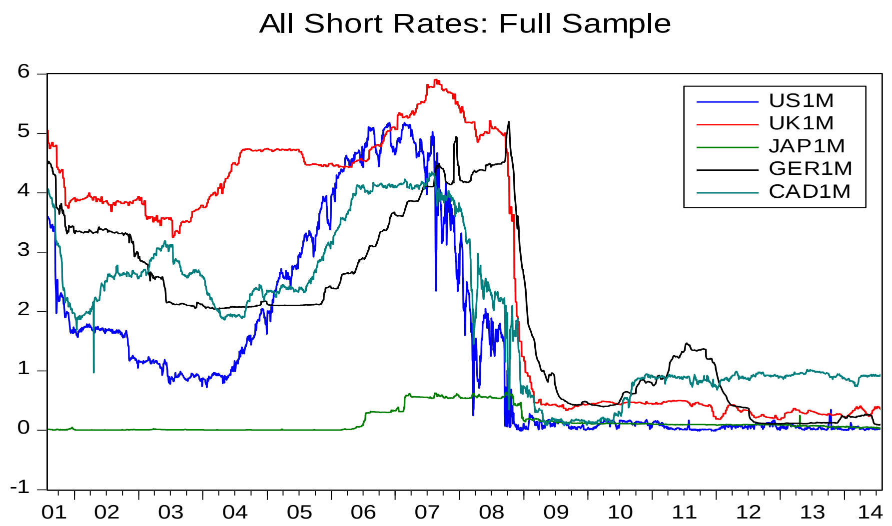

Figure 3. The time-series of short-term yields for all five countries during 2001-2014.

4. The Modelling Approach

The multivariate CKLS framework with feedbacks can also be applied to modelling return spillovers and contagion effects. The system of four stochastic differential equations is specified as follows:

$$
\begin{aligned}
dr_1(t) &= [\alpha_1 + \beta_{11} r_1(t) + \beta_{12} r_2(t) + \beta_{13} r_3(t) + \beta_{14} r_4(t)]dt + \zeta_1(dt) \\
dr_2(t) &= [\alpha_2 + \beta_{21} r_1(t) + \beta_{22} r_2(t) + \beta_{23} r_3(t) + \beta_{24} r_4(t)]dt + \zeta_2(dt) \\
dr_3(t) &= [\alpha_3 + \beta_{31} r_1(t) + \beta_{32} r_2(t) + \beta_{33} r_3(t) + \beta_{34} r_4(t)]dt + \zeta_3(dt) \\
dr_4(t) &= [\alpha_4 + \beta_{41} r_1(t) + \beta_{42} r_2(t) + \beta_{43} r_3(t) + \beta_{44} r_4(t)]dt + \zeta_4(dt)
\end{aligned} \tag{1}
$$

where the state vector $r = (r_1, r_2, r_3, r_4)$ is partitioned in two subsets, with (r_1, r_2) representing the log-returns of the stock indices (S&P500 and FTSE100, for example) and with (r_3, r_4) the yields for the two economies under consideration (US and UK, respectively). Therefore, the pair-indices $(1,2)$ and $(3,4)$ correspond to the same asset-class, either equity or bond markets within one country, while the pairs $(1,3)$ and $(2,4)$ correspond to cross-asset domestic markets inside the US and UK, respectively. The pairs of indices (1, 2) and (3, 4) indicate relationships within the same asset class in an international context.

The innovations $\zeta = (\zeta_1, \zeta_2, \zeta_3, \zeta_4)$ are correlated random measures (see Nowman, 1997) that satisfy

$$E[\zeta_i(dt)] = 0 \text{ for all } i = 1, \dots, 4 \tag{2}$$

and

$$E[\zeta(dt) \cdot \zeta'(dt)] = (dt)\Sigma(r,t), \tag{3}$$

where the local covariance matrix $\Sigma(r,t) = \{\sigma_{ij}(t)\}_{1 \le i, j \le 4}$ with $\sigma_{i,j}(t) = \rho_{ij}\sigma_i\sigma_j r_i^{\gamma_i}(t) r_j^{\gamma_j}(t)$ is a positive definite matrix with the following explicit structure:

$$
\Sigma(r,t) = \begin{pmatrix}
\sigma_1^2 r_1^{2\gamma_1}(t) & \rho_{12}\sigma_1\sigma_2 r_1^{\gamma_1}(t) r_2^{\gamma_2}(t) & \rho_{13}\sigma_1\sigma_3 r_1^{\gamma_1}(t) r_3^{\gamma_3}(t) & \rho_{14}\sigma_1\sigma_4 r_1^{\gamma_1}(t) r_4^{\gamma_4}(t) \\
\rho_{12}\sigma_2\sigma_1 r_2^{\gamma_2}(t) r_1^{\gamma_1}(t) & \sigma_2^2 r_2^{2\gamma_2}(t) & \rho_{23}\sigma_2\sigma_3 r_2^{\gamma_2}(t) r_3^{\gamma_3}(t) & \rho_{24}\sigma_2\sigma_4 r_2^{\gamma_2}(t) r_4^{\gamma_4}(t) \\
\rho_{13}\sigma_3\sigma_1 r_3^{\gamma_3}(t) r_1^{\gamma_1}(t) & \rho_{23}\sigma_3\sigma_2 r_3^{\gamma_3}(t) r_2^{\gamma_2}(t) & \sigma_3^2 r_3^{2\gamma_3}(t) & \rho_{34}\sigma_3\sigma_4 r_3^{\gamma_3}(t) r_4^{\gamma_4}(t) \\
\rho_{14}\sigma_4\sigma_1 r_4^{\gamma_4}(t) r_1^{\gamma_1}(t) & \rho_{24}\sigma_4\sigma_2 r_4^{\gamma_4}(t) r_2^{\gamma_2}(t) & \rho_{34}\sigma_4\sigma_3 r_4^{\gamma_4}(t) r_3^{\gamma_3}(t) & \sigma_4^2 r_4^{2\gamma_4}(t)
\end{pmatrix} \tag{4}
$$

The vector parameter to be estimated for each country-pair consists of 34 components: α_i are the intercepts in the drift component; β_{ij} represents the *return feedback* from market j to market i; the level-effect parameter γ_i indicates the *degree of dependence* of the volatility on the current level r_i; σ_i is a volatility scale-factor ; $\rho_{i,j}$ is the correlation coefficient between market i and market j; the matrix $\Sigma(r,t)$ measures the conditional covariances between the two countries internally and externally, while the parameter σ_i is a volatility scale-factor. A sudden change in the correlation parameter ρ_{ij} from the calm to the turbulent period will provide evidence of contagion between the markets i and j. An important feature of our continuous time specification is the elasticity of variance parameter γ that measures the so called *level-effect* or the degree of dependence of the local volatility on the level of the state variable. The level-effect parameter has been introduced by Cox (1975) in response to a possible inverse relationship observed in the equity market between stock price and the stock price volatility.

Nowman (1997) considered volatility as a step function, changing value at the beginning of each unit observation period and then remaining constant over that unit time interval. With a local constant volatility, the new model can be estimated over each observation interval by implementing the Gaussian methods developed by Bergstrom (1983, 1984). Bergstrom (1983) demonstrated that the continuous-time model has a unique solution that satisfies the following exact discrete stochastic difference equation:

$$r(t) = e^{\beta} r(t-1) + (e^{\beta} - I)\beta^{-1}\alpha + \varepsilon(t) \qquad t = 1, 2, ..., T \tag{5}$$

where $r(t) = [r_i(t)]'_{1\le i\le n}$, $\varepsilon(t) = [\varepsilon_i(t)]'_{1\le i\le n}$, $\alpha = (\alpha_i)'_{1\le i\le n}$, $e^{\beta} = I + \sum_{k=1}^{\infty} \frac{1}{k!}\beta^k$ and

$$E[\varepsilon(t)\cdot\varepsilon'(t)] = \int_0^1 e^{r\beta}\Sigma^*(r,t)e^{r\beta'}dr = \Omega(r,t) \tag{6}$$

The complete vector of structural parameters is $\theta = (\alpha_i, \beta_{ij}, \sigma_i, \gamma_i, \rho_{ij})_{1 \le i,j \le 4}$, comprising a total of 34 single-value parameters. Following Nowman (2001, 2003), we estimate the elements of θ by maximizing the Gaussian likelihood function or minimizing the expression $LF(\theta)$ which is equal to minus twice the logarithm of the Gaussian likelihood function:

$$LF(\theta) = \sum_{t=1}^{T} \log |\Omega(r,t)| + \sum_{t=1}^{T} \varepsilon_t' \Omega^{-1}(r,t) \varepsilon_t \quad (7)$$

5. Empirical Results

The estimates of the parameters are reported for the two sub-periods considered, the *pre-crisis* period from July 2001 to end of June 2007 and the *turbulent* period from July 2007 to July 2014. The parameters of most interest are the cross-market parameters: the elements of the feedback matrix β_{ij} and the covariance matrix Σ defined by three parameters: σ_i the scale factor, γ_i the level-effect parameter and ρ_{ij} the correlation coefficients that can provide evidence of contagion. The elements of the feedback matrix allow us to measure the return spillovers from one market to another. The results concerning the return channel are interpreted within three contexts: the internal-domestic channel (between two asset classes inside one economy), external-direct channel (between same types of markets from two economies) and the external-indirect channel (between two different types of markets from two different economies). In the case of the correlation coefficients a significant increase in the estimates of the correlation matrix among the factors from the calm to the turbulent period would provide (according to the definition of Baur and Lucey, 2009) evidence of contagion effects. Also, for each individual market the conditional volatility can be measured by the two conditional volatility parameters σ and γ .

First, we present and analyse the estimation results concerning the return spillovers. For each country pair the feedback parameters are organised in Tables 2, 3, 4 and 5. The results for the short- and long-term segments of the yield curve are displayed together to facilitate a comparative analysis of the relationship of the two types of interest rate markets with the equity markets. Second, the estimates of the volatility and correlation coefficients are displayed separately in Tables 6, 7, 8 and 9 for each country-pair, respectively.

5.1 The Return Spillovers Coefficients

For the US-UK pair (Table 2), inside the US, the stock market is the main transmitter of price discovery with significant positive feedback from S&P500 to both segments of the yield curve (all four values for β_{31} are positive and highly significant). However, within the UK we observe that after the crisis the money-market does not receive any price information from FTSE100 (β_{42} is insignificant) but it impacts the equity market negatively ($\beta_{24} = -0.0074$), while for the bond yields the positive feedbacks from the equity market have intensified from 0.1240 to 0.2717. In the international context, the direct return channels between the same asset classes indicate some surprising directions of information transmission. There is significant evidence of weak dominance from the FTSE100 to the S&P500 ($\beta_{12} = 0.0110$ and $\beta_{12} = 0.0753$ for both segments), whereas there are bidirectional return feedbacks (β_{34} and β_{43}), positive for the short-term segment and negative after the crisis from the US to the UK for the long-term segment of the yield curve ($\beta_{43} = -0.0448$). The external-indirect channels (different asset classes and different countries) are present only in the bond markets context (see also in Ehrmann et al., 2011), with only one bidirectional feedback between the S&P500 and the UK 10-year bond market (β_{14} and β_{41}). This indirect channel is also present as the UK bond market transmits (receives) positive (negative) feedback to (from) the US equity market.

The US-Japan results presented in Table 3, reveal evidence of return feedbacks in most directions after 2007, whereas before the crisis there were only two positive unidirectional feedbacks from the S&P500 to the domestic US bond market and to NIKKEI500. After the crisis, the return information flows through the internal channels in a different way from the U.S-UK context, as the Japanese equity and bond markets impact each other negatively (β_{24} and β_{42} are significant and negative for both maturity segments of interest rates). Comparing the two segments of the yield curve across the two countries, the internal flow of information has the same patterns in Japan, while in the US the feedback is unidirectional and positive from the bond market to S&P500 ($\beta_{13} = 0.0022$), and bidirectional and of opposite sign from the money-market to the US equity market ($\beta_{13} = -0.0057$). When analysing the external direct channel, the transmission of price discovery between the equity and money markets has the same bidirectional patterns (all estimates $\beta_{12}, \beta_{21}, \beta_{34}, \beta_{43}$ are all positive) as in the case of the UK. However, in the bond markets case the return feedbacks are different from the UK, as the Japanese bond market impacts positively the US 10-year bond yields with no influence in the opposite direction ($\beta_{34} = 0.0813$ and β_{43} is insignificant); and S&P500 affects positively NIKKEI500. There are slightly more international indirect channels for Japan, with new channels from the NIKKEI500 ($\beta_{32} = 0.0897$) to the US bond market and from US money market to Japanese equity market NIKKEI500 ($\beta_{23} = 0.0120$).

The results for the US-Germany pair are presented in Table 4. Internally, the German bond and equity markets communicate via the return channel in the same way as in the UK with a unidirectional positive feedback from DAX30 to the 10-year German bond market ($\beta_{42} = 0.1099$. In the money-market context, we observe the same consistent negative patterns as for the UK and Japan are observed as $\beta_{24} = -0.0128$ and $\beta_{42} = -0.1071$. Concerning the external direct channel, there is evidence of positive feedbacks from the S&P500 to DAX30, while the bidirectional feedback between the interest rate markets are negative from the US to the German bond market (as in the case of the UK, $\beta_{43} = -0.0099$), and positive from the US to the German money market (as for the UK and Japan, $\beta_{43} = 0.0128$). Interestingly, the external indirect return routes between Germany and the US become most complex, with both equity markets of the U.S and Germany impacting the 10-year yield of the other country, while in the money-market context three out four return indirect channels are active.

The estimation results for the US-Canada pair (see Table 5) show some return spillovers patterns especially after the crisis. The internal routes indicate clear dominance of the equity markets over both short- and long-term interest rates, although they are positive for the bond markets ($\beta_{42} = 0.1555$) and negative for the money-markets ($\beta_{42} = -0.0243$). Externally across asset classes, the Canadian bond market has the highest positive feedback effect on the US bond market ($\beta_{34} = 0.24$) and with a limited response from US to Canada. The money markets behave differently from the bond markets, as there are negative feedbacks from Canadian money market to the US money market ($\beta_{34} = -0.0725$). In contrast with the UK, Japan and Germany, the price discovery channel for the equity markets indicates negative feedbacks from SP/TSX to S&P500 (β_{12} are both negative), a pattern that accentuates after the crisis. This can be explained relative to the other major economies by the fact that the Canadian equity market had faster access to current information through the multiple-market listed shares and therefore it will have advantage in price discovery process (see Frijns et al., 2018). In terms of indirect external channels, there are insignificant feedbacks in general, with only the Canadian equity market influencing the US money-market ($\beta_{32} = 0.0418$ after the crisis).

The analysis of the price discovery channel highlights two important aspects. First, for all major economies the UK, Japan, Germany and Canada in relation to the US, we find evidence of flight-to-safety behaviour as a result of the crisis as long-term yields are positively related to equity returns. Investors react with fear towards negative equity returns by exercising higher demand for bonds perceived as safer investments, with the effect of declining long-term interest rates. Second, our results suggest a convergence among the international money markets with positive bidirectional return feedbacks (except for Canada). This can potentially be explained by the similar monetary policies adopted by most countries through both conventional (reduction of short-term interest rates) and unconventional (specific QE quantitative easing programmes) tools.

Table 2. The Return-feedback Coefficients US-UK
Stock Indices -Yields

US – UK	Long-Term Yields		Short-Term Yields	
Parameters	Before	After	Before	After
α_1	-0.0039***	-0.0035***	0.0000	0.0008***
α_2	-0.0001	-0.0001	-0.0001*	0.0069***
α_3	-0.0063***	-0.0033***	-0.0036***	-0.0070***
α_4	-0.0092***	-0.0191***	0.0004***	0.0045***
β_{11}	0.0386***	0.0371***	-0.0020	-0.1023***
β_{12}	0.0199***	0.0110***	0.0009	0.0753***
β_{13}	-0.0200***	-0.0285***	-0.0006***	-0.007**
β_{14}	0.0099***	0.0253***	0.0020***	-0.0000
β_{21}	0.0080	0.0024	0.0036	0.0360***
β_{22}	-0.0012	-0.0009	-0.0014	-0.1095***
β_{23}	-0.0045***	-0.0021	-0.0004*	0.0149***
β_{24}	-0.0020	0.0009	0.0008	-0.0074***
β_{31}	0.0894***	0.0525***	0.0639***	0.0931***
β_{32}	0.0117	-0.0022	-0.0048	-0.0008
β_{33}	-0.0898***	-0.0893***	-0.0010	-0.0370***
β_{34}	0.0644***	0.0717***	-0.0103***	0.0163***
β_{41}	-0.0049	-0.0582***	-0.0003	0.0517***
β_{42}	0.1240***	0.2717***	-0.0056	-0.0950
β_{43}	-0.1091***	-0.0448***	0.0008*	0.0328***
β_{44}	0.0841***	0.0316***	0.0006	-0.0177*

Note: ***, ** and * indicate that the estimate is statistically significant at 1%, 5% and 10%, respectively.

Table 3. The Return-feedback Coefficients US-Japan
Stock Indices - Yields

US - Japan	Long-Term Yields		Short-Term Yields	
Parameters	Before	After	Before	After
α_1	0.0000	0.0002***	0.0005***	-0.0029***
α_2	-0.0003***	0.0003***	-0.0009***	0.0041***
α_3	-0.0025***	-0.0053***	-0.0029***	-0.0090***
α_4	-0.0000	0.0019***	0.0000***	0.0019***
β_{11}	0.0005	-0.0045***	-0.0074**	-0.1076***
β_{12}	-0.0002	0.0007	-0.0010	0.1551***
β_{13}	-0.0007	0.0022***	0.00053	-0.0057**
β_{14}	0.0001	-0.0066***	0.0039**	0.00031
β_{21}	0.0163***	0.0266***	0.0420***	0.0203***
β_{22}	-0.0110***	-0.0351***	-0.0284***	-0.0810***
β_{23}	-0.0007	0.0084***	0.0007*	0.0120***
β_{24}	0.001489	-0.0104***	-0.0056***	-0.0350***
β_{31}	0.0418***	-0.0080	0.0241*	0.1234***
β_{32}	0.0024	0.0897***	0.0194*	0.0007
β_{33}	-0.0130***	-0.0397***	-0.0037***	-0.0577***
β_{34}	-0.0011	0.0813***	-0.0135*	0.0982***
β_{41}	0.0000	0.0011	-0.0021***	0.0009
β_{42}	0.0020	-0.0303***	0.00129	-0.0281***
β_{43}	-0.0002	0.0015	0.0000	0.0023*
β_{44}	-0.0113***	0.0022	-0.0049**	-0.0165**

Note: ***, ** and * indicate that the estimate is statistically significant at 1%, 5% and 10%, respectively.

Table 4. The Return-feedback Coefficients US- Germany
Stock Indices - Yields

US- Germany	Long-Term Yields		Short-Term Yields	
Parameters	Before	After	Before	After
α_1	-0.0000	-0.0001*	0.0000	-0.0014***
α_2	-0.0005***	0.0006***	0.0003**	0.0074***
α_3	-0.0073***	-0.0081***	-0.0012***	-0.0303***
α_4	0.0017***	-0.0035***	-0.0003***	0.0016***
β_{11}	-0.0043	-0.0050	-0.0153***	-0.0464***
β_{12}	0.0046	0.0065	0.0136***	0.0547***
β_{13}	-0.0007	-0.0003	-0.0000	-0.0030**
β_{14}	-0.0006	-0.0001	-0.0029***	-0.0024***
β_{21}	0.0121**	0.0355***	0.0198*	0.0319***
β_{22}	-0.0039	-0.0363***	-0.0210**	-0.1091***
β_{23}	0.0012	-0.0008	0.0011***	0.0204***
β_{24}	-0.0010	0.0006	0.0013*	-0.0128***
β_{31}	0.1169***	-0.1375***	0.0313**	0.4110***
β_{32}	0.0016	0.2076***	-0.0101	-0.0003
β_{33}	-0.0400***	-0.0378***	-0.0045***	-0.2056***
β_{34}	0.0182***	0.0290***	-0.0001	0.0867***
β_{41}	-0.0272**	-0.0848***	-0.0001	0.1077***
β_{42}	-0.0022	0.1099***	0.0049	-0.1071***
β_{43}	0.0164***	-0.0099***	0.0009***	0.0128***
β_{44}	-0.0105***	0.0066**	-0.0020**	-0.0051***

Note: ***, ** and * indicate that the estimate is statistically significant at 1%, 5% and 10%, respectively.

Table 5. The Return-feedback Coefficients US- Canada
Stock Indices - Yields

US - Canada	Long-Term Yields		Short-Term Yields	
Parameters	Before	After	Before	After
α_1	0.0017***	-0.0018***	0.0002***	0.0012***
α_2	0.0001***	-0.0002**	-0.0003***	0.0027***
α_3	0.0007***	-0.0136***	-0.0016***	-0.0029***
α_4	0.0069***	-0.0124***	-0.0007***	-0.0011***
β_{11}	-0.0143***	0.0404***	0.0019	0.0008
β_{12}	-0.0074***	-0.0110*	-0.0041***	-0.0139***
β_{13}	0.0060***	-0.00026	0.0003	-0.0004
β_{14}	-0.0075***	0.0004	0.0003	0.0003
β_{21}	-0.0078***	0.0315***	0.0205***	0.0161***
β_{22}	0.0046***	-0.0216***	-0.0119***	-0.0414***
β_{23}	0.0004	-0.0070**	-0.0000	0.0004
β_{24}	-0.0011***	0.0082**	0.0002	0.0005
β_{31}	0.0890***	0.1662***	-0.0674***	-0.0067***
β_{32}	-0.0660***	0.0088	0.0734***	0.0418***
β_{33}	-0.0066**	-0.2135***	-0.0024**	-0.0578***
β_{34}	-0.0155***	0.2442***	-0.0066***	-0.0725***
β_{41}	-0.0429**	-0.0257	-0.0473***	0.0529***
β_{42}	-0.0356**	0.1555***	0.0477***	-0.0243**
β_{43}	0.0180***	0.015633	0.0018**	0.0348***
β_{44}	-0.0327***	-0.0310**	-0.0102***	-0.0756***

Note: ***, ** and * indicate that the estimate is statistically significant at 1%, 5% and 10%, respectively

5.2 The Covariance Coefficients

Turning to the covariance matrix, we briefly discuss the individual conditional volatility parameters (σ_i, γ_i) and focus on the correlation coefficients ρ_{ij} as a measure of the cross-linkages between different types of markets and recognise that contagion effects are present if there are substantial changes in their estimated value between the two sub-periods.

For the US - UK analysis (see Table 6) almost all volatility scale factors increase, a special result being the volatility scale factor for S&P500 within the bond market context: as in Dontis-Charitos et al. (2013) S&P500 exhibits explosive volatility factor ($\sigma_1 = 588.43$) during the 2007-2014 period. Evidence of higher volatility is also provided by significant increases in the level-effect parameters $\gamma_i (i = 1,2,3,4)$ with some changing sign from negative to positive. Turning to the cross-linkages, internally the US bond market becomes less interlinked with the equity market, while there is a negative change in the correlation coefficient between the equity and money-markets in the US ($\rho_{13} = -89\%$). After 2007, in the UK the money-market also moves away from the equity market, while there is evidence of flight-to-safety as the bond and equity market seem to move closer ($\rho_{24} = 0.2934$)There are also significant changes in the indirect correlation coefficients with the main observation of negative correlations coefficients within the money-market context ($\rho_{14} = -0.3050$ and $\rho_{23} = 0.0431$).

If we accept a significant increase in the correlation coefficient as evidence of contagion, then in the US-UK analysis we can conclude that there has been contagion within the money-markets (supported by simultaneous flights between equity and money markets in both US and UK), while there are significant decoupling effects between the bond markets of these two economies (ρ_{34} has decreased from 0.71 to 0.46).

The analysis on US-Japan linkages (see Table 7) reveals several different patterns when compared with the U.S-UK relationship. The volatility scale factors σ_i are difficult to estimate with only a few significant estimates and without substantial changes between the two sub-periods. In contrast with the UK results, the level-effect parameters γ_3 and γ_4 for both bond and money-markets are decreasing. One reason for which this effect could not be better quantified could be the close-to-zero interest rate environment that persisted in Japan since 1999. The local volatility becomes more dependent on the level of interest rates only for the two stock indices S&P500 and NIKKEI500 when analysed in the money market context ($\gamma_1 = 2.67$ and $\gamma_2 = 3.86$

, see Table 7). Regarding the correlation coefficients, similar results with the UK suggest the decoupling effects inside the US economy between equity and both interest rate markets, while in Japan those markets seem to have larger co-movements following the last GFC ($\rho_{24} = 0.09$ and $\rho_{24} = 0.68$, respectively). The external direct linkages within the same asset class show that both short- and long-term interest rate markets between US and Japan become more interconnected with some contagion effects (ρ_{34} increased from -0.07 to 0.21 and from -0.14 to 0.15, respectively), whereas the linkage between US and UK bond markets has weakened.

The covariance estimation results for the US- Germany pair (see Table 8) are highly similar to those for US-Japan: the estimates of the volatility parameters (σ_i, γ_i) present the same change of direction. The level effects indicated by parameter γ exacerbated during the crisis in both equity markets in the bond context. The estimates of the correlation matrix between the two sub-periods indicate that the interdependencies between the stock markets of the two countries intensified from 0.66 to 0.71. The bond markets converged towards one another, with the correlation increasing from 0.31 to 0.58. Before the crisis, the equity and bond markets in Germany were uncorrelated $\rho_{24} = 0.02$, but during the crisis there was a significant correlation ($\rho_{24} = 0.22$).

Finally, the estimation results for the covariance matrix of the US-Canada pair show important similarities with the UK's relationship with the U.S but also considerable differences from all the other major economies analysed in this study. We found the GFC had the same impact in Canada as in the UK on most of the volatility scale-factor and level-effect parameters, except on the level-effect parameters of the equity markets in relation to the money market $\gamma_1 = -12.28$ for S&P500 and $\gamma_2 = -9.06$. Looking at the correlation coefficients within the same asset-class, there is an increase in the correlation between the S&P500 and SPTSX within both contexts of short- and long-term interest rates (after the crisis $\rho_{12} = 0.61$ and $\rho_{12} = 0.67$). This is a pattern observed only for the US - Canada pair, which may be explained by the existence of the cross-listed shares of Canadian companies on the NYSE. We may conclude that there has been contagion between the money-markets of the US and Canada as ρ_{34} has increased substantially from 0.20 to 0.63, while the interdependence between the bond markets of the US and Canada has diminished as the result of the crisis.

An overall comparison of the covariance parameters shows that across the asset classes the volatility of the equity markets has increased the most, followed by the money-markets; the volatility of the bond markets has decreased in Japan and Germany, while they became slightly more volatile in the UK and Canada. In terms of markets interlinkages, we observed clear evidence of contagion between the US money-market and all the other money-markets, whereas there is evidence of strong decoupling effects of the UK and Canada's bond markets from the bond market in the US.

Table 6. The Covariance Coefficients US-UK
Stock Indices -Yields

US – UK	Long-Term Yields		Short-Term Yields	
Parameters	Before	After	Before	After
γ_1	3.3182***	5.6097***	-6.0232***	3.0420***
γ_2	-0.1533	-0.1711	-12.1077***	0.6165***
γ_3	1.0045***	1.0267***	0.4381***	0.4302***
γ_4	2.4424***	2.0753***	0.1270***	0.6568***
σ_1	0.8555	588.4300***	0.00001	3.2289*
σ_2	0.0001	0.0001	0.0000	0.0007***
σ_3	0.0151	0.0271***	0.0027***	0.0198***
σ_4	0.9584***	1.3226***	0.0004***	0.0062***
ρ_{12}	0.4676***	0.6020***	0.4455***	0.0199***
ρ_{13}	0.1112***	0.1023***	-0.0002	-0.8983***
ρ_{14}	0.1027***	0.3928***	0.0916***	-0.3050***
ρ_{23}	0.0528***	0.0372*	0.0684***	-0.0431*
ρ_{24}	0.0159	0.2934***	0.0488**	-0.1741***
ρ_{34}	0.7097***	0.4621***	-0.0102	0.2780**
LogLF	**91,192.44**	**103,233.55**	**94,475.40**	**102,756.00**

Note: ***, ** and * indicate that the estimate is statistically significant at 1%, 5% and 10%, respectively.

LogLF is the logarithm of the likelihood function and represents the maximum value of the objective function used in the estimation process.

Table 7. The Covariance Coefficients for US - Japan

Stock Indices - Yields

US - Japan	Long-Term Yields		Short-Term Yields	
Parameters	Before	After	Before	After
γ_1	3.1358***	-13.2078***	-1.7977***	2.6778***
γ_2	-1.0022**	0.0503	-2.9307***	3.8591***
γ_3	0.7026***	0.2858***	0.5818***	0.4568***
γ_4	1.7635***	0.6302***	0.7503***	0.6831***
σ_1	0.4493	0.0000	0.0000	1.3221*
σ_2	0.0000	0.0002	0.0000	7.2669***
σ_3	0.0052***	0.0019***	0.0049***	0.0146***
σ_4	0.1982	0.0043***	0.0128***	0.0169***
ρ_{12}	0.4196***	0.5275***	0.4282***	-0.6003***
ρ_{13}	0.0110	0.0027	-0.0823***	-0.4452***
ρ_{14}	-0.0112	0.2033***	0.0573***	-0.8245***
ρ_{23}	0.0242	-0.0641***	0.00217	0.0820*
ρ_{24}	-0.0274	0.0943***	0.0835***	0.6782***
ρ_{34}	-0.1433***	0.1573***	-0.0766***	0.2138**
LogLF	**93,314.28**	**103,271.39**	**98,375.92**	**98,804.26**

Note: ***, ** and * indicate that the estimate is statistically significant at 1%, 5% and 10%, respectively.
LogLF is the logarithm of the likelihood function and represents the maximum value of the objective function used in the estimation process.

Table 8. The Covariance Coefficients for US - Germany
Stock Indices - Yields

US - Germany	Long-Term Yields		Short-Term Yields	
Parameters	Before	After	Before	After
γ_1	3.2890***	-10.7925***	-7.3698***	2.7349***
γ_2	0.1337	-10.5350***	-7.8939***	2.3521***
γ_3	0.9779***	0.5780***	0.5290***	0.4522***
γ_4	2.4106***	0.3347***	2.4218***	0.6075***
σ_1	0.6707	0.0000	0.0000**	0.7056
σ_2	0.0002	0.0000	0.0000**	0.0729
σ_3	0.0127	0.0052	0.0038***	0.0275***
σ_4	0.9587***	0.0017	0.8571***	0.0035***
ρ_{12}	0.6571***	0.7131***	0.6260***	-0.4054***
ρ_{13}	-0.0101	0.0073	-0.0006***	-0.2705***
ρ_{14}	0.0470**	0.1995***	-0.0121***	-0.5610***
ρ_{23}	-0.0429**	0.0741***	0.1207***	-0.1361***
ρ_{24}	0.0179	0.2221***	-0.0093***	0.4161***
ρ_{34}	0.3074***	0.5771***	0.0536***	0.3299***
LogLF	**89,170.72**	**109,769.54**	**96,465.05**	**104,990.82**

Note: ***, ** and * indicate that the estimate is statistically significant at 1%, 5% and 10%, respectively. LogLF is the logarithm of the likelihood function and represents the maximum value of the objective function used in the estimation process.

Table 9. The Covariance Coefficients for US - Canada
Stock Indices – Yields

US - Canada	Long-Term Yields		Short-Term Yields	
Parameters	Before	After	Before	After
γ_1	-8.0239***	3.6393***	-14.4754***	-12.2789***
γ_2	2.6828***	-0.2416	-4.1418***	-9.0621***
γ_3	0.0002	1.0369***	0.5586***	1.7325***
γ_4	2.3802***	2.2647***	1.6156***	1.6566***
σ_1	0.0000	2.7508*	0.0000	0.0000
σ_2	0.0541***	0.0001	0.0000	0.0000
σ_3	0.0006	0.0301	0.0042***	0.0261***
σ_4	0.7251**	2.2625***	0.0000***	0.0095***
ρ_{12}	0.5893***	0.6680***	0.5898***	0.6112***
ρ_{13}	0.0668***	-0.1289***	-0.0116	0.0046
ρ_{14}	0.0459**	0.1949***	-0.0036	0.0378
ρ_{23}	0.1307***	0.0515	0.1254***	-0.0056
ρ_{24}	0.0890***	0.4462***	0.1125***	0.0661*
ρ_{34}	0.7905***	0.4285***	0.1952***	0.6338***
LogLF	**91,778.35**	**103,055.58**	**91,653.65**	**104,290.72**

Note: ***, ** and * indicate that the estimate is statistically significant at 1%, 5% and 10%, respectively. LogLF is the logarithm of the likelihood function and represents the maximum value of the objective function used in the estimation process.

6. Conclusions

Given the high degree of integration of the global financial markets, shocks in financial systems are likely to spread simultaneously at both the domestic and international level. To include these two levels, we jointly model the dynamic interaction between equity and bond markets to capture internal effects, and across paired countries to gauge external effects. Employing a continuous-time methodology, we examine the propagation of the last financial crisis of 2007-2009 from the US to four major economies, namely the UK, Japan, Germany and Canada.

The analysis of the feedback transmission mechanism shows that among the equities, short-term bonds and long-term bonds, the equity markets are the dominant transmitter, while several markets dominate their US counterparty markets (FTSE100 over S&P500; Canadian and Japanese bond markets over the US bond market, Canadian money-market over the US money-market). We found that during turbulent times the money-markets of the other four major economies communicate with the US money-market in similar ways through the internal and external-direct channels. This result reflects a substantial degree of alignment across international money markets in terms of monetary policies. A particular result is that the only (negative) return feedbacks are those from Canada to the US for equity and money-markets. These findings can potentially explain the different position taken by the Canadian central bank regarding its short-term monetary policy that proved to protect the most the Canadian financial system during the last global financial crisis. We also found that in the context of the bond markets, the return estimation results present country-specific patterns in the return information transmission channels. For example, for the UK, the FTSE100 has a unique positive unidirectional impact on S&P500; the external indirect channels are most active between the Japanese and the US equity and bond markets; the Canadian bond market has the highest unidirectional positive feedback effect on the US bond market.

In terms of the interdependence, UK and Canada exhibited the same dynamics in the correlation patterns with the US. Internally, inside the UK and Canada the communication between the stock and the bond markets increased during the crisis, while in the US the two types of markets moved apart. Externally, equity markets between US-UK and US-Canada, respectively, moved even closer, in contrast with the bond markets relationships where both the UK and Canada seemed to decouple from the US bond market. The latter findings may indicate different approaches from the US where some fiscal policy interventions such as tax cuts could have affected long-term expectations regarding the economy. For Germany and Japan both types of markets, equity and bond markets, followed closely the evolution of the US markets during the crisis.

The main conclusion of the continuous-time analysis is that during the GFC the equity markets around the world became more integrated than the bond or money markets. For the bond and money markets our evidence suggests that country specifics such different monetary and fiscal policies and structure of the banking system, may be responsible for a lower degree of interconnectedness and even decoupling effects between the US and the other major economies, such as the UK and Canada.

References

Andersen, T.G., Bollerslev, T., Diebold, F.X. and Vega, C. (2007). Real-time price discovery in global stock, bond and foreign exchange markets, *Journal of International Economics 73* (2), 251–277.

Bae, K., Karolyi, G. A. and Stulz, R. M. (2003). A New Approach to Measuring Financial Contagion. *Review of Financial Studies 16*, 717 – 63.

Base, K.H. and Karolyi, G.A. (1994). Good News, Bad News and International Spillovers of Stock Return Volatility Between Japan and the US. *Pacific-Basin Finance Journal 2,* 405-38.

Baur, D.C. and Lucey, B.M. (2009). Flights and contagion - An Empirical Analysis of Stock-Bond Correlations. *Journal of Financial Stability 5,* 339-352.

Bergstrom, A. R. (1983). Gaussian Estimation of Structural Parameters in Higher-Order Continuous Time Dynamic Models. *Econometrica 51*, 117-152.

Bergstrom, A. R. (1984). Continuous Time Stochastic Models and Issues of Aggregation Over Time. In Z. Griliches and M. D. Intriligator (Eds.), *Handbook of Econometrics*. Amsterdam: North-Holland *2*, 1146-1212.

Black, F. (1976). Studies of Stock Price Volatility Changes. *Proceedings of the Business and Economics Section of the American Statistical Association* , 177–181.

Chan, K. C., Karolyi, G. A., Longstaff, F. A. and Sanders, A. B. (1992). An Empirical Comparison of Alternative Models of the Short-Term Interest Rate. *Journal of Finance 47*, 1209–1227.

Cheung, W., Fung, S. and Tsai, S-C. (2010). Global Capital Market Independence and Spillover Effect of Credit Risk: Evidence from the 2007-2009 Global Financial Crisis. *Applied Financial Economics 20*, 85–103.

Christiansen, C. (2010). Decomposing European Bond and Equity Volatility. *International Journal of Finance & Economics 15*, 105-122.

Claeys, P., and Vasicek, B. (2014). Measuring Bilateral Spillover and Testing Contagion on Sovereign Bond Markets in Europe. *Journal of Banking & Finance 46*, 151-65.

Connolly, R.A., Stivers, C. and Sun, L. (2007). Commonality in the Time-variation of Stock-stock and Stock–bond Return Comovements. *Journal of Financial Markets 10*, 192–218.

Cox, J. C. (1975). Notes on Option Pricing I: Constant Elasticity of Variance Diffusions. *Working Paper*, Stanford University.

Danielsson, J., Shin, H. S. and Zigrand, J.P. (2009). Risk Appetite and Endogenous Risk. Technical report, FRB of Cleveland/NBER Research Conference on Quantifying Systemic Risk.

Diebold, F.X. and Yilmaz, K. (2009). Measuring financial asset return and volatility spillovers, with application to global equity markets, *The Economic Journal 119*, 158–171.

Diebold, F. X., and Yilmaz, K. (2012). Better to Give Than to Receive: Predictive Directional Measurement of Volatility Spillovers. *International Journal of Forecasting 28*, 57-66.

Ding, L. and Pu, X. (2012). Market Linkage and Information Spillover: Evidence from Pre-crisis, Crisis, and Recovery Periods. *Journal of Economics and Business 64*, 145–59.

Dontis-Charitos, P., Jory, S.R., Ngo, T. and Nowman, K.B. (2013). A Multi-country Analysis of the 2007–2009 Financial Crisis: Empirical Results from Discrete and Continuous Time Models. *Applied Financial Economics 23*, 929–950.

Dungey, M., Fry, R., González-Hermosillo, B. and Martin, V. (2006). Contagion in international bond markets during the Russian and the LTCM crises. *Journal of Financial Stability 2*, 1-27.

Ehrmann, M.and Fratzscher, M. (2005). Equal Size, Equal Role? Interest Rate Interdependence Between the Euro Area and the United States. *The Economic Journal 115*, 928-48.

Ehrmann, M., Fratzscher, M., and Rigobon, R. (2011). Stocks, Bonds, Money Markets and Exchange Rates: Measuring International Financial Transmission. *Journal of Applied Econometrics 26*, 948-974.

Finta, M.A., Frijns, B. and Tourani-Rad, A. (2017). Contemporaneous Spillover Effects between the US and the UK Equity Markets. *The Financial Review 52*, 145-166.

Frijns, B., Indriawan, I. and Tourani-Rad, A. (2018). The Interactions Between Price Discovery, Liquidity and Algorithmic Trading for US-Canadian Cross-listed Shares. *International Review of Financial Analysis* 56, 136 -162.

Forbes, K. and Rigobon, R. (2002). No Contagion, Only Interdependence: Measuring Stock Market Co-movements. *The Journal of Finance* 57, 2223-61.

Hamao, Y. R., Masulis, R. W. and Ng, V. K. (1990). Correlations in Price Changes and Volatility across International Stock Markets. *The Review of Financial Studies 3*, 281-307.

Hartmann, P., Straetmans, S. and de Vries, C. G. (2004). Asset Market Linkages in Crisis Periods. *The Review of Economics and Statistics 86*, 313-326.

Hayo, B., Kutan, A.M. and Neuenkirch, M. (2010) The Impact of US Central Bank Communication on European and Pacific Equity Markets. *Economics Letters 108*, 172-174.

Karolyi, G. A. and Stulz, R. M. (1996). Why Do Markets Move Together? An Investigation of US-Japan Stock Return Comovements. *Journal of Finance 51*, 951-86.

Koutmos, G. and Booth, G. (1995). Asymmetric Volatility Transmission in International Stock Markets. *Journal of International Money and Finance 41*, 747-62.

Lo, A. W. (2012). Adaptive Markets and the New World Order. *Financial Analysts Journal 68*, 18–29.

Lin, W-L., Engle, R. F. and Ito, T. (1994). Do Bulls and Bears Move Across Borders? International Transmission of Stock Returns and Volatility. *Review of Financial Studies 7*, 507-38.

Longstaff, F.A. (2010). The Subprime Credit Crisis and Contagion in Financial Markets. *Journal of Financial Economics 97***,** 436–450.

Nowman, K. Ben. (1997) Gaussian Estimation of Single-Factor Continuous Time Models of the Term structure of Interest rates, *Journal of Finance 52*, 1695-1706.

Nowman, K.B. (2001). Gaussian estimation and forecasting of multi-factor term structure models with an application to Japan and the United Kingdom. *Asia-Pacific Financial Markets 8*, 23-34.

Nowman, K. B. (2003). A Note on Gaussian Estimation of the CKLS and CIR Models with Feedback Effects for Japan. *Asia Pacific Financial Markets 10***,** 275-279.

Tunaru, D. (2017). Gaussian Estimation and Forecasting of the UK Yield Curve with Multi-Factor Continuous Time Models. *International Review of Financial Analysis 52*, 119-129.