Geographical Changes in Influence of Stock Trading Centres Around the 2007 Global Financial Crisis

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Abstract

This paper analyses the evolution of interdependence and relative influence of major international stock markets in the three main geographical regions of Europe, USA and Asia around the Global Financial Crisis (GFC) of 2007. Using the Foreign Information Transmission (FIT) model of Ibrahim and Brzeszczyński (2009), we investigate changes in both the direct and the indirect channels of stock-return signal-transmission mechanisms across the three major geographical securities trading centres in London, New York and Tokyo. We further measure the impact of different factors on market interdependence patterns through the indirect channels. The results indicate that the influence of the USA market has weakened after the GFC, while the role of the main trading centres of the other two regions has strengthened over time. These findings are consistent with the concept of a geographical shift in the balance of economic powers between countries.

Keywords: Stock Markets Interdependence, Global Financial Crisis (GFC), Meteor Shower Effects, Foreign Information Transmission (FIT) model

Introduction

The Global Financial Crisis (GFC) of 2007 was a major event and a key milestone in the history of financial markets. Unparalleled in many respects, its economic consequences were stronger and its global impact wider than all earlier financial turmoil (Melvin and Taylor, 2009; Martin, 2011).

The GFC originated in the USA, and subsequently spread gradually to other geographical regions across the world. Melvin and Taylor (2009) chronicle the main events of the GFC and note that as early as the beginning of the summer of 2007 it was apparent to many participants of USA financial markets that fixed income markets were under considerable stress. In July 2007 equity markets in the USA and around the world exhibited remarkably high levels of volatility. A crisis in the foreign exchange market closely followed in August 2007, when carry trade positions in major currencies started to unwind. The contagion then spread across different asset classes resulting in significant price movements. Subsequently, the GFC moved to Europe, as the next geographical region, where many South European countries experienced macroeconomic problems and faced serious debt crises. The centre of gravity of the GFC continued to shift across global geographical regions over time (see also Martin, 2011).

An important feature of the GFC, therefore, was the transmission of shocks across markets around the world. The impact of the GFC on the changing roles and importance of stock trading centres in different geographical locations is interesting to study not only from the point of view of finance theory and practice but also from the perspective of economic geography. Such new knowledge may help better understand the nature of shifts in relative influence of stock markets across different countries, as well as across wider geographical regions, caused by events such as major financial crises. The role of geography in stock markets and in broader financial systems has been analysed by Clark and Wójcik (2007) and Wójcik (2009, 2011a, 2011b and 2013), among others.

The GFC brought into sharp focus a divide that was already emerging within the financial geography and international economics literatures: between scholars who emphasised global finance and capital market integration and those that focussed instead on the economic geography of specialisation and local agglomeration (see, for example, Clark and Wójcik, 2005). Since the 1990s, the emergence of “new” economic geography following the Fujita-Krugman-Venables approach (Fujita, 1988; Krugman, 1991a,b, 1998; Venables, 1996; Fujita et al., 1999), accompanied by the Nobel Prize in Economics awarded to Paul Krugman, brought major focus to the study of local processes of specialisation and agglomeration. By contrast, the technology-led dissipation of trading frictions across geographically-dispersed markets, together with massive contagion effects following the GFC, emphasised growing integration between major financial centres and markets (Lee et al., 2009; Martin, 2011; Wójcik, 2013). Taken together, there is growing appreciation within the literature of financial econometrics that adequate focus should be afforded to two somewhat distinct processes that affect financial markets: the effect of global shocks, and local spillovers generated by agglomeration (Holly et al., 2011; Pesaran and Tosetti, 2011). A new branch within the spatial econometrics literature has developed methods to estimate structural models that place focus on both the above (see, for example, Bhattacharjee and Holly, 2011 and 2013, Bhattacharjee and Jensen-Butler, 2013, and Bailey et al., 2016).

In this paper, we focus on the question of integration of global markets. We investigate the effects that the GFC has had on the evolution of interdependence of the three largest stock markets of London, New York and Tokyo, as the representative security trading centres in their broader geographical regions of Europe, USA and Asia. Identification of such interdependences among markets requires development of appropriate structural models. Here we extend the literature by developing structural models that are identified by time sequencing of the order in which different markets open and close. Thus, we measure changes in the interdependence of stock market daily returns using a framework of models that captures the ‘meteor shower’ phenomenon documented first in volatility by Engle et al.

(1990) and in returns by Hamao et al. (1990).[1,2] However, we additionally take advantage of a relatively recent methodological development in this field, namely the Foreign Information Transmission (FIT) model of Ibrahim and Brzeszczyński (2009). This approach allows for analyses beyond linear correlation relations between markets by modelling the time-variation of cross-market influences in as far as they transmit information to each other within the chronological sequence in which they trade. Ibrahim and Brzeszczyński (2009 and 2014) present evidence that the intensity of meteor showers in returns (direct transmission channels), between pairs of international stock markets located in different geographical regions, changes over time. These changes are affected by information (return) signals from yet other international stock markets in different geographical locations that operate in the interim (indirect transmission channels). In this study, we use these modelling features to investigate time variations around the GFC in the degree of interdependence of major geographical stock trading centres in their direct and indirect channels of information transmission. On the main, the existing literature presents results based on models that can provide evidence about direct channels only.

A related economic issue is the discussion by Whalley (2009) on different concepts of economic power. He emphasises that relatively little has been done in studying both the conceptual issues and the metrics designed to describe and quantify effects of power shifts. Our study and the reported results contribute to the literature on the changing balance of economic power between countries in different geographical regions; particularly from the point of view of the relative strength of the influence of their financial markets, both

[1] Other early papers about signal transmission effects include Eun and Shim (1989), King and Wadhwani (1990), Ito, Engle and Lin (1992), Lin, Engle and Ito (1994), Bekaert and Harvey (2000), and Longin and Solnik (2001), among others.

[2] The 'Meteor Shower' effect refers to the transmission of information across different geographical regions in the respective chronological sequences in which they trade. Engle et al. (1990) describe it using an astronomical metaphor as a process similar to the effect of meteor showers falling on Earth from outer space, where geographical regions may be affected differently as the Earth spins around (for example: first Europe, then the Americas followed by Asia, and the cycle continues in the same order). Originally, the meteor shower effect was analysed in the transmission of volatility across markets located in different geographical regions. However, its applications were later extended to the transmission of returns and other variables capturing various types of other economic information.

conceptually (by proposing a method for the measurement of power shifts in the context of stock markets) and empirically.

More specifically, our paper contributes to the following five areas of research: (i) economic geography of financial markets and the changing influence of major stock trading centres on each other, (ii) international stock markets interdependence and stock returns spillovers / contagion, (iii) time-varying integration of international stock markets, (iv) financial crises and the quantification of their effects (specifically the GFC) and (v) changing balance of economic power between countries and between broader geographical regions as well as changes in the relative influence of their financial markets.

The remainder of the paper is organised as follows. Section I presents a review of the relevant literature, Section II describes and discusses the Global Financial Crisis (GFC), Section III presents the methodology and reviews relevant features of the FIT model, Section IV describes the data, Section V reports and discusses empirical results and robustness analysis, and finally Section VI summarises and concludes.

Literature Review

This section presents a review of the literature on stock trading centres as key elements of a global network of international stock markets, on financial crises, and on the broader global economic trends that have been present in the world economy in the background to the effects analysed in this paper. As discussed above, we draw a distinction between networks that are local and highlight agglomeration of economics activity from the networks that represent the transmission of global shocks (Pesaran and Tosetti, 2011). Our structural model is primarily of the second type, but may also have implications for further development of the first type of models.

Geography of Finance

The literature on the geography of finance is concerned to a large degree with spatial relationships between markets around the world (see, for example, Clark, 2005; Clark and

Wójcik, 2005; Engelen and Grote, 2009; Lee et al., 2009; Martin, 2011; and Wójcik, 2013). However, as opposed to traditional finance or economics literature, which deals with both spatial and inter-temporal relations, there is in this literature a much stronger focus on the inter-temporal aspects of financial market interactions with only limited emphasis on their spatial dimensions and spatial relationships.

From a spatial perspective, the cities where the stock exchanges are located play a crucial role of key elements in a global network within which they are positioned on a map of international stock trading centres. This network has been conceptually and theoretically viewed broadly from two different perspectives: exogenous and endogenous networks. The first refers to “traditional” economic geography highlighting institutions shaped by path dependent and slow historical processes, but subject to distance decay (Yeung and Kelly, 2007; Garretsen and Martin, 2010). At the same time, there is emergence of models based on “new” economic geography that consider the development of markets, both individually and as part of a network, as the endogenous outcome of the behaviour of economic and financial agents (Martin, 1999; Krugman, 1998; Behrens and Thisse, 2007). Following the recent literature in spatial econometrics, a spatial (economic geography) approach can bring substantial advances to this field, particularly in developing models with a clear sense of cause and effect relationships between markets. Such causation can be either temporal Granger-causation (Granger, 1969) or contemporaneous Rubin-causation (Rubin, 2005). The model used in this paper lies somewhere in between. The causal models are contemporaneous in the sense that they relate to market behaviour on the same day, but are temporal in the sense that the causal effects are identified by the sequencing in the operations of these markets.

The origin of this line of literature about cities as financial centres dates back to the Global City theory proposed by Sassen (1991), according to which financial services functions are growing in importance due to the process of globalisation of the world economy, but they tend to become concentrated in a limited number of geographical locations through outsourcing them to companies which are close in spatial proximity to each other. This process occurs because of economic, information and technological benefits resulting from their co-location. This idea also bears strong connections to an earlier literature in urban economics, highlighting monocentric and polycentric spatial organisation of cities in the Alonso-Muth-Mills tradition (Alonso, 1964; Mills, 1967; Muth, 1969; Wheaton, 1974).

In this context, the existing studies in economic geography and, in particular, in the geography of finance deal with such topics as locational advantages within the financial services industry (Clark, 2002), role and structure of stock markets across different geographical regions (Peck and Theodore, 2007, and Clark and Wójcik, 2007), centralisation and decentralisation processes in financial systems (Klagge and Martin, 2005), corporate governance in global financial markets (Clark, Wójcik and Bauer, 2007, and Clark and Wójcik, 2007) or the growing role of virtual space in stock trading (Wójcik, 2007). In highlighting important roles for both locality (individual features of each market) and location (positioning and linkages within the network) in determining the outcomes of behavioural rules that shape equilibrium (spatial) landscapes and evolutionary paths, the above literature is closely aligned with new economic geography (Krugman, 1998; Fujita et al., 1999). A review of different other issues in this area is further provided by Wójcik (2009, 2011b).

With direct relevance to our study, Wójcik (2011a) discusses securitisation as a mechanism which determines institutional and geographic dispersion of financial asset ownership, that in turn feeds into the development of the securities industry, and he introduces the concept of the ‘securities industry centres’. There exist also related research findings from the individual stocks data level. For example, Wójcik (2011b) analysed the case of HSBC bank as a global stock listed simultaneously in a few different international markets (New York, London and Hong Kong) and presented evidence about the nature of transmission of daily stock changes within particular sequences of the HSBC stocks trading venues as well as about its stock price variability in the periods before, during and after the GFC financial crisis (between January 2006 and December 2009).

Finally, there are studies that further investigate such topics as the evolution of the securities industry centres and the transformation of the global map of stock markets, which includes an examination of the changing roles of individual cities as financial centres over time (see Grote, 2007 and Wójcik, 2011a and 2011b). The issue of the evolution of stock market roles, particularly in response to such an event as the GFC, is also the subject of analysis in our paper. Further, our work extends the current literature by developing structural models that explain how a stock market affects other markets within the network, and in turn, how the network itself is endogenously shaped by the flow of information between the markets. For this purpose, we draw upon the recent literature in spatial econometrics that places focus on identification of causal effects and structural models of interdependence (Bailey et al., 2016; Bhattacharjee et al., 2016).

Financial Crises

The existing literature presents rather mixed empirical evidence about the impact of financial turmoil on return and volatility spillovers across financial markets located in different geographical regions, with return and volatility being measures of the magnitude and the rate of flow of information, respectively. King and Wadhwani (1990) analyse correlations between the stock markets of the USA, UK and Japan around the 1987 USA stock market crash, and find a substantial increase in their interdependence following the event. Bertero and Mayer (1990) examine daily and monthly returns on twenty-three stock markets in various geographical locations, and present evidence that correlations with the USA market have increased after the 1987 crash. Lee and Kim (1993) reach similar conclusions using weekly data. Hamao, Masulis and Ng (1991) examine markets in New York, London and Tokyo using GARCH-in-mean models, and find that volatility spillovers emanating from Japan have strengthened over time, especially after the 1987 crash. Forbes and Rigobon (2002) point out, however, that the simple correlation coefficients applied in models used by some of the earlier studies are biased upwards due to these models' failure to account for heteroskedasticity. This leads to incorrect conclusions about the nature and strength of market interdependence. They suggest an alternative that adjusts for the bias, and present evidence of contagion during the 1987 USA market crash, the 1994-1995 Mexican crisis, and the 1997 Asian crisis. The authors also point to a long-term trend of increased interdependence starting prior to these events, which have little impact on changes in co-movements. Candelon, Hecq and Vershoor (2005) apply a different measure of interdependence based on business cycles and also conclude that market co-movements exist in all periods in similar strength and that there is no evidence of a particular increase in intensity of co-movements during or after the financial crises. Bekaert, Harvey and Ng (2005), Corsetti, Pericoli and Sbracia (2005) and Nam, Yuhn and Kim (2008), however, report evidence in favour of contagion in the case of the 1997 Asian crisis. In particular, Nam, Yuhn and Kim (2008) observe a tendency for the USA market influence on stock prices in the major Asian markets of Hong Kong, Singapore, South Korea, Malaysia and Taiwan, to increase after the crisis, while the impact on market volatility decreases substantially. In contrast, Yilmaz (2010) report increased return spillovers to East Asian equity markets, as well as bursts of volatility spillovers during major financial turmoil, including the East Asian crisis.

Dimpfl and Peter (2014) use the concept of transfer entropy, which captures non-linearity, to investigate the dynamic interactions between European and USA stock markets around the GFC. They find a bi-directional information transfer with a dominant flow from the USA market. Dimpfl and Peter (2014) also report increased dynamic interactions during the crisis, but the USA market does not entirely regain its leading role in the period following the crisis.

In this study, we use the time-varying dynamics of direct *versus* indirect channels of information transmission characteristic of the FIT model to investigate these effects. Here again, the connection with the spatial econometrics literature is quite prominent. Specifically, the spatial econometrics literature places great emphasis on the distinction between direct effects of market features on an index market, and the indirect effects upon other markets, which arise through the network interactions. This framework informs the structural models which we develop later in the paper.

Global Economic Trends

The issues of relative market influence and ‘power shifts’ have also been analysed in the context of broader macro-economic trends on the global scale. For example, the November 2012 report of the Organisation for Economic Co-operation and Development (OECD) argues that the world will experience a “dramatic shift” in the balance of economic power in the near future. It also predicts China’s GDP to overtake that of the USA within a decade, implying the latter losing the lead position as the world's largest economy. Further, OECD data shows that the USA’s share in global GDP (calculated as the sum of GDP of 34 OECD and 8 non-OECD G20 countries) will drop from 23 per cent in 2011 to 18 per cent by 2030, although other economic superpowers, such as Japan and countries in the Euro area, will also experience a decrease in their share of the world GDP.

Similar predictions have also been forwarded by private economic and business consultancies and think tanks. For example, the January 2011 report of PricewaterhouseCoopers (PwC) concludes that the GFC has further accelerated the shift in global economic power to the emerging economies, and that the largest emerging market countries (so called E7) are likely to become larger than the current G7 economies by 2020 and China may overtake the USA as the world’s largest economy by that time.

Although most of the available studies focus mainly on the changing roles of emerging markets, PwC (2011) presents an outlook indicating that the size of the developed economies (and their respective geographical regional networks) will undergo significant changes *relative to each other* as well.

Using PwC data on GDP from 2009 and the projected GDP in 2050 for individual countries located in different geographical regions, measured at Purchasing Power Parity (PPP) prices, the size of the three major Asian economies (Japan, China and India combined) relative to that of the USA will grow from 117.69 per cent to 291.26 per cent – an increase of almost 150 per cent. The same tendency in terms of the direction can be observed in the case of the relation to the USA of the five largest European economies (Germany, United Kingdom, France, Italy and Spain) as reported in PwC (2011). Their relative size will grow from 75.97 per cent to 83.11 per cent. However, if other fast-growing emerging market countries from the Central and Eastern Europe (CEE) region are included in this comparison (for which PwC(2011) reports no data), then this rate of change is likely to be substantially higher and decidedly in favour of the size of the European economic area.[3] Comparable patterns are revealed in a PwC variant that adjusts GDP data for exchange rates (the ‘Market Exchange Rates (MER) prices’ variant).

The literature on power shifts and the changing roles of countries from various geographical regions tends to focus mainly on the debate about the growing influence of emerging markets and the declining pre-eminence of developed countries, which have been shaping the global economic landscape for the last two centuries. Yet, there are many aspects of economic power and, as Cox (2011) argues, although various emerging market economies, such as China or India, are growing fast (partly due to increasing populations), the traditional economic superpowers possess certain “structural advantages” in such key processes as high specification production, quality of higher education and research activity. These advantages certainly also embrace the ability to generate advanced technologies, increase R&D intensity and sustain the level of development and sophistication of financial markets as mechanisms that drive long-term economic growth (but, occasionally, also behind the financial and macroeconomic crises).[4] The latter issue, i.e. the role and the influence of financial markets represented by the three largest stock trading centres of the world, is the subject of the analysis in this paper.

[3] This effect is even stronger when Turkey is counted as a country from the European economic area in 2050 (depending whether current negotiations will lead to its accession to the European Union in the near future). According to PwC (2011) study, Turkey’s GDP is predicted to grow substantially by over 440 per cent in the period 2009 – 2050.

[4] See also Aggarwal, Lucey and Muckley (2010), Gillingham (2003), Kearney and Lucey (2004) and Kearney and Poti (2006).

Global Financial Crisis (GFC)

Our paper focuses on the Global Financial Crisis (GFC) of 2007 and its impact on the geographical shifts in relative influence of major financial centres. In this section, we present a discussion about geographical aspects of the GFC, its main events, and the amplification effects. In the next two sub-sections we refer, in particular, to the review studies of Melvin and Taylor (2009) and Blanchard (2008), who provide a detailed account of major developments and discuss the most important GFC mechanisms.

Geography of the Global Financial Crisis (GFC) of 2007

First, we outline the most important developments of the GFC in their respective geographical locations. The sequence of events started in the USA in the fixed income securities markets, when it was apparent that the first problems emerged already in the early summer of 2007. In July 2007, volatility of the USA equity market (and to large degree also other stock markets across the globe) increased. Melvin and Taylor (2009) state that *"supposedly market-neutral equity portfolios suffered huge losses and it was common to hear people referring to a 'five (or larger) standard deviation event'"*. In August 2007, the contagion from other asset classes spread to the currency market when carry trades started to unwind. As Melvin and Taylor (2009) document, the unwinding of carry trades on August 16, 2007, was a devastating event for many investors, when foreign exchange volatility increased substantially.

The next stage of the crisis was during November 2007 when USA investors started to recognise problems with credit quality including difficulties in issuing asset-backed securities by many USA firms. The flight to quality decreased yields on USA Treasury Bills. This was followed by a decline in commodity prices and deleveraging. In 2008 further relevant events in the USA included the bankruptcies of large USA financial institutions: Bear Stearns in March 2008 and Lehman Brothers in September 2008. These highlighted severe problems with counterparty risk and liquidity and the dilemma regarding the "too big to fail" question faced by USA policy makers (and, subsequently, other decision makers in central banks and governments around the world).

The next stages involved a geographical shift and network spillovers of increased counterparty risk to Europe, which reduced confidence in the ability of certain European countries to service their sovereign debt that was on the increase due to bank bailouts. This became the 'Eurozone crisis' unfolding for varying reasons across fiscal regimes of Eurozone and members of the European Union. The downgrading of their sovereign debt rating made it even more costly to service their increasing debt levels causing widespread alarm in financial markets. The scramble for stability and lack of liquidity prompted wide governmental rescue plans associated with harsh austerity measures that inevitably introduced further risk due to political and financial uncertainty. Although this was most pronounced in Greece, the range and scope of the repercussions of the financial crisis are still unfolding worldwide with substantial initial contagion and information transmission.

The GFC has had serious impact in Europe, and it shifted further to Asia, although its consequences for Asian economies (and for the broader Asia–Pacific Basin regional network) were much milder, since many of them avoided a sovereign debt crisis and, at least initially, went through the global recession with only modest corrections of their business cycles.

Initial Conditions, Amplification Mechanisms and Consequences of the GFC

Blanchard (2008) provides a detailed discussion of initial conditions, further amplification mechanisms, and consequences of the GFC. This analysis is particularly valuable as it encompasses a policy-makers' perspective (including the views on necessary policies to deal with the GFC and other possible future financial crises). According to Blanchard (2008), the initial conditions of the crisis were the underestimation of risk of newly issued assets, the opacity of some of the securities on the balance sheets of financial institutions, the connectedness between financial institutions within and across countries, and the high leverage of the entire financial system. These initial conditions were accompanied by amplification mechanisms such as fire sales of assets to satisfy liquidity runs by investors who tried to re-establish capital ratios. As Blanchard (2008) notes, this process has led to very large effects of a small trigger on world's economic activity.

Blanchard (2008) also reports data that demonstrates that the subprime loan crisis in the USA had a multiplier-type effect of very large magnitude on different aspects of the broader world economy in its different geographical regions. Although the losses on USA subprime loans and securities were estimated at about $250 billion (as of October 2007), the expected cumulative loss in world output for the years 2008 to 2015 associated with the crisis was estimated at $4,700 billion (i.e., about 20 times the initial subprime loss). Further, the decrease in the value of international stock markets (decrease in stock market capitalisation from July 2007 to November 2008) was about $26,400 billion (i.e., over 100 times (!) the initial subprime loss). These numbers illustrate the seriousness of the magnified impact of the GFC, which undoubtedly makes it one of the most important events and milestones in the history of international financial markets and the world economy.

Although the macroeconomic consequences of the GFC are now rather obvious, and can be measured more precisely, still relatively little is known about how this event changed the interdependence of international stock markets in their different geographical locations, their influence on each other, and their roles in the broader global financial system. We analyse this issue through the useful characteristics of the FIT framework in modelling information channels. We use this framework to empirically quantify the evolution of relationships among the largest stock trading centres in the three main geographical regions of the world.

Foreign Information Transmission (FIT) Methodology

FIT is a conditional time-varying sequential information transmission methodology that describes the effect some variables have on the time-varying relationships that exist between other variables. In its simplest form, it can be described by a regression of y on x with time-varying coefficients α_t and β_t and an error term w_t:

$$y_t = \alpha_t + \beta_t x_t + w_t. \tag{1}$$

Further, the dynamics of the coefficients are assumed to depend on another exogenous variable, z, according to the following equations:

$$(\alpha_{t+1} - \bar{\alpha}) = [a + b(z_t - \bar{z})](\alpha_t - \bar{\alpha}) + v_{\alpha,t+1}, \tag{2}$$

$$(\beta_{t+1} - \bar{\beta}) = [c + d(z_t - \bar{z})](\beta_t - \bar{\beta}) + v_{\beta,t+1}, \tag{3}$$

where a, b, c and d are constant coefficients; $\bar{z}$, $\bar{\alpha}$ and $\bar{\beta}$ are long-run average values or 'steady states' of the variable z and the time-varying coefficients α_t and β_t; and $v_{\alpha,t+1}$ and $v_{\beta,t+1}$ are associated error terms. Conditional on x_t and data observed through t-1, gathered in the vector $\boldsymbol{Y}_{t-1}$, it is assumed that the vector of error terms $(\boldsymbol{v}_{t+1} \ w_t)'$ has a Gaussian distribution:

$$\begin{bmatrix} \boldsymbol{v}_{t+1} \\ w_t \end{bmatrix} \bigg| x_t, \boldsymbol{Y}_{t-1} \sim \left(\begin{bmatrix} \boldsymbol{0} \\ 0 \end{bmatrix}, \begin{bmatrix} \boldsymbol{Q} & \boldsymbol{0} \\ \boldsymbol{0}' & \sigma_w^2 \end{bmatrix} \right), \tag{4}$$

where $\boldsymbol{v}_{t+1} = (v_{\alpha,t+1} \ v_{\beta,t+1})'$, and $\boldsymbol{Q}$ is a diagonal matrix. Stationarity is ensured if, for all t = $1, \dots, T$, the eigenvalues of the matrix:

$$\boldsymbol{F}(z_t) = \begin{pmatrix} a + b(z_t - \bar{z}) & 0 \\ 0 & c + d(z_t - \bar{z}) \end{pmatrix} \tag{5}$$

are inside the unit circle. Ibrahim and Brzeszczyński (2009) provide full technical description and detail of the estimation procedure.

Specifically, $\bar{\beta}$ captures the long-term direct-channel effect of interdependence between x and y, or the 'steady state' information transmission from x to y, while estimates of the parameters b and d provide further information about the existence and nature of the interdependence through an indirect channel of information transmission through z.

The terms $(\alpha_t - \bar{\alpha})$, $(\beta_t - \bar{\beta})$ and $(z_t - \bar{z})$ are time-t (or day t) deviations of alpha, beta and the variable z from their long-run averages, or steady states. Equations (2) and (3), therefore, describe how deviations from average in the level and intensity of the relationship between two markets (x and y) change over time, and how these changes are affected by information from a third stock market, z. In particular, the coefficients b and d measure the impact of news that arise in the z market on changes over time in the relationship between the y and x markets. In other words, they measure the effect of intermediate foreign, z, information on the evolution over time in the interdependence between two markets. The measurement of such effects is not possible using other, more traditional, methodologies.[5] This represents the main incremental information that the FIT model provides over linear (OLS) regressions of y on x. If d is significantly positive (negative) then a positive deviation of z has an increasing (decreasing) effect on the intensity of the interdependence between markets x and y.

In this study, we use two different sources of information for the indirect channel of transmission (i.e., two types of the variable z). First, we use open-close daily returns from markets that are active during the interim between the trading hours of markets y and x. Ibrahim and Brzeszczyński (2009) use this as a proxy for overnight information, which incorporates the z-market's interpretation of the x-market return signal. Second, we add here variables that capture differences in activity and price uncertainty between markets y and x as well as differences in the outlook for economic growth between the economies of these

[5] Another advantage of the FIT methodology is that it incorporates the phenomenon of volatility clustering that is often modelled by ARCH, GARCH and stochastic volatility specifications. It does so through its formulation of the deterministic structure of the system (i.e., expected returns) rather than accounting for heteroskedasticity through innovations or residuals (unexpected returns). Specifically, the intercept α_t changes over time and is a function of its own past values, values of the exogenous variable z, and a stochastic term. Further, the term $\beta_t x_t$ of equation (1) is a product of an AR(1) process for β_t with a random variable, x_t, and this is a type of specification shown by Granger and Machina (2002) to generate volatility drift, or clustering. Thus, conditional heteroskedasticity is structurally inherent.

markets. Differences in market activity, price uncertainty and economic outlook are measured by the differentials (between markets y and x) in trading volume by turnover, return volatility and interest rate term spreads (yield curve), respectively. Specifically,

$$Volume\ Differential\ (z_t) = turnover(y_t)\ - turnover(x_{t\ or\ t-1}) \tag{6}$$

$$Volatility\ Differential\ (z_t) = volatility(y_t)\ - volatility(x_{t\ or\ t-1}) \tag{7}$$

$$Term\ Spread\ Differential\ (z_t) = ITS(y_t) - ITS(x_{t\ or\ t-1}) \tag{8}$$

where the time subscripts follow the chronological sequence of trading hours of markets y and x; '*volatility*' is defined as the amplitude of intra-daily changes in index values (i.e., the difference between daily $high_t$ and daily low_t) divided by their midpoint:

$$volatility_t = (high_t - low_t)/(\tfrac{high_t + low_t}{2}); \tag{9}$$

and ITS is the interest rate term spread measured by the difference between the daily redemption yield of 10-year government bonds and the daily middle rate of the 1-month Treasury Bill of a particular market. The term spread has been used in the literature to gauge the outlook on economic growth and to predict economic cycle downturns (see, e.g., Harvey, 1991, Estrella and Hardouvelis, 1991, and Wheelock and Wohar, 2009).[6]

The distinction between exogenous and endogenous variation is key towards identification of our model. In our study, there are three key variables representing the three important stock exchanges – Tokyo, London and New York – and outcomes (stock price movements) in each of these markets are endogenously determined within our model. The regressors are exogenous in the sense that traders in one market can observe outcomes in other markets that opened earlier in the day and, hence, these other markets have the potential to affect not only the outcomes in another market but also the influence that other markets may exert upon each other. In this sense, identification arises from 'meteor shower' effects (Engle et al., 1990; Hamao et al., 1990). Figure 1 provides a visual representation of

[6] Another possible variable that can be used in the indirect channel of transmission (i.e., as the variable z) within our methodological framework could be the difference in measures of technological development between markets y and x (see more detail on this variable in Donald, 2015). However, data availability issues and the frequency of data that we apply in this paper (i.e., daily data frequency) make it difficult in practice to incorporate it in this particular model. Nonetheless, we would like to thank David Donald for helpful discussions about this idea and for his comments and suggestions.

our model. Consider the New York market (y) on a given day. By the time this market opens, the market in Tokyo is already closed for the day, and therefore information from the Tokyo market (x) is fully internalised in the pricing processes so that it can affect New York directly. However, the influence can be moderated by developments in the London market, which occupies an intermediate position (z). Similarly, London is directly affected by New York, but the influence is moderated by Tokyo, and Tokyo is affected by London with influences moderated by New York.

Figure 1: Schematic description of the model

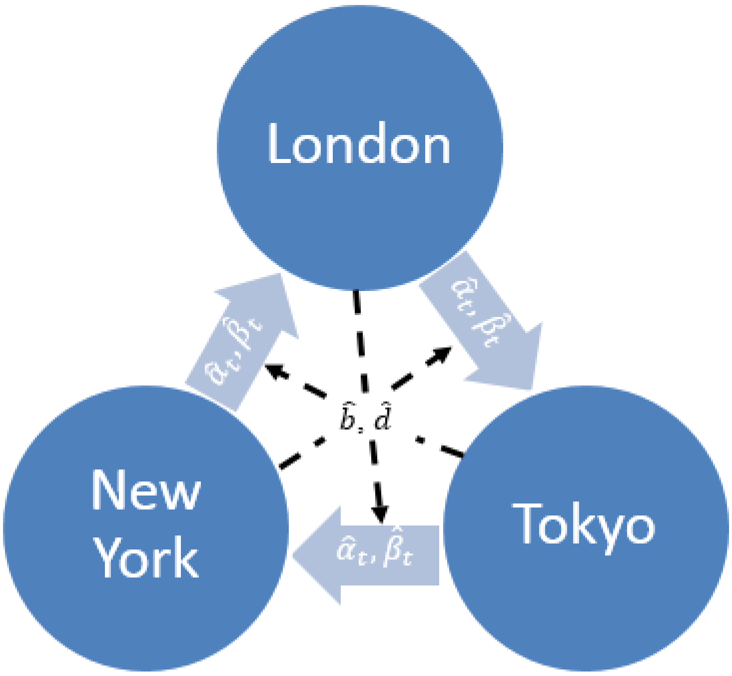

Figure 1 illustrates in a simple way the structural model of endogenous influences that describes causal relationships between the markets. The broad arrows represent causal influences between the markets and the dashed arrows indicate the impact of other markets on the strength of the causal relationship. This model is identified by a combination of the FIT model (Ibrahim and Brzeszczyński, 2009) describing the flow of information, together with the ‘meteor shower’ model (Engle et al., 1990). As discussed in Bhattacharjee et al. (2016), the causal effects here are identified by our model of information flow, which in turn relies on time sequencing of the markets. The model describes contemporaneous causal influences in the sense that the influences occur over short time intervals of less than a day. However, the identification mechanism is based on temporal ordering, which is similar to Granger-causation. Looking at it in a different way, our model depicts global capital market integration in the sense that the influences are across markets that are geographically well separated. At the same time, the model pays attention to local agglomeration in the sense of moderating intermediate influences that are instantaneously transmitted. Thus, it is quite rich and allows for nuanced interpretation. In the next section, we present the empirical application of our model using empirical data from major international stock markets.

Data

Our database, extracted from Thomson Reuters Datastream, spans a ten-year period from 1 July 2002 to 29 June 2012. It covers the world's three largest stock trading centres: New York, Tokyo and London as measured by their main stock market capitalisation.[7,8] The database contains daily open, high, low and close levels of the Dow Jones Industrial Average (DJIA) index, the Financial Times Stock Exchange (FTSE) index and the Tokyo Price Index (TOPIX), as well as trading volume and interest rate data, for these three major stock trading centres in their distinct geographical locations in the USA, UK and Japan. Japan is chosen instead of China to represent the Asian geographical region, because it is a larger market, and the two main markets in China (Shanghai and Shenzhen) trade different shares for foreign investors (B shares) at different prices than for Chinese mainland citizens (A shares). In addition, choosing the stock market of Hong Kong would not be representative due to its smaller size and volatile nature. The sample period selected for the study brackets

[7] Some other studies use Hong Kong as the market representative for the Asian region and other markets in Europe to represent the European region. In our case, we decide to select the largest three markets in the world (and, simultaneously, also the largest ones in their own regions), as measured by their market capitalisation. Accordingly, we focus on Tokyo, London and New York.

[8] Our choice of these three largest international markets is also consistent with the concept of the Global City proposed by Sassen (1991), which we refer to earlier in the literature review section. The Global City idea was introduced in Sassen's (1991) book "*The Global City: New York, London, Tokyo*", where New York, London and Tokyo serve as model examples of the cities which illustrate this concept, in particular from the perspective of international financial markets development and the growth of securities trading centres.

the GFC, which started in equity markets in July 2007, and allows for two pre-crisis and post-crisis sub-samples of equal length of five years each (1/7/2002 – 29/6/2007 and 2/7/2007 – 29/6/2012).

Figure A1 in the Appendix depicts the distribution of daily open-to-close returns of the three indices. Table A1, also in the Appendix, presents basic statistics on these variables as well as on the volume, volatility and interest rate differentials between these markets. They illustrate the following patterns. First, volatility of daily returns has increased in all three markets after the GFC. Standard deviations increased from 0.0077 to 0.0134 for DJIA, from 0.0105 to 0.0153 for FTSE, and from 0.0085 to 0.0123 for TOPIX. These translate to percentage changes of +74 per cent, +46 per cent and +45 per cent, respectively. Second, a similar effect is also observed in the three markets when volatility is measured by the daily amplitude between high and low index levels. This has increased from 0.0113 to 0.0167 for DJIA, from 0.0121 to 0.0186 for FTSE, and from 0.0108 to 0.0137 for TOPIX. These translate to percentage changes of +48 per cent, +54 per cent and +27 per cent. Third, the skewness of open-to-close daily returns increased (became less negative) from -0.48 to -0.23 in Japan and from -0.21 to -0.08 in the UK, but decreased from 0.32 to -0.02 in the USA. The return kurtosis increased in all markets, especially in Japan. Fourth, trading volume (Table A1 reports the re-scaled values) has increased from 0.0144 to 0.0188 in Japan, decreased from 0.0016 to 0.0011 in the UK, and remained largely unchanged at the 0.0022 to 0.0023 level in the USA. Fifth, the volatility (standard deviation) of trading volume has increased from 0.0007 to 0.0010 in the USA, remained at a constant level of 0.0005 in the UK and decreased slightly from 0.0070 to 0.0064 in Japan. Finally, the interest rate spread increased from 0.0025 to 0.0183 in the UK and from 0.0170 to 0.0251 in the USA, but narrowed from 0.0131 to 0.0104 in Japan.

In general, therefore, the crisis has instilled large changes across markets. These effects are investigated next in more detail around the crisis, where we analyse interdependence through the direct and indirect channels of information transmission.

Empirical Results

This section discusses the estimation results of FIT model specifications. The next sub-section presents results when the z variable is taken as stock index returns (Table 1) and the following sub-section presents the results when this variable is the differential in trading volume (Table 2), price volatility (Table 3) or the term spread (Table 4). In this discussion we refer to three main meteor shower relationships that we dub the 'DJIA Model', the 'FTSE Model' and the 'TOPIX Model'. The first is the meteor shower from Japan to the USA, where the return on the DJIA index (at t) is variable y, and the return on the TOPIX index (at t) is variable x.[9] The second is the meteor shower from the USA to the UK, where the return on the FTSE (at t) is variable y and the return on the DJIA (at t-1) is variable x. The third is the meteor shower from the UK to Japan, where the return on the TOPIX (at t) is variable y and the return on the FTSE at (t-1) is variable x.

Stock Index Returns as Indirect Information

Estimation results of the DJIA Model in Table 1, where the return on the FTSE at day t is taken as the intermediate market z, reveal that in the entire sample period of 10 years, $\bar{\beta}$ is equal to 0.18 and significant at the 1 per cent level, which indicates a significant meteor shower from Japan to the USA. Estimates of parameters b and d are also statistically significant, providing evidence of the existence of an indirect channel of returns transmission from Japan to the USA *via* the UK. However, the steady state direct meteor shower from Japan to the USA, as captured by estimates of $\bar{\beta}$, changes substantially after the crisis. While both are significant at the 1 per cent level, the estimate of $\bar{\beta}$ during the post-crisis period (0.2511) is nearly twice that during the pre-crisis period (0.1387). This indicates that the influence of Japan's TOPIX return signals on USA's DJIA almost doubled after the crisis.

[9] The chronological sequence of trading is followed whereby, in Greenwich Mean Time (GMT), Asian markets open at around midnight and close at around 6:00 - 8:00 a.m., European markets open at 8:00 - 9:00 a.m. and close at around 4:00 - 5:00 p.m. and USA markets open at around 2:00 - 3:00 p.m. and close around 8:00 - 9:00 p.m. In the DJIA Model, for example, the signalling x market is Japan and the signal-receiving y market is the USA with European markets that open in the interim and prior to USA markets, or micro or macro differentials between markets x and y, are variable z.

Estimation results of the FTSE Model in Table 1 (where the return on the TOPIX at day t is the variable of the intermediate market z) show an opposite effect. The estimate of $\bar{\beta}$ for the entire sample period is 0.3144 (significant at 1 per cent), but drops from 0.36 before the crisis to 0.28 afterwards (both estimates are significant at 1 per cent). Accordingly, DJIA's influence on the FTSE decreased by nearly 33 per cent after the crisis. Most estimates of parameters b and d are also statistically significant indicating an indirect effect of the USA on the UK through Japan.

Estimation results of the TOPIX model in Table 1 (where the return on the DJIA at day t-1 is the intermediate market z) show that $\bar{\beta}$ is 0.1449 during the entire sample period (significant at 1 per cent), but increases from 0.0765 before the crisis to 0.1773 after the crisis (both estimates also statistically significant at 1 per cent). Thus, the influence of FTSE on TOPIX has more than doubled after the crisis. Again, most estimates of parameters b and d are statistically significant indicating an indirect effect of the UK on Japan through the USA.

The steady state estimates of alpha, $\bar{\alpha}$, for all three relationships reported in Table 1 are mostly insignificantly different from zero, which indicates that the level of meteor showers is mostly zero (even though the intensity, i.e., $\bar{\beta}$, is significant).

In summary, the three models indicate that $\bar{\beta}$ is positive and significant before and after the GFC. Thus, meteor showers are strong. Furthermore, during the pre-crisis period estimates of $\bar{\beta}$ ranged in magnitude between 0.08 and 0.36, while during the post-crisis period its range narrowed between 0.18 and 0.28. This shows that the role of the USA market as the influencer (when it acts as the x variable) diminishes, since estimates of $\bar{\beta}$ decrease from 0.36 to 0.28 (i.e. by over 20 per cent), while the roles of the London and Tokyo markets gain influence, since estimates of their $\bar{\beta}$ increased from 0.08 to 0.18 (i.e., by over 120 per cent) and from 0.14 to 0.25 (i.e., by nearly 80 per cent). This is one of the main findings of this study.[10]

[10] The change of the influence of those three markets is even more pronounced when the NIKKEI 225 index is used instead of TOPIX to represent the Japanese market. Estimates of $\bar{\beta}$ during the pre-crisis period are 0.12, 0.36 and 0.08 in the DJIA, FTSE and NIKKEI models, respectively, and they change

We now turn our attention to the analysis of estimates of parameters a, b, c and d, of which b and d capture indirect channels of interdependence. In particular, we focus on parameter d which measures the role of the intermediate market z on the intensity of the meteor shower relationship from market x to market y.

In the DJIA Model, the estimate of d changes sign from positive to negative (6.24 to -6.89), but remains statistically significant at the 2 per cent level. However, in the FTSE Model it increases from negative -4.78, and not statistically significant, to negative -11.54 and becomes significant at the 1 per cent level. This means that the Japanese market index TOPIX gained significant influence in this indirect channel in the post-crisis period relative to the pre-crisis period. The estimate of d in the TOPIX model changes sign from -7.35 to 2.50 but is insignificant during the pre-crisis period and is on the borderline of significance (at 9 per cent) during the post-crisis sub-period. This indicates that the USA market index DJIA does not have a significant influence through this indirect channel.

Overall, the estimation results from Equations (2) and (3) confirm the significant role of the UK and Japanese market indices in the indirect channels (with TOPIX clearly gaining significance in the post-crisis period). This supports the findings reported above about the evolution of $\bar{\beta}$, which provides evidence of the role of these markets in direct channels.

Volume, Volatility and Interest Rate Differentials as Indirect Information

We now analyse the influence of other factors as sources of indirect information, namely the differentials in volume, volatility and term spreads. This is carried out for two reasons. First, as differentials of relevant micro and macro-economic indicators these variables may have, in their own right, an influence (through the indirect channel) on time variation in the direct meteor shower relationships between the largest stock trading centres. This would provide further insights into the effect of the crisis. Second, it would act as a robustness check that the changes around the crisis in the direct channel of interdependence reported in the

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to much more levelled values (0.26, 0.27 and 0.21) in the period after the GFC. Hence, the role of the London and Tokyo markets relative to the New York market seems to increase even more strongly using the NIKKEI index data.

previous sub-section are not an aberration of choosing only stock market returns as the z variable, but persist if other micro- and macro-economic variables are used instead.

The existing literature, for example, provides evidence about the role of trading volume in the relationships among stock markets and its importance in the explanation of the nature of information transmission effects (see, e.g., Campbell, Grossman and Wang, 1993; Wang, 1994; Conrad, Hameed and Niden, 1994; Llorente, Michaely, Saar and Wang, 2002; Connolly and Stivers, 2003; Gagnon and Karolyi, 2006; and, more recently, Gagnon and Karolyi, 2009, and Gębka, 2012). We use volume of trade as a proxy of market activity, and the calculated differential aims to capture effects that may arise when trading activity in one market is substantially different than the other in each analysed pair. We also test whether a change in activity in one market affects the strength of the meteor shower to another market (i.e., interdependence between these two stock trading centres), and how this changes around the crisis.

Similarly, the constructed volatility differential aims to capture transmission effects that may appear if price uncertainty in market y is substantially higher (or lower) than that in market x. We also test whether this affects the strength of interdependence (the meteor shower) between the two respective stock markets located in different geographical regions and how this changes around the crisis.

The interest rate spread measures macro-economic effects related to economic growth and its future prospects. Harvey (1991), for example, shows that short-term rates exceeded long-term rates prior to the five USA recessions that occurred prior to 1991. This variable also partially captures distress in bond markets and is an integral element in the construction of indices that measure systemic risk (see, e.g., Wright, 2006). The differential in this variable between two countries aims to capture differences in the turning points in their economic cycles.

Table 2 presents estimates from the three models where the differential in trading volume between markets y and x acts as the z variable. A remarkable finding is that the estimate of the d parameter in the DJIA Model decreases in magnitude nearly five-fold from

-53.31 to -11.68 and becomes insignificant in the post-crisis period (while the estimate during the pre-crisis period is statistically significant at the 1 per cent level). Exactly the same effect is observed in the FTSE Model, where the estimate of d drops from 226.27 (statistically significant at the 1 per cent level) to -61.57 (not significant). In contrast, the estimate of d in the TOPIX Model gains significance in the post-crisis period, where it increases two-fold from -10.08 (not significant) to -20.32 (significant at 1 per cent). These results provide evidence on changes in the relative strength of information about market activity in these three trading centres. The volume of trade in New York, and the resulting differential of volume with the UK and the Japanese markets, seems to matter in the pre-crisis period but is irrelevant in the post-crisis period, while the volume differential between the UK and Japanese markets appears to gain importance in the post-crisis period.

Table 3 presents the results when the differential in stock price volatility is used as the indirect channel of interdependence. In the DJIA Model, the estimate of parameter d remains significant at the 1 per cent level, but changes magnitude from -19.70 during the pre-crisis period to -12.29 during the post-crisis period. In the FTSE Model, the estimate of parameter d decreases more than four-fold, from 14.29 (statistically significant at the 1 per cent level) to 3.33 (and not statistically significant). However, in the TOPIX Model, the estimate of parameter d increases in magnitude from -7.11 (and not statistically significant) to -15.65 (and significant at the 1 per cent level). Hence, the findings when z is the volatility differential seem to paint the same picture as the results presented in Table 2 where the volume differential is used: the role of the USA market has weakened post the crisis while the role of the other two markets has a stronger influence on each other and on the USA.

Table 4 presents estimation results where the z variable is the term spread differential. The results show no evidence about significance of the d parameter in any of the samples of the FTSE Model and the TOPIX Model, and weak significance in the DJIA Model (with some significance of parameters a and b). Hence, the term differential does not seem to have a significant impact on the relationships between these three stock markets.

Overall, we find evidence that the trading volume and volatility differentials do affect the interdependence between major stock trading centres, but very little evidence about the impact of the interest rate differential, perhaps because either economic cycles are rather synchronised or that differences in them are small and have no effect on the interdependence of markets.

Finally, the changes after the crisis in estimates of $\bar{\beta}$ reported in Tables 3 to 5 are in line with those reported in Table 1. Thus, the effects of the crisis on the direct channel of information transmission reported and discussed in the previous sub-section are largely robust to whether the source of the indirect channel is stock index returns or differentials in micro- and macro-economic activities.

These results clearly indicate that the role of the USA market as the influencer of price movements in other stock markets located in other geographical regions has weakened after the GFC, while the role of the other two trading centres in the UK and Japan has strengthened.

Summary and Conclusions

This paper provides new evidence about the evolution of interdependence of major stock markets located in three distinct geographical regions in New York, London and Tokyo around the Global Financial Crisis. Using the framework of the Foreign Information Transmission (FIT) methodology, we investigate inter-market relations through direct and indirect channels of information transmission, and analyse the impact of other factors, such as differentials in trading volume, stock price volatility and interest rates, on the direct channels.

The model is causal and identified by the ‘meteor shower’ effects that determine the direction of information flow. It is very rich in structure, incorporating notions of both Granger- and Rubin-causation. At the same time, it contains factors representing global network and local agglomeration effects at the same time. It, therefore, offers very nuanced interpretation.

Our findings, which are robust to different model specifications, clearly indicate that the role of the USA market as the influencer of price movements in other stock markets in different geographical regions has weakened after the Global Financial Crisis of 2007, while the role of the other two trading centres in the UK and Japan has strengthened.

A possible explanation of our findings may be related to the fact that the centre of gravity of the GFC moved geographically from the USA to Europe soon after 2007 when many South European countries experienced macroeconomic problems and faced serious debt crises. This would be consistent with this part of our results, which clearly indicates that the role of Europe, as represented in our models by the FTSE, has strengthened in the post-crisis period. This effect is also consistent with the results of Dimpfl and Peter (2014). This is reasonable to expect even though the 'Eurozone' crisis started later than 2007 and the UK is in the EU but not the Eurozone, because stock markets are prospective in nature and the UK is one of the largest financial centres in the European Union.

However, the findings presented in this study may reflect a different phenomenon, namely, broader macro-economic trends on a global scale. As Figure A1 in the Appendix illustrates, the changes in distributions of returns between the pre- and post-crisis periods (lower peaks and fatter tails) are similar across all three indices, but the change is most prominent in the case of the USA market, which is supportive of the rest of our results. In addition, Figure A1 and Table A1 show that return kurtosis increased most substantially for Japan, which could be related to the flight of capital to safer Japan for the positive side of returns and fears of trade effects for the negative side of returns. This effect is consistent with the story about the change of balance of economic power across countries and, possibly also, across entire geographical regions.

An explanation related to the geographical shift in the balance of economic power between countries, as predicted by the OECD and other international institutions, calls for further research in market interdependence and the changing role of other stock trading centres located in different geographical regions across the world, including those that are still considered today as emerging markets.

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Table 1: Estimation Results of Simple Meteor Shower Models

	DJIA Model: Meteor shower from Japan(t) to USA(t) with UK(t) as variable z								
	All sample period			Pre-crisis			Post-crisis		
	Estimate	*t*-stat	*p*-value	Estimate	*t*-stat	*p*-value	Estimate	*t*-stat	*p*-value
$\bar{\alpha}$	0.0002	1.0983	0.14	0.0005	1.8225	0.03	0.0001	0.1480	0.44
$\bar{\beta}$	0.1836	6.2441	0.00	0.1387	4.3101	0.00	0.2511	5.4599	0.00
σ_α	0.0018	12.9325	0.00	0.0006	4.3053	0.00	-0.0051	-7.0136	0.00
σ_β	0.6035	22.5829	0.00	0.2572	5.8836	0.00	0.6280	12.8958	0.00
σ_w	0.0099	97.6803	0.00	0.0084	62.4628	0.00	0.0107	23.4792	0.00
a	-0.7771	-37.0491	0.00	-0.8298	-18.4004	0.00	-0.5700	-15.3815	0.00
b	23.4517	38.4705	0.00	-41.0714	-27.5942	0.00	16.6404	9.8606	0.00
c	-0.2246	-3.3335	0.00	-0.7052	-10.0503	0.00	-0.1765	-1.5610	0.06
d	-3.2727	-1.9480	0.03	6.2416	3.0761	0.00	-6.8854	-2.1045	0.02
	FTSE Model: Meteor shower from USA(t-1) to UK(t) with Japan(t) as variable z								
$\bar{\alpha}$	0.0000	0.0577	0.48	0.0002	0.8535	0.20	-0.0002	-0.6074	0.27
$\bar{\beta}$	0.3144	11.2063	0.00	0.3594	8.6322	0.00	0.2769	7.3008	0.00
σ_α	-0.0040	-13.9416	0.00	-0.0026	-7.8415	0.00	0.0039	9.3537	0.00
σ_β	0.6042	26.4422	0.00	0.6629	20.4075	0.00	0.4798	13.5683	0.00
σ_w	0.0087	42.7617	0.00	0.0067	36.0750	0.00	0.0113	35.3774	0.00
a	-0.7041	-31.8284	0.00	-0.8089	-29.0362	0.00	-0.7177	-24.2453	0.00
b	18.2859	15.5125	0.00	23.5457	6.5637	0.00	18.2655	11.6728	0.00
c	0.0198	0.3179	0.38	0.0647	0.8013	0.21	0.0266	0.2660	0.40
d	-5.1242	-2.3849	0.01	-4.7773	-0.6517	0.26	-11.5380	-4.3548	0.00
	TOPIX Model: Meteor shower from UK(t-1) to Japan(t) with USA(t-1) as variable z								
$\bar{\alpha}$	-0.0005	-2.5759	0.00	-0.0004	-1.5233	0.06	-0.0006	-2.0694	0.02
$\bar{\beta}$	0.1449	6.4979	0.00	0.0765	2.7855	0.00	0.1773	5.7030	0.00
σ_α	-0.0059	-16.1238	0.00	0.0009	1.0329	0.15	0.0070	13.6343	0.00
σ_β	0.3913	22.8064	0.00	0.2181	5.1348	0.00	0.4159	17.3103	0.00
σ_w	0.0061	15.3814	0.00	0.0081	44.0365	0.00	0.0060	9.0601	0.00
a	-0.0776	-3.6146	0.00	-0.1083	-0.9481	0.17	-0.0858	-3.3843	0.00
b	24.4479	27.2286	0.00	53.7343	6.9292	0.00	23.5235	21.5588	0.00
c	0.1480	2.7491	0.00	0.0025	0.0071	0.50	0.1752	2.5822	0.00
d	2.7648	1.9094	0.03	-7.3544	-0.5368	0.30	2.4980	1.3218	0.09

Notes: Table 1 presents estimation results of the FIT model (Eqs. (1)-(3)) for three stock market relationships where variables x, y and z are (a) Japan(t), USA(t) and the UK(t) (dubbed the DJIA Model), (b) UK(t), USA(t-1) and Japan(t) (dubbed the FTSE Model), and (c) Japan(t), UK(t-1) and USA(t-1) (dubbed the TOPIX Model). The sample period is 1 July 2002 through 29 June 2012, divided equally around 29 June 2007 for pre-crisis and post-crisis sub-samples.

Table 2: Estimation Results of Meteor Shower Models with Volume Differential as the Indirect Information Channel

	DJIA Model: Meteor shower from Japan(t) to USA(t) with volume differential as variable z								
	All sample period			Pre-crisis			Post-crisis		
	Estimate	*t*-stat	*p*-value	Estimate	*t*-stat	*p*-value	Estimate	*t*-stat	*p*-value
$\bar{\alpha}$	0.0003	1.3648	0.09	0.0005	1.8470	0.03	0.0002	0.6714	0.25
$\bar{\beta}$	0.2005	7.1183	0.00	0.1356	4.1862	0.00	0.2576	5.8065	0.00
σ_α	0.0082	6.9335	0.00	-0.0019	-6.4560	0.00	-0.0121	-5.3624	0.00
σ_β	0.5187	19.5177	0.00	0.3307	11.5928	0.00	0.5688	11.9958	0.00
σ_w	0.0066	4.5138	0.00	0.0079	57.4169	0.00	0.0033	0.4153	0.34
a	-0.2295	-4.7261	0.00	-0.5065	-3.6012	0.00	-0.2226	-3.4189	0.00
b	12.7842	4.0948	0.00	-48.4804	-2.9762	0.00	10.8405	2.5979	0.00
c	-0.3624	-6.6706	0.00	-0.3715	-2.8250	0.00	-0.3121	-3.1070	0.00
d	-26.1885	-5.3183	0.00	-53.3102	-3.7751	0.00	-11.6843	-0.7033	0.24

	FTSE Model: Meteor shower from USA(t-1) to UK(t) with volume differential as variable z								
$\bar{\alpha}$	–	–	–	–	–	–	–	–	–
$\bar{\beta}$	0.3588	12.6746	0.00	0.4016	10.1673	0.00	0.3686	10.0256	0.00
σ_α	-0.0073	-15.8832	0.00	-0.0050	-13.5769	0.00	0.0123	12.7148	0.00
σ_β	0.6029	28.0260	0.00	0.6394	17.9267	0.00	0.4658	12.5450	0.00
σ_w	0.0066	15.2597	0.00	0.0054	20.4326	0.00	0.0030	0.8322	0.20
a	-0.4778	-12.8243	0.00	-0.6056	-14.4199	0.00	-0.3013	-6.2101	0.00
b	51.9362	2.3901	0.01	5.0628	0.1630	0.44	-10.2539	-0.3340	0.37
c	-0.0307	-0.4192	0.34	-0.0172	-0.2314	0.41	-0.0832	-0.6499	0.26
d	-24.4888	-0.3946	0.35	226.2657	2.4713	0.01	-61.5712	-0.6572	0.26

	TOPIX Model: Meteor shower from UK(t-1) to Japan(t) with volume differential as variable z								
$\bar{\alpha}$	–	–	–	–	–	–	–	–	–
$\bar{\beta}$	0.1341	6.3506	0.00	0.0749	2.7008	0.00	0.1637	5.5703	0.00
σ_α	0.0021	5.7243	0.00	0.0053	0.9920	0.16	-0.0021	-5.1466	0.00
σ_β	0.3946	21.9881	0.00	0.2395	5.8313	0.00	0.4134	17.0622	0.00
σ_w	0.0084	72.6140	0.00	0.0061	1.3101	0.10	0.0093	60.8233	0.00
a	-0.5770	-7.7565	0.00	-0.0477	-0.4312	0.33	-0.7491	-17.9063	0.00
b	-25.3034	-4.7005	0.00	-14.1643	-0.5349	0.30	-23.8128	-3.4987	0.00
c	-0.0145	-0.1493	0.44	-0.0060	-0.0188	0.49	-0.0093	-0.0830	0.47
d	-15.9475	-2.1415	0.02	-10.0804	-0.2640	0.40	-20.3194	-2.2851	0.01

Notes: Table 2 presents estimation results of the FIT model (Eqs. (1)-(3)) for the three stock market relationships where variables x, y are (a) Japan(t) and USA(t) (dubbed the DJIA Model), (b) UK(t), and USA(t-1) (dubbed the FTSE Model), and (c) Japan (t) and UK(t-1) (dubbed the TOPIX Model). The variable z is the volume differential between the respective pairs of markets. The sample period is 1 July 2002 through 29 June 2012, divided equally around 29 June 2007 for pre-crisis and post-crisis sub-samples. Models that would not converge by forcing the estimation of an insignificant $\bar{\alpha}$ are denoted by a dash '–' in the $\bar{\alpha}$ cell.

Table 3: Estimation Results of Meteor Shower Models with Volatility Differential as the Indirect Information Channel.

DJIA Model: Meteor shower from Japan(t) to USA(t) with volatility differential as variable z

	All sample period			Pre-crisis			Post-crisis		
	Estimate	*t*-stat	*p*-value	Estimate	*t*-stat	*p*-value	Estimate	*t*-stat	*p*-value
$\bar{\alpha}$	0.0003	1.5654	0.06	0.0004	1.7073	0.04	0.0003	1.0586	0.14
$\bar{\beta}$	0.2092	7.2927	0.00	0.1313	3.9674	0.00	0.2761	6.2465	0.00
σ_α	0.0036	10.2358	0.00	0.0012	4.9380	0.00	0.0119	7.2910	0.00
σ_β	0.5500	19.8669	0.00	0.3383	11.3426	0.00	0.5640	13.1382	0.00
σ_w	0.0096	62.2418	0.00	0.0082	57.0018	0.00	0.0033	0.5746	0.28
a	-0.3378	-8.3012	0.00	-0.7024	-11.6421	0.00	-0.3531	-5.5646	0.00
b	-23.7726	-27.5572	0.00	-19.6427	-5.2904	0.00	9.5155	7.0992	0.00
c	-0.2793	-3.3578	0.00	-0.4171	-4.1935	0.00	-0.2920	-2.9678	0.00
d	-8.4841	-2.7924	0.00	-19.7051	-3.8776	0.00	-12.2876	-3.4591	0.00

FTSE Model: Meteor shower from USA(t-1) to UK(t) with volatility differential as variable z

	All sample period			Pre-crisis			Post-crisis		
	Estimate	*t*-stat	*p*-value	Estimate	*t*-stat	*p*-value	Estimate	*t*-stat	*p*-value
$\bar{\alpha}$	0.0000	-0.0470	0.48	0.0001	0.5804	0.28	–	–	–
$\bar{\beta}$	0.3660	13.3603	0.00	0.4039	9.8774	0.00	0.3686	10.2344	0.00
σ_α	-0.0077	-19.3258	0.00	0.0052	17.1661	0.00	0.0123	10.8362	0.00
σ_β	0.5969	28.0294	0.00	0.6500	18.7637	0.00	0.4617	12.3395	0.00
σ_w	0.0063	15.1863	0.00	0.0053	20.0270	0.00	0.0031	0.7353	0.23
a	-0.4047	-11.0453	0.00	-0.4603	-10.5594	0.00	-0.2790	-5.6314	0.00
b	-8.2267	-4.3594	0.00	-19.1949	-7.4390	0.00	-2.9777	-1.2386	0.11
c	-0.0465	-0.7515	0.23	-0.1368	-1.2758	0.10	-0.0684	-0.6282	0.26
d	3.8298	1.3247	0.09	14.2875	3.1940	0.00	3.3292	0.6441	0.26

TOPIX Model: Meteor shower from UK(t-1) to Japan(t) with volatility differential as variable z

	All sample period			Pre-crisis			Post-crisis		
	Estimate	*t*-stat	*p*-value	Estimate	*t*-stat	*p*-value	Estimate	*t*-stat	*p*-value
$\bar{\alpha}$	-0.0005	-2.8130	0.00	-0.0004	-1.4649	0.07	-0.0007	-2.4218	0.01
$\bar{\beta}$	0.1340	6.2109	0.00	0.0788	2.7083	0.00	0.1669	5.1539	0.00
σ_α	0.0009	5.2872	0.00	0.0040	4.0831	0.00	0.0062	10.9332	0.00
σ_β	0.4167	23.0153	0.00	0.2557	6.2934	0.00	0.4587	19.3982	0.00
σ_w	0.0084	80.3583	0.00	0.0069	11.2769	0.00	0.0064	10.9575	0.00
a	-0.9085	-90.1174	0.00	0.0977	1.1731	0.12	-0.4919	-11.7562	0.00
b	11.8575	12.1314	0.00	-29.5919	-4.4048	0.00	18.3149	10.8497	0.00
c	-0.0221	-0.3674	0.36	0.0519	0.1650	0.43	0.1027	1.7096	0.04
d	-9.5213	-5.4550	0.00	-7.1090	-0.3812	0.35	-15.6472	-9.6614	0.00

Notes: Table 3 presents estimation results of the FIT model (Eqs. (1)-(3)) for the three stock market relationships where variables x, y are (a) Japan(t) and USA(t) (dubbed the DJIA Model), (b) UK(t), and USA(t-1) (dubbed the FTSE Model), and (c) Japan (t) and UK(t-1) (dubbed the TOPIX Model). The variable z is the volatility differential between the respective pairs of markets. The sample period is 1 July 2002 through 29 June 2012, divided equally around 29 June 2007 for pre-crisis and post-crisis sub-samples. Models that would not converge by forcing the estimation of an insignificant $\bar{\alpha}$ are denoted by a dash '–' in the $\bar{\alpha}$ cell.

Table 4: Estimation Results of Meteor Shower Models with Interest Rate Spread Differential as the Indirect Information Channel.

	DJIA Model: Meteor shower from Japan(t) to USA(t) with interest differential as variable z								
	All sample period			Pre-crisis			Post-crisis		
	Estimate	*t*-stat	*p*-value	Estimate	*t*-stat	*p*-value	Estimate	*t*-stat	*p*-value
$\bar{\alpha}$	0.0033	1.4666	0.07	0.0042	1.6840	0.05	0.0026	0.7640	0.22
$\bar{\beta}$	0.2019	7.4835	0.00	0.1421	4.3218	0.00	0.2566	6.4128	0.00
σ_α	-0.0333	-9.7930	0.00	0.0237	4.3350	0.00	0.1226	4.7826	0.00
σ_β	0.5190	18.2219	0.00	0.3362	9.2224	0.00	0.5374	12.4129	0.00
σ_w	0.0974	69.2795	0.00	0.0786	37.3673	0.00	0.0324	0.3387	0.37
a	-0.5936	-9.7737	0.00	-0.4945	-2.7371	0.00	-0.1952	-2.6542	0.00
b	-15.5193	-4.3827	0.00	-19.3663	-1.7967	0.04	-0.5934	-0.1565	0.44
c	-0.3383	-3.7321	0.00	-0.5652	-6.2570	0.00	-0.3250	-2.1609	0.02
d	-13.1563	-1.9511	0.03	-11.3331	-1.5750	0.06	-20.1251	-1.3364	0.09
	FTSE Model: Meteor shower from USA(t-1) to UK(t) with interest differential as variable z								
$\bar{\alpha}$	0.0000	0.0178	0.49	0.0016	0.7633	0.22	-0.0018	-0.5558	0.29
$\bar{\beta}$	0.3612	12.6547	0.00	0.3999	9.8240	0.00	0.3580	9.3832	0.00
σ_α	0.0799	24.8459	0.00	0.0485	12.6860	0.00	0.1203	8.5225	0.00
σ_β	0.5963	27.2603	0.00	0.6432	20.2416	0.00	0.4801	13.2814	0.00
σ_w	0.0592	17.0737	0.00	0.0554	20.6492	0.00	0.0356	0.7960	0.21
a	-0.4319	-13.3402	0.00	-0.6074	-13.0424	0.00	-0.2881	-4.6445	0.00
b	7.4114	3.7561	0.00	9.7234	2.1979	0.01	6.7756	2.7556	0.00
c	-0.0021	-0.0295	0.49	-0.0050	-0.0501	0.48	-0.0016	-0.0113	0.50
d	0.0994	0.0195	0.49	-5.2450	-0.2800	0.39	2.4730	0.2997	0.38
	TOPIX Model: Meteor shower from UK(t-1) to Japan(t) with interest differential as variable z								
$\bar{\alpha}$	-0.0054	-2.8429	0.00	-0.0036	-1.5292	0.06	-0.0071	-2.3275	0.01
$\bar{\beta}$	0.1346	6.3327	0.00	0.0792	2.8363	0.00	0.1826	6.3276	0.00
σ_α	0.0606	1.7633	0.04	0.0178	1.4288	0.08	0.0464	4.4676	0.00
σ_β	0.3973	22.0043	0.00	0.2269	5.4747	0.00	0.4170	16.4545	0.00
σ_w	0.0638	1.9901	0.02	0.0789	25.7861	0.00	0.0826	13.6044	0.00
a	-0.1262	-1.0233	0.15	-0.4387	-1.0806	0.14	-0.3704	-3.8698	0.00
b	-0.0500	-0.8969	0.18	0.2942	1.0808	0.14	-0.1530	-4.6839	0.00
c	-0.0648	-1.0711	0.14	-0.0207	-0.0520	0.48	-0.1059	-1.3118	0.09
d	0.0023	0.0396	0.48	-0.1439	-0.2857	0.39	-0.0451	-0.6959	0.24

Notes: Table 4 presents estimation results of the FIT model (Eqs. (1)-(3)) for the three stock market relationships where variables x, y are (a) Japan(t) and USA(t) (dubbed the DJIA Model), (b) UK(t), and USA(t-1) (dubbed the FTSE Model), and (c) Japan (t) and UK(t-1) (dubbed the TOPIX Model). The variable z is the interest rate spread differential between the respective pairs of markets. The sample period is 1 July 2002 through 29 June 2012, divided equally around 29 June 2007 for pre-crisis and post-crisis sub-samples. Models that would not converge by forcing the estimation of an insignificant $\bar{\alpha}$ are denoted by a dash '–' in the $\bar{\alpha}$ cell.

APPENDIX

Table A1: Descriptive Statistics

All Sample	*JPpcHL*	*JPlnCO*	*JPV*	*JPS*	*UKpcHL*	*UKlnCO*	*UKV*	*UKS*	*USpcHL*	*USlnCO*	*USV*	*USS*
Mean	0.0123	-0.0005	0.0166	0.0117	0.0154	0.0001	0.0014	0.0104	0.0140	0.0002	0.0023	0.0211
Median	0.0106	0.0000	0.0173	0.0117	0.0123	0.0000	0.0014	0.0072	0.0113	0.0004	0.0022	0.0240
Std Dev	0.0091	0.0106	0.0071	0.0028	0.0114	0.0131	0.0006	0.0140	0.0113	0.0125	0.0009	0.0123
Kurtosis	29.8140	12.7625	1.2689	-0.1021	9.6066	6.7024	1.0296	-1.1617	17.0275	8.7146	2.8913	-0.7081
Skewness	3.7296	-0.3213	-0.1822	0.2415	2.4113	-0.1363	0.1455	0.4651	3.1811	0.0314	0.5939	-0.6576
Range	0.1357	0.1969	0.0578	0.0154	0.1074	0.1865	0.0045	0.0499	0.1214	0.1848	0.0072	0.0475
Minimum	0.0000	-0.0844	0.0000	0.0042	0.0000	-0.0927	0.0000	-0.0118	0.0000	-0.0810	0.0000	-0.0078
Maximum	0.1357	0.1126	0.0578	0.0196	0.1074	0.0938	0.0045	0.0381	0.1214	0.1038	0.0072	0.0397
Count	2602	2602	2602	2602	2602	2602	2602	2602	2602	2602	2602	2602

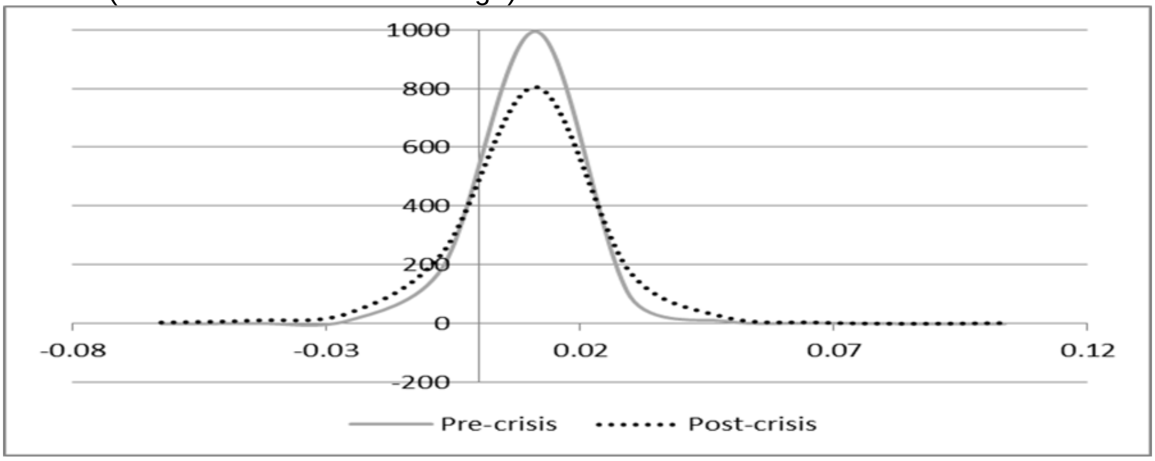
Pre-crisis	*JPpcHL*	*JPlnCO*	*JPV*	*JPS*	*UKpcHL*	*UKlnCO*	*UKV*	*UKS*	*USpcHL*	*USlnCO*	*USV*	*USS*
Mean	0.0108	-0.0004	0.0144	0.0131	0.0121	0.0003	0.0016	0.0025	0.0113	0.0004	0.0023	0.0170
Median	0.0098	0.0000	0.0143	0.0135	0.0094	0.0003	0.0016	0.0008	0.0093	0.0004	0.0023	0.0210
Std Dev	0.0062	0.0085	0.0070	0.0030	0.0094	0.0105	0.0005	0.0055	0.0077	0.0093	0.0007	0.0136
Kurtosis	4.7562	2.0378	0.8426	0.4265	8.8972	5.5324	3.5437	-1.2011	11.1378	5.1620	4.6303	-1.3709
Skewness	1.3100	-0.4783	0.3488	-0.6091	2.5172	-0.2090	-0.4782	0.3838	2.4291	0.3183	-0.1282	-0.2373
Range	0.0543	0.0817	0.0456	0.0154	0.0789	0.1149	0.0045	0.0205	0.0851	0.1092	0.0072	0.0475
Minimum	0.0000	-0.0522	0.0000	0.0042	0.0000	-0.0559	0.0000	-0.0059	0.0000	-0.0471	0.0000	-0.0078
Maximum	0.0543	0.0296	0.0456	0.0196	0.0789	0.0590	0.0045	0.0146	0.0851	0.0621	0.0072	0.0397
Count	1301	1301	1301	1301	1301	1301	1301	1301	1301	1301	1301	1301

Post-crisis	*JPpcHL*	*JPlnCO*	*JPV*	*JPS*	*UKpcHL*	*UKlnCO*	*UKV*	*UKS*	*USpcHL*	*USlnCO*	*USV*	*USS*
Mean	0.0137	-0.0007	0.0188	0.0104	0.0186	-0.0002	0.0011	0.0183	0.0167	0.0001	0.0022	0.0251
Median	0.0114	-0.0001	0.0193	0.0103	0.0157	0.0000	0.0010	0.0237	0.0135	0.0004	0.0020	0.0263
Std Dev	0.0110	0.0123	0.0064	0.0016	0.0124	0.0153	0.0005	0.0154	0.0134	0.0150	0.0010	0.0093
Kurtosis	24.3219	13.0563	4.1865	-0.8677	9.4756	5.6027	2.7686	-1.0353	13.1472	7.0332	2.1671	0.1964
Skewness	3.6425	-0.2269	-0.7459	-0.0148	2.3775	-0.0819	0.8554	-0.6646	2.9094	-0.0233	0.9744	-0.8232
Range	0.1357	0.1969	0.0578	0.0076	0.1074	0.1865	0.0039	0.0499	0.1214	0.1848	0.0067	0.0432
Minimum	0.0000	-0.0844	0.0000	0.0065	0.0000	-0.0927	0.0000	-0.0118	0.0000	-0.0810	0.0000	-0.0036
Maximum	0.1357	0.1126	0.0578	0.0141	0.1074	0.0938	0.0039	0.0381	0.1214	0.1038	0.0067	0.0396
Count	1301	1301	1301	1301	1301	1301	1301	1301	1301	1301	1301	1301

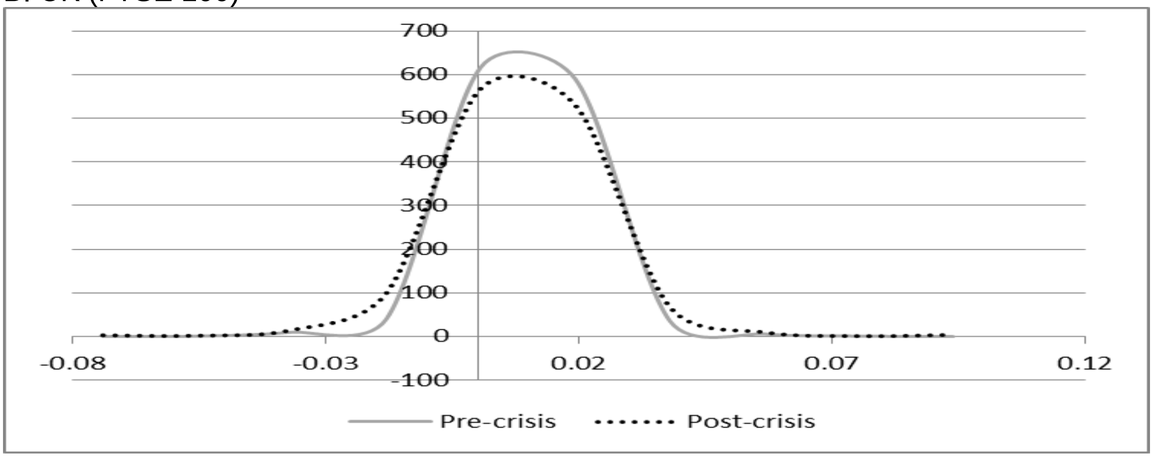
Notes: Prefixes *JP* =Japan, *UK* = United Kingdom, *US*= United States. *pcHL* = percentage difference between daily High(H) and daily Low (L) = (H-L)/(H+L)/2; *lnCO* = continuous compounded open-close returns; *V* = volume rescaled by dividing by 100 for USA and Japan and by 1000 for UK; *S* = interest rate spread = yield to maturity (YTM) of 10-year bonds less the middle rate of 1-month T-Bills, rescaled by dividing by 100. Tabulated descriptive statistics are of the rescaled variables. The sample period is 1 July 2002 through 29 June 2012, divided equally around 29 June 2007 for pre-crisis and post-crisis sub-samples.

Figure A1: Distribution of Daily Returns in the Pre- and Post-Crisis Periods

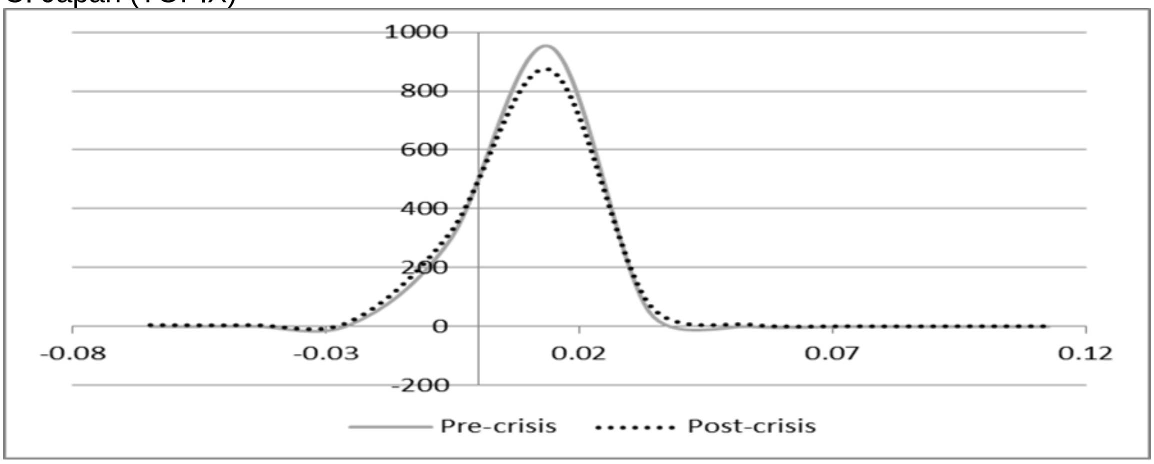
A. USA (Dow Jones Industrial Average)



B. UK (FTSE 100)



C. Japan (TOPIX)



Notes: Figure A1 presents the frequency distribution of continuously-compounded open-to-close daily returns. The *y*-axis is the frequency count and the *x*-axis is the returns.