Volatility transmission in global financial markets

A.E. Clements, A.S. Hurn, and V.V. Volkov
School of Economics and Finance, Queensland University of Technology,
and
National Centre for Econometric Research.

Abstract

This paper considers the transmission of volatility in global foreign exchange, equity and bond markets. Using a multivariate GARCH framework which includes measures of realized volatility as explanatory variables, significant volatility and news spillovers on the same trading day between Japan, Europe, and the United States are found. All markets exhibit significant degrees of asymmetry in terms of the transmission of volatility associated with good and bad news. There are also strong links between diffusive volatility in all three markets, jump activity is only important within equity markets. The results of this paper deepen our understanding of how news and volatility are propagated through global financial markets.

Keywords
GARCH, realized volatility, asymmetry, jumps, volatility transmission

JEL Classification Numbers
C32, C51, C52, G10

Corresponding author
email `v.volkov@qut.edu.au`

1 Introduction

The practical importance of modelling the volatility of financial assets has given rise to a voluminous body of research. Much of the modern literature stems from the seminal work of Engle (1982) and Bollerslev (1986) who treat volatility as an unobserved quantity. More recent developments treat volatility as a realized (observed) variable, which is estimated from the squared returns of high-frequency financial asset returns (Barndorff-Nielsen and Shephard, 2002; Andersen, Bollerslev, Diebold and Labys, 2003). Hansen, Huang and Shek (2012) provide one avenue for combining these two approaches. The vast majority of this work relates to modelling and forecasting the trajectory of the volatility of an asset in one particular market.

A relatively recent but growing area of interest addresses the important question of how volatility is propagated from one region of the world to another. The series of papers by Ito (1987), Ito and Roley (1987) and Engle, Ito and Lin (1990) examine how volatility is transmitted through different regions of the world during the course of a global financial trading day. The approach is to partition each 24 hour period (calendar day) into four trading zones, namely, Asia, Japan, Europe and the United States, and examine international linkages in volatility between these regions in the context of the foreign exchange market. Engle, Ito and Lin (1990) describe two particular patterns, namely, the *heatwave* in which volatility in one region is primarily a function of the previous day's volatility in the same region, and the *meteor shower* in which volatility in one region is driven by volatility in the region immediately preceding it in terms of calendar time. Their major conclusion is that volatility in the foreign exchange market is best described by the meteor shower pattern. Using a similar research protocol, Fleming and Lopez (1999) and Savva, Osborn and Gill (2005) find that the heatwave hypothesis best describes the behaviour of volatility in the bond and equity markets, respectively. Treating volatility as an observed measure, Melvin and Melvin (2003) investigate the transmission of volatility in the foreign exchange market using realized volatility. While there is some support for both the meteor shower and heatwave hypotheses, the evidence marginally favours the latter.[1]

This paper contributes to the literature examining volatility patterns in global foreign exchange, equity, and bond markets. In the spirit of Fleming and Lopez (1999), the trading day is partitioned into three zones, Japan, Europe, and the United States, for each market. The original Engle, Ito and Lin (1990) model is extended in order to entertain a more complex set of volatility interactions. Incorporating realized volatility as an explanatory variable in the regional conditional variance equations turns out to be valuable way of investigating volatility linkages and allows extensions in a number of dimensions. Using the jump and continuous components of realized volatility reveals that the diffusive component has more explanatory power than the jump component. The jump component which reflects more extreme news arrival is only significant for the equity market. Furthermore, decomposing realized volatility into positive and negative semivariances allows the asymmetric transmission of volatility to be explored. It is found that the foreign exchange and bond markets are mainly driven by a positive semivariance, whereas the equity market is driven mainly by the negative semivariance.

The rest of the paper proceeds as follows. Section 2 revisits the original Engle, Ito and Lin (1990) framework and re-examines their results in the context of a different sample period and for a broader selection of financial markets. Section 3 extends the GARCH framework to try and separate the effects of the news and smoothed conditional variances on volatility transmission between regions. Section 4 constructs measures of realized volatility in the each of the trading zones and decomposes the basic measure into a number of constituent components which are used later in the estimation. Section 5 introduces realized volatility as an explanatory factor of volatility interactions within the three regions and examines how different constituents of realized volatility contributed to

[1] More recent research has also documented significant linkages in volatilities between different financial markets within a particular region. See for example, Hakim and McAleer (2010), Bubak, Kocenda and Zikes (2011), Ehrmann, Fratzscher and Rigobon (2011) and Engle, Gallo and Velucchi (2012)

our understanding of the global transmission of volatility. Section 6 is a brief conclusion.

2 Revisiting Heatwaves and Meteor Showers

In their seminal paper, Engle, Ito and Lin (1990) find evidence that the role of news from adjacent regions (the meteor shower) is to be preferred to local influences from the previous day (the heatwave) as an explanation of the transmission of volatility in the foreign exchange market. In this section the results of Engle, Ito and Lin (1990) for the foreign exchange market are revisited in the context of the current data 2005 to 2013, and extended to the equity and bond markets.

A high frequency (10 minutes) data set was gathered from the Thomson Reuters Tick History for the period from 3 January 2005 to 28 February 2013 for instruments representative of the foreign exchange, bond and equity markets. Specifically, the following series were collected:

1. Euro-Dollar futures contracts traded on the Chicago Mercantile Exchange (foreign exchange market);
2. US 10 year Treasury bond futures contracts (one of the most traded securities in the bond market (Fleming and Lopez, 1999));
3. S&P 500 futures contracts (equity markets).

Each of these instruments is traded continuously (23 hours per calendar day). Following the standard approach in the literature (Andersen, Bollerslev, Diebold and Labys, 2003) days where one market is closed are eliminated, as are public holidays or other occasions when trading is significantly curtailed.

This continuously-traded, high-frequency data on futures contracts is now used to construct returns to the instruments in each of three trading zones, namely, Japan (JP), Europe (EU), and the United States (US). The protocol of Fleming and Lopez (1999) to delimit a global trading day is adopted. The Japanese trading zone is defined as 12am to 7am GMT, the European trading zone is taken to be 7am to 2pm GMT and the United States zone is 2pm to 9pm GMT. Note that the period denoted as Asian trading (2 hours prior to Japan opening) by Engle, Ito and Lin (1990), is excluded here. The setup may be illustrated as follows:

$$\underbrace{\overbrace{12\text{am}\cdots 7\text{am}}^{\text{Japan}}\quad\overbrace{7\text{am}\cdots 2\text{pm}}^{\text{Europe}}\quad\overbrace{2\text{pm}\cdots 9\text{pm}}^{\text{U.S.}}}_{\text{One Trading Day}}$$

Following Engle, Ito and Lin (1990) each zone return is calculated as the difference between the last and the first transaction price within the same calendar day which can be expressed as

$$R_t^i = \ln PC_t^i - \ln PO_t^i, \tag{1}$$

in which, PC_t^i is a closing price in zone i on day t, and PO_t^i is an opening price in zone i on day t. All in all, returns to each region are computed for 1902 trading days each.

The original model proposed by Engle, Ito and Lin (1990) applies to $i = 1, \cdots, N$ non-overlapping trading zones and takes the form

$$r_{i,t} = \sqrt{h_{i,t}}\,\epsilon_{i,t}\,, \qquad \epsilon_{i,t} \sim N(0,1) \tag{2}$$

$$h_{i,t} = \kappa_i + \beta_{ii} h_{i,t-1} + \sum_{j=1}^{i-1} \alpha_{ij}\epsilon_{j,t}^2 + \sum_{j=i}^{n} \gamma_{ij}\epsilon_{j,t-1}^2\,, \tag{3}$$

in which $r_{i,t}$ is a time-series of returns, $h_{i,t}$ is the conditional variance of returns and $\epsilon_{i,t}^2$ is the squared innovation (news) all defined for zone i at time t. This specification deviates from a traditional GARCH model by recognising that the structure of the global trading day allows for news from preceding regions to influence volatility, an effect which is labelled 'diurnal' news.[2]

[2] On a purely pedantic note, the use of the adjective 'diurnal' here may not be correct strictly speaking

The calendar structure implied by equation (3) is perhaps best seen by writing the equation in matrix form and tailoring it to the current modelling environment in which $N = 3$. The relevant equation is now

$$h_t = K + A\,h_{t-1} + B\,\epsilon_t^2 + G\,\epsilon_{t-1}^2 \tag{4}$$

where $h_t = [h_{\text{jp},t}\ h_{\text{eu},t}\ h_{\text{us},t}]'$, $\epsilon_t^2 = [\epsilon^2_{\text{jp},t}\ \epsilon^2_{\text{eu},t}\ \epsilon^2_{\text{us},t}]'$ and the subscripts are self evident. The parameter matrices of interest are

$$A = \begin{bmatrix} \alpha_{11} & 0 & 0 \\ 0 & \alpha_{22} & 0 \\ 0 & 0 & \alpha_{33} \end{bmatrix}, \quad B = \begin{bmatrix} 0 & 0 & 0 \\ \beta_{21} & 0 & 0 \\ \beta_{31} & \beta_{32} & 0 \end{bmatrix}, \quad G = \begin{bmatrix} \gamma_{11} & \gamma_{12} & \gamma_{13} \\ 0 & \gamma_{22} & \gamma_{23} \\ 0 & 0 & \gamma_{33} \end{bmatrix}.$$

The calendar structure is now apparent, particularly in the matrix B. Specifically, new developments in Japan, $\epsilon^2_{\text{jp},t}$, at the start of the trading day can potentially influence volatility in Europe and the United States via the coefficients β_{21} and β_{31}. Similarly news from Europe, $\epsilon^2_{\text{eu},t}$, can influence volatility in the United States on the same day, β_{32}. The natural calendar structure, however, implies that events in the United States will be transmitted to Japan only on the following day. The restrictions on the matrix G which require it to be an upper diagonal matrix are not strictly necessary as all information at $t-1$ can affect all trading zones, but they are imposed by Engle, Ito and Lin (1990) in their original formulation. The system (4) is characterised by an information matrix which is block diagonal with respect to the required parameters. For this reason single equation estimation of the model by the maximum likelihood can be preformed on each zone.

Table 1 reports the estimation results for equation (4) based on the foreign exchange, equity and bond markets. [3] There are two general conclusions that emerge from inspection of these results.

in referring to impacts from event in different regions earlier in the same trading day. The only other available term seems to be 'contemporaneous' but this may erroneously give the impression of events taking place at the same time.

[3] In Table 1 and all subsequent reporting of estimation results the constant term in the covariance equation is suppressed.

1. It is immediately apparent that the pattern of volatility interaction is a combination of both heat waves and meteor showers. There is no support for the hypothesis that one of these patterns dominates, although the argument in favour of a heatwave is probably strongest in the bond market, where Japanese news seems to have no explanatory effect on the United States and the size of the remaining two significant coefficients are relatively small.

2. There is significant persistence of volatility in each region with all the coefficients on the lagged conditional variance term, $h_{i,t-1}$, being significant. It is probably fair to say that persistence is uniformly greatest in the foreign exchange market. Moreover, the sizes of the coefficients on $h_{i,t-1}$ in the foreign exchange market are larger than those of Engle, Ito and Lin (1990). Perhaps this difference it attributable to the different periods are used in the analysis. Engle, Ito and Lin (1990) use data from 1985 to 1986, while this paper deals with data from 2005 to 2013.

Turning now to each market in turn, a few observations are in order. Rather surprisingly, the diurnal impact of European news on the United States volatility, $\epsilon^2_{eu,t}$, is not significant at the 5% level. This may perhaps be due to the fact that Japanese news has a strong diurnal effect on both Europe and the United States and this crowds out the effect of European news. In the equity market all the coefficients across all the regions are significant. This pattern of interaction suggests that world equity markets are very strongly interrelated. Finally, in the bond market the insignificance of Japanese news on the United States and the comparatively small coefficient estimates of the remaining coefficients capturing the impact from the immediately preceding regions has already been alluded to. This is a very interesting result in that it tends to support the results of Fleming and Lopez (1999) and Savva, Osborn and Gill (2005) who find that the heatwave hypothesis best describes the behaviour of volatility in the bond market.

These results vindicate the original insight of Engle, Ito and Lin (1990), made in the

Table 1:
Coefficient estimates of the equation (4) for the foreign exchange, equity and bond markets for each of the three trading zones. Coefficients that are significant at the 5% level are marked (*).

		Japan	Europe	United States
FX Market	$\epsilon^2_{\mathrm{jp},t}$	-	0.0459*	0.0388*
	$\epsilon^2_{\mathrm{eu},t}$	-	-	0.0053
	$\epsilon^2_{\mathrm{us},t}$	-	-	-
	$\epsilon^2_{\mathrm{jp},t-1}$	0.0432*	-	-
	$\epsilon^2_{\mathrm{eu},t-1}$	0.0036	0.0147*	-
	$\epsilon^2_{\mathrm{us},t-1}$	0.0072*	0.0139*	0.0428*
	$h_{i,t-1}$	0.9321*	0.9463*	0.9283*
		Japan	Europe	United States
Equity Market	$\epsilon^2_{\mathrm{jp},t}$	-	0.0783*	0.3116*
	$\epsilon^2_{\mathrm{eu},t}$	-	-	0.3326*
	$\epsilon^2_{\mathrm{us},t}$	-	-	-
	$\epsilon^2_{\mathrm{jp},t-1}$	0.0841*	-	-
	$\epsilon^2_{\mathrm{eu},t-1}$	0.0355*	0.0442*	-
	$\epsilon^2_{\mathrm{us},t-1}$	0.0055*	0.0081*	0.1131*
	$h_{i,t-1}$	0.7882*	0.9065*	0.6831*
		Japan	Europe	United States
Bond Market	$\epsilon^2_{\mathrm{jp},t}$	-	0.0150*	0.0051
	$\epsilon^2_{\mathrm{eu},t}$	-	-	0.0153*
	$\epsilon^2_{\mathrm{us},t}$	-	-	-
	$\epsilon^2_{\mathrm{jp},t-1}$	0.3216*	-	-
	$\epsilon^2_{\mathrm{eu},t-1}$	0.0513*	0.0136*	-
	$\epsilon^2_{\mathrm{us},t-1}$	0.0319*	0.0106*	0.0362*
	$h_{i,t-1}$	0.5534*	0.9629*	0.9451*

context of the foreign exchange market, to the effect that the transmission of news between different regions of the world on the same trading day is a potentially important explanation of volatility. The result stands the test of time, from the perspectives of different sample periods and different markets. There is therefore strong motivation to pursue this avenue of inquiry beyond the confines of the original study.

3 Volatility Spillovers and News

It has been shown that volatility in the current zone depends on current and lagged innovations from the preceding zones and also lagged conditional variance in the current zone. However, this specification analysis does not allow for diurnal volatility effect, $h_{i,t}$, from the immediately preceding zone to influence volatility in the current zone. This effect may be labelled fairly loosely as a volatility spillover. To take this into account the model must be specified as follows

$$\tilde{A}h_t = K + A\,h_{t-1} + B\,\epsilon_t^2 + G\,\epsilon_{t-1}^2 \tag{5}$$

in which the matrix $\tilde{A}$ now captures the effect of the the conditional variance in preceding zones on the current zone on the same trading day. In the case of the three zones dealt with here, the structure is

$$\tilde{A} = \begin{bmatrix} 1 & 0 & 0 \\ \tilde{\alpha}_{21} & 1 & 0 \\ 0 & \tilde{\alpha}_{32} & 1 \end{bmatrix},$$

which emphasises that the current conditional variance term appropriate for Japan is in fact the lagged conditional variance from the previous days close in the United States. This is now a system of equations that must be estimated simultaneously.

As a precursor to the estimation of equation (5) a model is estimated in which the restriction $B = 0$ is imposed. The resultant model is therefore one in which there are volatility spillovers between regions but no allowance is made for diurnal effects from the news in preceding regions. The results are reported in Table 2 from which it is immediately apparent that the pattern of the estimated coefficients is very similar to that in Table 1. In most instances the appropriate current conditional variance terms is significant in explaining volatility in each of the regions. Furthermore, in most cases the inclusion of the conditional variance from the immediately preceding zone has the effect of dramatically reducing volatility persistence as can be ascertained from the size of the estimated coefficient on lagged volatility.

Table 2:
Coefficient estimates of the equation (5) with the restriction $B = 0$ imposed for the foreign exchange, equity and bond markets in each of the trading zones. Coefficients that are significant at the 5% level are marked (*)

		Japan	Europe	United States
FX Market	$h_{\mathrm{jp},t}$	-	0.1786*	-
	$h_{\mathrm{eu},t}$	-	-	0.0642*
	$h_{\mathrm{us},t-1}$	0.0410*	-	-
	$\epsilon^2_{\mathrm{jp},t-1}$	0.0748*	-	-
	$\epsilon^2_{\mathrm{eu},t-1}$	-	0.0172*	-
	$\epsilon^2_{\mathrm{us},t-1}$	-	-	0.0641*
	$h_{i,t-1}$	0.8405*	0.9012*	0.8556*
		Japan	Europe	United States
Equity Market	$h_{\mathrm{jp},t}$	-	0.2596*	-
	$h_{\mathrm{eu},t}$	-	-	0.2864*
	$h_{\mathrm{us},t-1}$	0.0324*	-	-
	$\epsilon^2_{\mathrm{jp},t-1}$	0.2391*	-	-
	$\epsilon^2_{\mathrm{eu},t-1}$	-	0.0919*	-
	$\epsilon^2_{\mathrm{us},t-1}$	-	-	0.1601*
	$h_{i,t-1}$	0.4959*	0.8264*	0.7154*
		Japan	Europe	United States
Bond Market	$h_{\mathrm{jp},t}$	-	0.0181*	-
	$h_{\mathrm{eu},t}$	-	-	0.0043
	$h_{\mathrm{us},t-1}$	0.0385*	-	-
	$\epsilon^2_{\mathrm{jp},t-1}$	0.3581*	-	-
	$\epsilon^2_{\mathrm{eu},t-1}$	-	0.0258*	-
	$\epsilon^2_{\mathrm{us},t-1}$	-	-	0.0398*
	$h_{i,t-1}$	0.6136*	0.9611*	0.9524*

Table 3:
Coefficient estimates of equation (5) for the foreign exchange, equity and bond markets in each of the trading zones. Coefficients that are significant at the 5% level are marked (*)

		Japan	Europe	United States
FX Market	$h_{\mathrm{jp},t}$	-	0.1045	-
	$h_{\mathrm{eu},t}$	-	-	0.0537*
	$h_{\mathrm{us},t-1}$	0.0438*	-	-
	$\epsilon^2_{\mathrm{jp},t}$	-	0.0296	-
	$\epsilon^2_{\mathrm{eu},t}$	-	-	0.0025
	$\epsilon^2_{\mathrm{us},t}$	0.0000	-	-
	$\epsilon^2_{\mathrm{jp},t-1}$	0.0732*	-	-
	$\epsilon^2_{\mathrm{eu},t-1}$	-	0.0144	-
	$\epsilon^2_{\mathrm{us},t-1}$	-	-	0.0613*
	$\mathrm{h}_{i,t-1}$	0.8359*	0.9235*	0.8685*
		Japan	Europe	United States
Equity Market	$h_{\mathrm{jp},t}$	-	0.2752*	-
	$h_{\mathrm{eu},t}$	-	-	0.0159
	$h_{\mathrm{us},t-1}$	0.0225*	-	-
	$\epsilon^2_{\mathrm{jp},t}$	-	0.0761*	-
	$\epsilon^2_{\mathrm{eu},t}$	-	-	0.4438*
	$\epsilon^2_{\mathrm{us},t}$	0.0060*	-	-
	$\epsilon^2_{\mathrm{jp},t-1}$	0.1633*	-	-
	$\epsilon^2_{\mathrm{eu},t-1}$	-	0.0439*	-
	$\epsilon^2_{\mathrm{us},t-1}$	-	-	0.0994*
	$\mathrm{h}_{i,t-1}$	0.5862*	0.8408*	0.7307*
		Japan	Europe	United States
Bond Market	$h_{\mathrm{jp},t}$	-	0.0000	-
	$h_{\mathrm{eu},t}$	-	-	0.0000
	$h_{\mathrm{us},t-1}$	0.0516*	-	-
	$\epsilon^2_{\mathrm{jp},t}$	-	0.0203	-
	$\epsilon^2_{\mathrm{eu},t}$	-	-	0.0363*
	$\epsilon^2_{\mathrm{us},t}$	0.0000	-	-
	$\epsilon^2_{\mathrm{jp},t-1}$	0.3524*	-	-
	$\epsilon^2_{\mathrm{eu},t-1}$	-	0.0256*	-
	$\epsilon^2_{\mathrm{us},t-1}$	-	-	0.0438*
	$\mathrm{h}_{i,t-1}$	0.5930*	0.9609*	0.9300*

Once again, volatility in the bond market is most likely to be generated by a heatwave. There seems little doubt that a correctly specified model of volatility and news transmission between regions must make allowance for the diurnal effect of conditional variance from the preceding zones. The Engle, Ito and Lin (1990) approach which does not allow for this effect therefore runs the risk of being misspecified.

The results obtained after estimation of the unrestricted version of equation (5) are reported in Table 3. The message here is somewhat mixed, particularly in the foreign exchange and bond markets. It appears that in these two markets making allowance for both volatility and news spillovers from the immediately preceding regions obfuscates the effect of news. Indeed only one of the six possible coefficients is significant. Three of the six possible coefficients representing volatility spillovers are significant, so the result in this instance is slightly stronger but not unambiguously so. This degree of ambiguity is absent in the equity market where the coefficients on both volatility and news spillovers are significant.

It seems that extending the Engle, Ito and Lin (1990) framework to allow for diurnal influences from both the news and from smoothed conditional variances causes somewhat of a conundrum. Although strong evidence from each of these channels of influence individually, the current attempt to estimate a general model seems to be unsatisfactory. It may be that too much is being asked in the estimation of a model where the proliferation of coefficients requiring estimation is leading to inefficiency. Ideally what is required now is to be able to include both these effects in a parsimonious framework, a task to which attention is now turned.

4 Computing Realized Volatility

The ten-minute data from the Thomson Reuters Tick History for the period from 3 January 2005 to 28 February 2013 is now used to construct various measures of realised volatility. To start with, the intra-daily returns at the frequency Δ for each trading zone are calculated as

$$r^i_{t,j}(\Delta) = \log p^i_{t,j} - \log p^i_{t,j-1}, \tag{6}$$

in which $p^i_{t,j}$ is the ten-minute price in zone i on the day t and in the time interval j. Once the intra-daily returns are available, a daily realized volatility for each zone is easily computed as a sum of the squared intra-day returns

$$RV_t(\Delta) \equiv \sum_{j=1}^{1/\Delta} r^2_{t,j}. \tag{7}$$

To detect jumps from the realized volatility at the frequency Δ, the minimum realised volatility estimator

$$\mathrm{MinRV}_t(\Delta) \equiv \frac{\pi}{\pi - 2}\left(\frac{1}{1-\Delta}\right)\sum_{j=2}^{1/\Delta} \min(|r_{t,j}|, |r_{t,j-1}|)^2 \tag{8}$$

of Andersen, Dobrev and Schaumburg (2012) is used. This jump robust estimator provides better finite sample properties than well known bi-power variation of Barndorff-Nielsen and Shephard (2002). Based on the asymptotic results of Barndorff-Nielsen and Shephard (2004,2006) and using the fact that[4]

$$\sqrt{\frac{1}{\Delta}}\left(\mathrm{MinRV}_{t+1} - \int_t^{t+1} \sigma^2(s)ds\right) \overset{stableD}{\rightarrow} MN\left(0, 3.81\int_t^{t+1} \sigma^4(s)ds\right),$$

statistically significant jumps are identified according to

$$Z_t(\Delta) \equiv \frac{[RV_t(\Delta) - \mathrm{MinRV}_t(\Delta)]/RV_t(\Delta)}{[1.81\Delta \max(1, \mathrm{MinRQ}_t(\Delta)/\mathrm{MinRV}_t(\Delta)^2)]^{1/2}} \sim N(0,1)$$

where MinRQ is a minimum realised quarticity

$$\mathrm{MinRQ}_t(\Delta) \equiv \frac{\pi}{\Delta(3\pi - 8)}\left(\frac{1}{1-\Delta}\right)\sum_{j=2}^{1/\Delta} \min(|r_{t,j}|, |r_{t,j-1}|)^4.$$

[4]See proposition 2 and 3 in Andersen, Dobrev and Schaumburg (2012), p. 78.

Significant jumps at an α level of significance are identified as

$$J_t(\Delta)(Z) \equiv 1[Z_t(\Delta) > \Phi_{1-\alpha}] \cdot [RV_t(\Delta) - \mathrm{MinRV}_t(\Delta)]. \tag{9}$$

Following Evans (2011) among others, the level of significance $\alpha = 0.999$ is chosen. The continuous component can be consistently estimated by minimum realized volatility MinRV_t, but to maintain the property that the sum of the continuous and jump components is equal to realized volatility, the removal of the negative jumps is made. The continuous component is given by

$$CC_t = RV_t - J_t(\Delta)(Z). \tag{10}$$

The volatility and jump estimates for the foreign exchange, equity, and bond markets calculated using equations (7) and (9) are presented in Figures 1, 2 and 3 respectively.

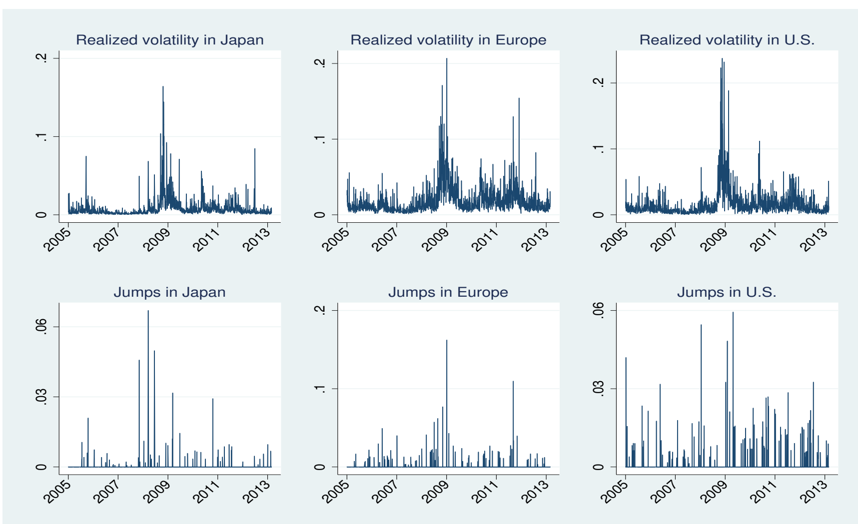

Figure 1: Realised volatility and jump estimates (scaled by 1000) for the foreign exchange market during Japanese, European, and United States trading hours, respectively, for the period 3 January 2005 to 28 February 2013.

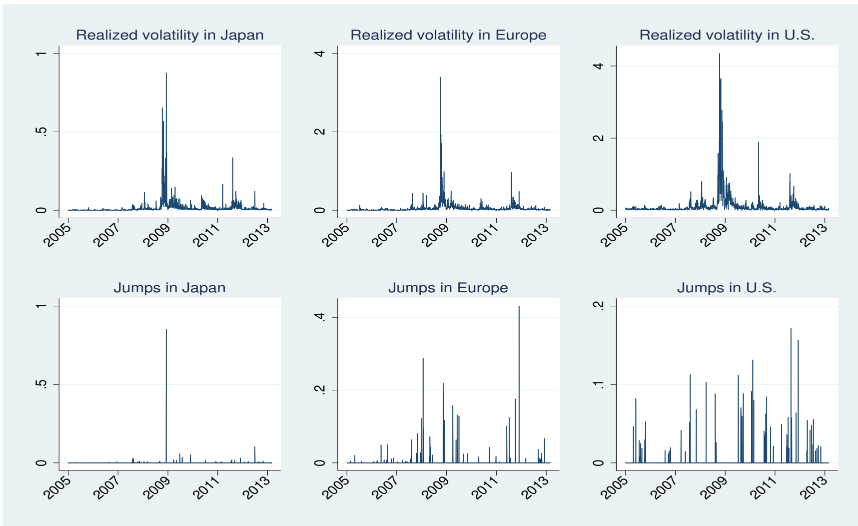

Figure 2: Realised volatility and jump estimates (scaled by 1000) for the equity market during Japanese, European and United States trading hours, respectively, for the period 3 January 2005 to 28 February 2013.

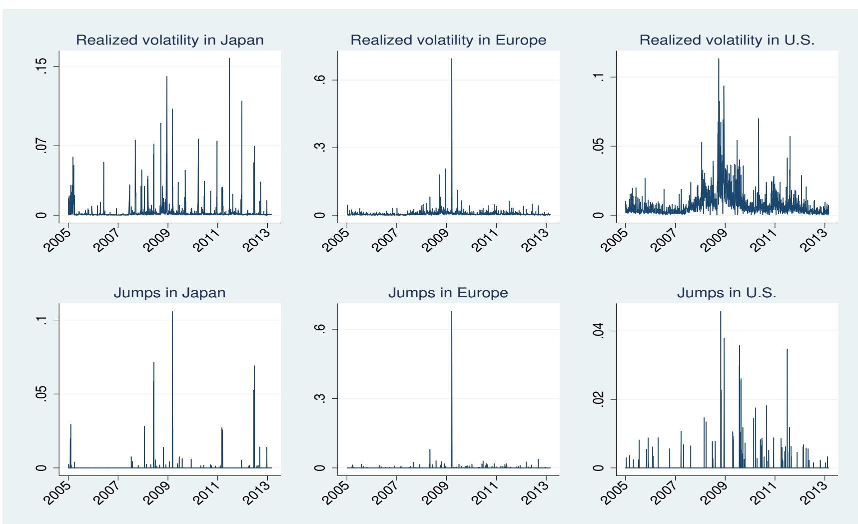

Figure 3: Realised volatility and jump estimates (scaled by 1000) for the bond market during Japanese, European and United States trading hours, respectively, for for the period 3 January 2005 to 28 February 2013.

To the naked eye it appears that the estimates of realised volatility in foreign exchange market have similar patterns across the trading zones. The volatility in the United States is perhaps a little more pronounced during the Global Financial Crises period of 2007 - 2009. However, the similarity across the three zones is not as pronounced in the equity and bond markets. Figure 2 indicates that while realised volatility in the European and the United States equity markets is very similar, Japanese volatility for this market is much lower and less prone to jump activity. Figure 3 shows that realised volatility in the bond market during European trading hours appears to behave differently to the other zones.

Table 4:

Descriptive statistics multiplied by 1000 for daily estimates of the realised volatility in the foreign exchange, equity and bond markets in Japan, Europe and United States.

		Mean	St.dev.	Min.	Max.	Skew.	Kurt.
	Japan	0.0075	0.0113	0.0002	0.1641	6.0338	55.5895
FX	Europe	0.0178	0.0165	0.0013	0.2067	3.4350	24.0533
	U.S.	0.0153	0.0190	0.0004	0.2373	5.0888	44.2786
	Japan	0.0142	0.0399	0.0003	0.8754	11.1558	182.7359
Equity	Europe	0.0472	0.1274	0.0010	3.3966	14.1367	302.0841
	U.S.	0.1095	0.2730	0.0006	4.3473	8.0528	89.1200
	Japan	0.0027	0.0090	0.0001	0.1577	9.5301	117.7135
Bond	Europe	0.0067	0.0186	0.0004	0.6955	28.0103	995.7895
	U.S.	0.0077	0.0090	0.0001	0.1134	3.8468	27.3901

Table 4 reports summary statistics for the realised volatility series. On average it seems that the mean level of volatility in the equity market is greater than that in the foreign exchange market which in turn is greater than the mean volatility in the bond market. Across the three markets, no one trading zone consistently experiences higher mean volatility. Volatility on average in the foreign exchange market is highest during European trading whereas the United States experiences the highest volatility in the equity and bond markets. The curious behaviour of volatility in European bond markets is clearly shown in the enormous kurtosis statistic of 995.79. This must be due to the absence of jump activity for large parts of the sample taken together with a huge jump during the global financial crisis.

Engle, Ito and Lin (1990) find that volatility is substantially higher during the New York trading hours than during Tokyo or London trading hours. Their view is that much of this volatility seems to originate from macroeconomic announcements released during New York trading hours. The results in Table 4 do not support the notion that United States volatility is uniformly higher. As expected, because realized volatility is essentially a sum of squared returns, the skewness and kurtosis statistics indicate a marked difference from what would be expected from a normal distribution.

As a quick consistency check on the accuracy of the procedure for isolating the jump component of realized volatility, days which exhibited the greatest volatility are presented in Table 5. It is useful to try and ascertain whether the largest jumps actually correspond to important events in the relevant markets and in this way establish the internal consistency of the method. The largest levels of volatility happened in all markets in the last quarter of 2008, which can be related to the bankruptcy of Lehman Brothers and the bridging loan from the Federal Reserve to the world largest insurance company A.I.G. The highest volatility in the crisis period was experienced in the equity market with the major effect in the United States. Another interesting event that significantly affects the equity market occurred in the middle of August 2011.

On 8 August 2011 fears of contagion of the European sovereign debt crisis to Spain and Italy led to a fall in the S&P 500 of 79.92 points (6.7%). As a result, Japanese and European equity markets experienced their 5th and 6th largest volatility episodes the next day. In the bond market, by far the biggest crisis appears to have been the decision by Fitch in March 2009 to downgrade Ireland's government debt from AAA to AA+.

	Foreign exchange			Equity			Bond		
Order	Jp	Eu	U.S.	Jp	Eu	U.S.	Jp	Eu	U.S.
1	0.1641	0.2068	0.2373	0.8754	3.3966	4.3473	0.1578	0.6955	0.1134
	22/10/08	05/01/09	19/11/08	08/12/08	08/10/08	10/10/08	22/06/11	19/03/09	29/09/08
2	0.1443	0.1710	0.2317	0.6538	1.9383	3.6569	0.1396	0.2060	0.0937
	30/10/08	30/10/08	17/12/08	10/10/08	10/10/08	29/10/08	17/12/08	17/12/08	12/12/08
3	0.1153	0.1543	0.2230	0.5683	1.7068	3.6004	0.1148	0.1798	0.0825
	31/10/08	30/11/11	29/10/08	27/10/08	16/10/08	23/10/08	21/12/11	17/09/08	08/10/08
4	0.1038	0.1300	0.2068	0.3691	1.0492	3.3000	0.1072	0.1119	0.0699
	24/10/08	08/10/08	13/11/08	12/12/08	17/10/08	16/10/08	06/03/09	12/06/09	06/05/10
5	0.1038	0.1297	0.1884	0.3345	0.9848	2.7714	0.0925	0.0823	0.0691
	16/09/08	06/09/11	20/02/09	09/08/11	25/11/08	13/11/08	18/09/08	02/05/08	01/12/08
6	0.1005	0.1202	0.1714	0.3300	0.9682	2.4491	0.0872	0.0813	0.0676
	05/11/08	25/11/08	24/10/08	24/11/08	09/08/11	21/11/08	12/12/08	08/10/08	18/09/08
7	0.0946	0.1197	0.1428	0.2948	0.9126	2.3421	0.0769	0.0764	0.0675
	28/10/08	24/10/08	05/11/08	16/10/08	23/10/08	24/10/08	23/03/10	12/03/09	29/10/08
8	0.0924	0.1175	0.1384	0.2712	0.8820	1.9344	0.0757	0.0642	0.0595
	12/12/08	18/09/08	21/11/08	08/10/08	11/08/11	20/11/08	10/09/07	07/08/09	28/10/08
9	0.0887	0.1034	0.1302	0.2601	0.8370	1.9341	0.0748	0.0627	0.0592
	27/10/08	15/01/09	25/11/08	15/10/08	27/10/08	08/10/08	22/12/10	08/07/11	16/09/08
10	0.0884	0.0969	0.1118	0.2464	0.8134	1.9040	0.0719	0.0611	0.0574
	23/10/08	06/11/08	20/05/10	13/10/08	07/10/08	28/10/08	09/06/08	07/10/08	09/10/08

Table 5: Ten largest changes for the foreign exchange, equity, and bond prices in Japan, Europe, and the United States. The dates of the events are in the bottom cells. The values of realized volatility on this day in the basis points (multiplied by 1000) are in the upper cell.

There is one final manipulation of the realized volatility series which proves useful and this relates to the asymmetric transmission of volatility relating to good and bad news. Note that this effect should not be confused with the well established leverage effect in equity markets. The leverage effect allows for asymmetric impacts on volatility due to bad and good news of an identical size. In the multivariate context, the asymmetric BEKK model of Kroner and Ng (1998) and the matrix exponential GARCH of Kawakatsu (2006) are the most popular models to capture such asymmetric effects.

A potentially interesting avenue of research is one which allows for the the transmission of volatility to be different depending on whether the volatility is due to good or bad news. To capture this asymmetry, realized volatility is decomposed into realized volatility related to positive and negative returns (Barndorff-Nielsen, Kinnebrock and Shephard, 2008) as follows

$$RV_t = RS_t^- + RS_t^+, \tag{11}$$

in which

$$RS_t^- = \sum_{\Omega=\{r_{t,j}<0\}} (r_{t,j})^2 1_{r_{t,j}\in\Omega} \tag{12}$$

is the downside realized semivariance and

$$RS_t^+ = \sum_{\mho=\{r_{t,j}\geq 0\}} (r_{t,j})^2 1_{r_{t,j}\in\mho} \tag{13}$$

is the upside realized semivariance, in which 1_a is the indicator function taking the value 1 if the argument a is true, and $\Omega \cup \mho = \{1, 2, ..., 1\backslash\Delta\}$. Note that zero returns are treated as an indication of good news which is different from the formulation of Barndorff-Nielsen, Kinnebrock and Shephard (2008)

5 Volatility Linkages: Asymmetry and Jumps

At the end of Section 3, it emerged that using a traditional GARCH framework to investigate the diurnal effects of both the smoothed conditional variance and the news yield ambiguous results. Armed with estimates of realized volatility from all the regions, however, this questions may be addressed using the following econometric model

$$h_t = K + A\, h_{t-1} + B\, \mathrm{RV}_t + G\, \epsilon_{t-1}^2\,, \tag{14}$$

in which $RV_t = [RV_{jp,t}\ RV_{eu,t}\ RV_{us,t-1}]'$, parameter matrices K, A and G are unconstrained and B now has form

$$B = \begin{bmatrix} 0 & 0 & \beta_{13} \\ \beta_{21} & 0 & 0 \\ 0 & \beta_{32} & 1 \end{bmatrix}.$$

This model is the realized GARCH of Hansen, Huang and Shek (2012) changed slightly in order to deal with the calendar structure imposed by the global trading day. It is important to note that the diurnal effect of realized volatility on Japan comes from realized volatility at the close of the previous trading day. In this specification the vector of realized volatilises will contain observable elements of both the smoothed conditional variance and news from the preceding region and therefore equation (14) provides a parsimonious way of incorporating both elements into a comprehensive explanation of volatility transmission.

The coefficient estimates for equation (14) estimated on data from the foreign exchange, equity and bond markets are reported in Table 6. The most striking result is that all the coefficients on the diurnal effects are significant once again. There can therefore be little doubt that the meteor shower affect of news in regional markets is an important component of volatility. It is also true that all the own lagged conditional variance terms are significant indicating that the heatwave effect is also present, although this affect is fairly muted in the equity market. Indeed, the most striking results appear to be those obtained in the equity market where it is apparent that the diurnal effect of realized volatility from Japan on Europe and Europe on the United States are significant. These diurnal effects on the volatility in the United States appear much larger in absolute size than the heatwave effect obtained from the lagged United States conditional variance.

Table 6:
Coefficient estimates for equation (6) for the foreign exchange, equity and bond markets in each of the trading zones. Coefficients that are significant at the 5% level are marked (*)

		Japan	Europe	United States
FX Market	$RV_{\mathrm{jp},t}$	-	0.0672*	-
	$RV_{\mathrm{eu},t}$	-	-	0.0418*
	$RV_{\mathrm{us},t-1}$	0.0297*	-	-
	$\epsilon^2_{\mathrm{jp},t-1}$	0.0448*	-	-
	$\epsilon^2_{\mathrm{eu},t-1}$	-	0.0096	-
	$\epsilon^2_{\mathrm{us},t-1}$	-	-	0.0363*
	$\mathrm{h}_{i,t-1}$	0.8942*	0.9562*	0.9138*
		Japan	Europe	United States
Equity Market	$RV_{\mathrm{jp},t}$	-	0.7358*	-
	$RV_{\mathrm{eu},t}$	-	-	1.3380*
	$RV_{\mathrm{us},t-1}$	0.0272*	-	-
	$\epsilon^2_{\mathrm{jp},t-1}$	0.1297*	-	-
	$\epsilon^2_{\mathrm{eu},t-1}$	-	0.0240	-
	$\epsilon^2_{\mathrm{us},t-1}$	-	-	0.0476*
	$\mathrm{h}_{i,t-1}$	0.6565*	0.7146*	0.2908*
		Japan	Europe	United States
Bond Market	$RV_{\mathrm{jp},t}$	-	0.0235*	-
	$RV_{\mathrm{eu},t}$	-	-	0.0175*
	$RV_{\mathrm{us},t-1}$	0.0669*	-	-
	$\epsilon^2_{\mathrm{jp},t-1}$	0.2851*	-	-
	$\epsilon^2_{\mathrm{eu},t-1}$	-	0.0270*	-
	$\epsilon^2_{\mathrm{us},t-1}$	-	-	0.0341*
	$\mathrm{h}_{i,t-1}$	0.5847*	0.9599*	0.9472*

Another really interesting result is the fact that the heatwave hypothesis no longer seems completely appropriate in the bond market. It is true that the diurnal effects in from Japan to Europe and Europe to the United States, although significant, are fairly small in size. However, the effect from the United States to Japan appears to be a significant driver of bond market volatility during Japanese trading hours.

At this stage is seems appropriate to make use of equations (9) and (10) to decompose the realized volatility series into its constituent diffusive and jump components in each of the three trading zones. The obvious extension to equation (14) is therefore

$$h_t = K + A\,h_{t-1} + B\,\mathrm{CC}_t + \tilde{B}\mathrm{J}_t\, + G\,\epsilon^2_{t-1}\,, \tag{15}$$

in which $CC_t = [CC_{jp,t}\ \ CC_{eu,t}\ \ CC_{us,t-1}]'$ represents the continuous components of realized volatility and $JJ_t = [JJ_{jp,t}\ \ JJ_{eu,t}\ \ JJ_{us,t-1}]'$, represents the jump component. The matrices B and $\tilde{B}$ have the same structure as matrix B in equation (14). This model is simple extension of the realized GARCH of Hansen, Huang and Shek (2012) which breaks down realized volatility into its two constituent components.

The coefficient estimates for equation (15) are reported in Table 7. The major result is fairly unambiguous. Jumps are only really important in the transmission of volatility in the equity market and play no real significant role in the diurnal transmission of volatility across regions in the foreign exchange and the bond markets. On the other hand, the continuous component of realized volatility exhibits strong strong explanatory power across all three markets.

Given the importance of the diurnal effects of realized volatility in explaining the conditional variance and also the relative importance of the diffusive component of volatility relative to the jump component, the estimates of the realized semivariances can be used to build an asymmetric volatility model for each of the three markets. The relevant equation for the conditional variance is

$$h_t = K + A\,h_{t-1} + B\,\mathrm{RS}^+_t + \tilde{B}\,\mathrm{RS}^-_t + G\,\epsilon^2_{t-1}\,, \tag{16}$$

where the vector RV_t as defined after equation (14) is decomposed into its positive and negative semi-variances.[5]

[5]This model may be considered as a special case of the volatility model with a persistent leverage effect introduced by Corsi and Reno (2012).

Table 7:
Coefficient estimates of the equation (15) for the foreign exchange, equity and bond markets in each of the trading zones. Coefficients that are significant at the 5% level are marked (*)

		Japan	Europe	United States
FX Market	$CC_{\mathrm{jp},t}$	-	0.0642*	-
	$CC_{\mathrm{eu},t}$	-	-	0.0442*
	$CC_{\mathrm{us},t-1}$	0.0348*	-	-
	$J_{\mathrm{jp},t}$	-	0.0952	-
	$J_{\mathrm{eu},t}$	-	-	0.0245
	$J_{\mathrm{us},t-1}$	0.0000	-	-
	$\epsilon^2_{\mathrm{jp},t-1}$	0.0461*	-	-
	$\epsilon^2_{\mathrm{eu},t-1}$	-	0.0097	-
	$\epsilon^2_{\mathrm{us},t-1}$	-	-	0.0359*
	$\mathrm{h}_{i,t-1}$	0.8872*	0.9570*	0.9126*
		Japan	Europe	United States
Equity Market	$CC_{\mathrm{jp},t}$	-	0.7561*	-
	$CC_{\mathrm{eu},t}$	-	-	1.3379*
	$CC_{\mathrm{us},t-1}$	0.0270*	-	-
	$J_{\mathrm{jp},t}$	-	0.4070*	-
	$J_{\mathrm{eu},t}$	-	-	1.4286*
	$J_{\mathrm{us},t-1}$	0.0514*	-	-
	$\epsilon^2_{\mathrm{jp},t-1}$	0.1314*	-	-
	$\epsilon^2_{\mathrm{eu},t-1}$	-	0.0238	-
	$\epsilon^2_{\mathrm{us},t-1}$	-	-	0.0475*
	$\mathrm{h}_{i,t-1}$	0.6520*	0.7132*	0.2890*
		Japan	Europe	United States
Bond Market	$CC_{\mathrm{jp},t}$	-	0.0239*	-
	$CC_{\mathrm{eu},t}$	-	-	0.0314*
	$CC_{\mathrm{us},t-1}$	0.0720*	-	-
	$J_{\mathrm{jp},t}$	-	0.0204*	-
	$J_{\mathrm{eu},t}$	-	-	0.0000
	$J_{\mathrm{us},t-1}$	0.0000	-	-
	$\epsilon^2_{\mathrm{jp},t-1}$	0.2781*	-	-
	$\epsilon^2_{\mathrm{eu},t-1}$	-	0.0264*	-
	$\epsilon^2_{\mathrm{us},t-1}$	-	-	0.0302*
	$\mathrm{h}_{i,t-1}$	0.5848*	0.9606*	0.9429*

Table 8:
Coefficient estimates of the equation (16) for the foreign exchange, equity and bond markets for each of the trading zones. Coefficients that are significant at the 5% level are marked (*)

		Japan	Europe	United States
FX Market	$RS^{+}_{\mathrm{jp},t}$	-	0.1231*	-
	$RS^{+}_{\mathrm{eu},t}$	-	-	0.0103
	$RS^{+}_{\mathrm{us},t-1}$	0.0556*	-	-
	$RS^{-}_{\mathrm{jp},t}$	-	0.0142	-
	$RS^{-}_{\mathrm{eu},t}$	-	-	0.0674*
	$RS^{-}_{\mathrm{us},t-1}$	0.0019	-	-
	$\epsilon^{2}_{\mathrm{jp},t-1}$	0.0457*	-	-
	$\epsilon^{2}_{\mathrm{eu},t-1}$	-	0.0090	-
	$\epsilon^{2}_{\mathrm{us},t-1}$	-	-	0.0339*
	$\mathrm{h}_{i,t-1}$	0.8948*	0.9537*	0.9177*
		Japan	Europe	United States
Equity Market	$RS^{+}_{\mathrm{jp},t}$	-	0.0000	-
	$RS^{+}_{\mathrm{eu},t}$	-	-	0.1750
	$RS^{+}_{\mathrm{us},t-1}$	0.0614*	-	-
	$RS^{-}_{\mathrm{jp},t}$	-	1.2208*	-
	$RS^{-}_{\mathrm{eu},t}$	-	-	1.8313*
	$RS^{-}_{\mathrm{us},t-1}$	0.0086	-	-
	$\epsilon^{2}_{\mathrm{jp},t-1}$	0.1392*	-	-
	$\epsilon^{2}_{\mathrm{eu},t-1}$	-	0.0265	-
	$\epsilon^{2}_{\mathrm{us},t-1}$	-	-	0.0570*
	$\mathrm{h}_{i,t-1}$	0.5835*	0.7453*	0.4021*
		Japan	Europe	United States
Bond Market	$RS^{+}_{\mathrm{jp},t}$	-	0.0245*	-
	$RS^{+}_{\mathrm{eu},t}$	-	-	0.0311*
	$RS^{+}_{\mathrm{us},t-1}$	0.0704*	-	-
	$RS^{-}_{\mathrm{jp},t}$	-	0.0213*	-
	$RS^{-}_{\mathrm{eu},t}$	-	-	0.0000
	$RS^{-}_{\mathrm{us},t-1}$	0.0000	-	-
	$\epsilon^{2}_{\mathrm{jp},t-1}$	0.2723*	-	-
	$\epsilon^{2}_{\mathrm{eu},t-1}$	-	0.0255*	-
	$\epsilon^{2}_{\mathrm{us},t-1}$	-	-	0.0295*
	$\mathrm{h}_{i,t-1}$	0.5907*	0.9609*	0.9428*

The coefficient estimates from equation (16) are presented in Table 8. As the general pattern of the coefficients on ϵ_{t-1}^2 and h_{t-1}^2 for all three markets are similar to those in Table 6 they are not reported here. The results reported in Table 8 allow several general observations to be drawn about the symmetric transmission of volatility relating to good and bad news. Interestingly enough, all of these observations, to a greater or lesser degree, involve Japan.

1. There is strong evidence to support the hypothesis that volatility responds asymmetrically to the realized volatility from preceding zones. Remembering that the overall diurnal effects are seen in Table 6 to be significant in all cases, there is only one instance in which there are significant coefficients of equal size recorded in Table 8. This is the case of the Japanese influence on Europe in the bond market.

2. Volatility in the bond market responds strongly to the diurnal impact of the positive semivariances, as all coefficients on RS^+ are significant.

3. In all three markets the part of volatility relating to good news is passed from the United States region into all the Japanese markets at the start of trade on the next global trading day. Similarly, in all three markets bad news in the United States appears to be quarantined. This is an unequivocal result and may be attributable to the fact that the entire sample period corresponds to a period of slow growth in Japan with a knock-on effect that Japanese markets were particularly attuned to the prospect of good news from the United States.

4. Equity markets in Europe and the United States appear particularly susceptible to volatility arising from bad news in the immediately preceding zones (Japan and Europe, respectively). This provides limited support for a claim that bad news travels fast in equity markets. The fact that Japan seems immune to this effect is perhaps due again to the long bear market in the Japanese equity market.

These results indicate fairly strongly the need for further research in this area.

6 Conclusion

The paper investigates volatility transmission in the global financial markets. In so doing, the seminal analysis of Engle, Ito and Lin (1990) is extended in a number of different directions using a high frequency data set drawn from continuously-traded futures contracts from the foreign exchange, equity and bond markets. Returns to the futures contracts are constructed for a hypothetical global trading day in which developments in Japan can influence Europe and the United States on the same calendar day. Similarly events in Europe can influence the United States. The influence of the United States on Japan occurs at the beginning of the next trading day. The potential volatility and news spillovers in the transmission of volatility across trading zones are referred to as diurnal effects.

On the evidence presented here, it is evident that the meteor shower effect in the transmission of volatility from one region to another on the same trading day are significant. It is clear that this effect is at least as important as the heatwave effect, which is the normal effect estimated in traditional volatility models. Moreover, the result of previous research in the bond market which suggest that the diurnal effect of volatility from preceding zones on the same trading day is not important is clearly refuted when realized volatility from previous zones is used as an explanatory factor. There can therefore be no doubt that there exist significant volatility linkages between financial markets.

The realized volatility GARCH approach to the problem of volatility linkages is a promising avenue of research and has yielded some interesting insights. The first is that volatility transmission appears to be asymmetric, particularly in the equity market where volatility related to negative news appears to be transmitted more readily that volatility linked to good news. Furthermore the decomposition of realized volatility into its continuous and jump components yields the unexpected result that jumps in volatility are not as readily transmitted as might be expected a priori.

References

Andersen, T.G., Bollerslev, T., Diebold, F.X., and Labys, P. 2003. Modeling and forecasting realized volatility. *Econometrica*, **71**, 579–625.

Andersen, T.G., Dobrev, D., and Schaumburg, E. 2012. Jump-robust volatility estimation using nearest neighbor truncation. *Journal of Econometrics*, **169**, 75–93.

Barndorff-Nielsen, O. E., and Shephard, N. 2004. Power and bi-power variation with stochastic volatility and jumps. *Journal of Financial Econometrics*, **2**, 1–37.

Barndorff-Nielsen, O.E., and Shephard, N. 2002. Econometric Analysis of realized volatility and its use in estimating stochastic volatility models. *Journal of Royal Statisitcal Society, Series B*, **64**, 253–280.

Barndorff-Nielsen, O.E., and Shephard, N. 2006. Econometrics of testing for jumps in financial economics using bipower variation. *Journal of Financial Econometrics*, **4**, 1–30.

Barndorff-Nielsen, O.E., Kinnebrock, S., and Shephard, N. 2008. Measuring downside risk-realised semivariance. *Working paper*, Department of Economics, University of Oxford, 42.

Bollerslev, T. 1986. Generalized autoregressive conditional heteroskedasticity. *Journal of Econometrics*, **31**, 307–327.

Bubák, V., Kočenda, E., and Žikeš, F. 2011. Volatility transmission in emerging European foreign exchange markets. *Journal of Banking & Finance*, **35**, 2829–2841.

Corsi, F., and Renò, R. 2012. Discrete-time volatility forecasting with persistent leverage effect and the link with continuous-time volatility modeling. *Journal of Business & Economic Statistics*, **30**, 368–380.

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.

Engle, R.F. 1982. Autoregressive conditional heteroskedasticity with estimates of the variance of United Kingdom inflation. *Econometrica*, **50**, 987–1008.

Engle, R.F., Ito, T., and Lin, W.L. 1990. Meteor showers or heat waves? Heteroskedastic intra-daily volatility in the foreign exchange market. *Econometrica*, **58**, 525–542.

Engle, R.F., Gallo, G.M., and Velucchi, M. 2012. Volatility spillovers in East Asian financial markets: a MEM-based approach. *Review of Economics and Statistics*, **94**, 222–233.

Evans, K.P. 2011. Intraday jumps and US macroeconomic news announcements. *Journal of Banking and Finance*, **35**, 2511–2527.

Fleming, M.J., and Lopez, J.A. 1999. Heat waves, meteor showers, and trading volume: an analysis of volatility spillovers in the U.S. Treasury market. *Working paper*, Federal Reserve Bank of New York, 82.

Hakim, A., and McAleer, M. 2010. Modelling the interactions across international stock, bond and foreign exchange markets. *Applied Economics*, **42**, 825–850.

Hansen, P.R., Huang, Z., and Shek, H.H. 2012. Realized GARCH: a joint model for returns and realized measures of volatility. *Journal of Applied Econometrics*, **27**, 877–906.

Ito, T. 1987. The intra-daily exchange rate dynamics and monetary policy after the G5 agreement. *Journal of Japanese and International Economies*, **1**, 275–298.

Ito, T., and Roley, V.V. 1987. News from the U.S. and Japan which moves the Yen/Dollar exchange rate? *Journal of Monetary Economics*, **19**, 255–278.

Kawakatsu, H. 2006. Matrix exponential GARCH. *Journal of Econometrics*, **134**, 95–128.

Kroner, K.F., and Ng, V.K. 1998. Modeling asymmetric comovements of asset returns. *Review of financial studies*, **11**, 817–844.

Melvin, M., and Melvin, B.P. 2003. The global transmission of volatility in the foreign exchange market. *The Review of Economics and Statistics*, **85**, 670–679.

Savva, C., Osborn, D.R., and Gill, L. 2005. Volatility, spillover effects and correlations in US and major european markets. *Unpublished Manuscript*, University of Manchester.