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Abstract

This paper uses trivariate generalized autoregressive conditional heteroscedasticity (GARCH) models to study price and volatility spillovers between the foreign exchange and associated money markets. Three models are estimated using data on U.S. dollar/Canadian dollar, U.S. dollar/Deutsche Mark, and U.S. dollar/Japanese yen daily exchange rate returns together with returns on 90-day Eurodollar, Euro Canada, Euromark, and Euroyen deposits. The paper finds strong evidence of price and volatility spillovers in all three models, and some volatility spillovers are found to be asymmetric. Although the volatilities of some innovations share common features, pairwise contemporaneous correlations between innovations in the three models are low. These results suggest either that common factors between markets are small, with investors in one market processing information from other markets gradually, or that the spillovers are the result of market contagion effects. The paper also outlines the ramifications of these findings from the perspective of economic policy-makers.

JEL classification: G15
Bank classification: International financial markets

Résumé

À l'aide de modèles GARCH à trois variables, l'auteur étudie la propagation des prix et de leur volatilité entre les marchés des changes et les marchés monétaires correspondants. Il estime trois modèles au moyen de données relatives aux rendements quotidiens réalisés sur le marché du dollar É.-U. contre le dollar canadien, contre le deutsche mark et contre le yen et sur le marché des dépôts à 90 jours en eurodollars américains et canadiens, en euromarks et en euroyens. Les résultats obtenus à l'aide des trois modèles militent fortement en faveur de la propagation entre les marchés; dans certains cas, la volatilité des prix se propagerait de façon asymétrique. Bien que les volatilités aient parfois des traits en commun, les corrélations contemporaines entre chocs pris deux à deux sont faibles dans chacun des trois modèles. Ces résultats peuvent s'expliquer de deux façons : soit qu'il existe peu de facteurs communs aux différents marchés, les investisseurs actifs sur un marché assimilant graduellement l'information qui provient des autres marchés, soit que la propagation entre les marchés résulte d'effets de contagion. L'auteur souligne aussi les conclusions que peuvent en tirer les responsables des politiques économiques.

Classification JEL : G15
Classification de la Banque : Marchés financiers internationaux

Executive Summary

The flow of information across financial markets is an issue that has been studied extensively in the empirical finance literature. Research in this area examines the extent to which price shocks in the equity, foreign exchange, and fixed-income markets affect prices and volatilities in other geographically or temporally distinct segments of those markets.

The study of information transmission between financial markets has several ramifications for economic policy-makers. First, from a financial stability perspective, it is important to understand how shocks are propagated across markets in order to determine the persistence and magnitudes of their effects over time. Second, linkages between markets can affect the success with which policies are implemented. For example, if a central bank wishes to alter interest rates and at the same time minimize exchange rate volatility, it would be useful to understand how an unanticipated interest rate change could affect the conditional variance of the exchange rate. Third, if financial markets are informationally efficient (and news about fundamentals is serially uncorrelated), it should not be possible to predict returns and volatility in one market using lagged information generated in another market. To the extent that there are price and volatility spillovers, this could indicate a failure of weak-form market efficiency.

This paper uses trivariate generalized autoregressive conditional heteroscedasticity (GARCH) models to study price and volatility spillovers between the foreign exchange and associated money markets. Three models are estimated using data on U.S. dollar/Canadian dollar (USD/CAD), U.S. dollar/Deutsche mark (USD/DEM), and U.S. dollar/Japanese yen (USD/JPY) daily exchange rate returns together with returns on 90-day Eurodollar, Euro Canada, Euromark, and Euroyen deposits between 4 January 1988 and 31 December 1998. This study contributes to the literature in two principal ways. First, it examines the nature of information transmission across different asset classes involving the foreign exchange and money markets rather than movement of news between markets in each asset class. Second, returns in the three markets are modelled in a way that does not restrict correlations between markets to be constant, but instead allows them to be time-varying.

The interdependence between foreign exchange and money markets can be motivated through interest rate parity conditions. Uncovered interest rate parity states that the interest rate differential between two countries is related to the difference

between expected future spot and current spot exchange rates, while covered interest rate parity relates the interest rate differential to the forward exchange rate less the current spot exchange rate. Thus, these conditions suggest theoretical reasons for the contemporaneous correlations between spot exchange rates and domestic and foreign interest rates. However, as long as news about fundamentals is serially uncorrelated, there should not be a relationship between lagged returns or innovations in one market and returns or volatilities in another. Such a relationship could imply a lack of informational efficiency in those markets, or could be suggestive of a market contagion hypothesis. According to this contagion hypothesis, agents who observe price declines in one market become more risk-averse and reduce their positions in the other market, thereby creating the appearance of a spillover effect.

This paper finds strong evidence of price and volatility spillovers in all three models. Some volatility spillovers are found to be asymmetric: bad news in one market raises the volatility in another market more than does good news in the originating market. Although the volatilities of some innovations share common features, pairwise contemporaneous correlations between innovations in the three models are low. These results suggest either that the common factors between markets are small, with investors in one market processing information from other markets gradually, or that the spillovers are the result of market contagion effects.

The results for all three models demonstrate that shocks from Eurocurrency markets have small quantitative effects on foreign exchange markets. Although volatility spillovers from Eurocurrency to foreign exchange markets are small in all cases, the volatility in the Euro Canada market is more susceptible to exchange rate shocks than are Euromark and Euroyen volatilities in their respective models. Furthermore, shocks in the foreign exchange market have noticeable effects on Eurocurrency volatilities, particularly in the USD/CAD model. Indeed, a 0.29 per cent shock in the USD/CAD exchange rate initially raises the conditional variance in the Euro Canada market by about 6.3 per cent, with this effect decreasing to about 1 per cent only after 15 days.

The fact that exchange rate shocks can cause persistent increases in the volatility of short-term interest rates suggests that the Bank of Canada might wish to take policy actions following a large exchange rate shock should it want to mitigate the higher money market volatility. However, while an increase in interest rates in response to a large depreciation in the Canadian dollar against the U.S. dollar could curb the currency depreciation, it would further raise short-term interest rate volatility. Thus, attempts to stabilize the exchange rate through changes in short-term interest rates will often come at the expense of heightened volatility in the money market for some time.

The low observed contemporaneous correlations between pairs of innovations in the three models suggest that spillover effects are less likely to be the result of investors processing news about fundamentals from other markets in an inefficient fashion and more likely to be caused by a market contagion effect. However, these low correlations could follow from the fact that the data being studied are sampled at the daily frequency in which idiosyncratic components of returns dominate the common factors. It would be interesting to estimate these models using data sampled at lower frequencies to see if correlations between innovations are higher and to determine whether price and volatility spillover effects continue to exist. These issues await future research.

1 Introduction

The flow of information between financial markets is an issue that has attracted considerable attention in the empirical finance literature. Research in this area examines the extent to which a price shock in one market affects returns and volatilities in other geographically or temporally distinct markets. These studies focus on spillovers across markets within the equity, foreign exchange, and fixed-income segments and often show that information is transmitted across markets within those segments.

An analysis of the transmission of information between markets is important for several reasons. First, the notion of market efficiency dictates that it should not be possible to predict returns or volatility in one market using lagged information generated in another market. To the extent that there are price and volatility spillovers, this could indicate a failure of market efficiency. On the other hand, if news about fundamentals is serially correlated, then the existence of spillovers need not imply a failure of market efficiency. Second, it is important to understand the manner in which shocks are propagated across markets in order to determine the persistence of these innovations and the magnitudes of their effects over time. Third, the study of price and volatility spillovers between markets is useful from a risk management perspective both in terms of understanding how markets are interrelated and in permitting the development of effective strategies for hedging against shocks that are propagated across markets.

A heightened awareness of the nature of volatility transmission across markets is also of importance to economic policy-makers for the following reasons. First, this issue is significant from a financial stability perspective. To the extent that volatility is transmitted across markets, it may be possible for a large shock in one market to have a destabilizing impact on another market. Second, linkages across markets can affect the success with which policies are implemented. For example, if a central bank wishes to change interest rates and at the same time minimize exchange rate volatility, it would be useful to understand how an unanticipated interest rate change could affect the conditional variance of the exchange rate. Finally, if policy-makers could gauge the depth and duration of the impact of any policy initiative in one financial market on other markets, they could develop more effective policies.

Engle et al. (1990) develop a univariate model of the intradaily U.S. dollar/Japanese yen (USD/JPY[1]) exchange rate to study the influence of country-specific news on the

[1] According to standard industry practice, the first currency in the pair is called the base currency,

volatility of subsequent market segments. The authors adapt the class of generalized autoregressive conditional heteroscedasticity (GARCH) models originally developed by Engle (1982) and Bollerslev (1986) by dividing the day into four major market segments. They do not find evidence in favour of a "heat wave" hypothesis, in which shocks in one market affect the conditional variance of only that particular market, but instead find support for a "meteor shower" hypothesis, in which shocks raise volatilities across a number of market segments, not only for the market that sustained the shock.

A number of papers consider the role of volatility spillovers between global equity markets; the results differ, depending on the specific techniques and data used. King and Wadhwani (1990) find support for their contagion model using high-frequency data for the London, New York, and Tokyo stock markets. Hamao et al. (1990) analyze the Tokyo, London, and New York stock markets and observe volatility spillovers from the U.S. and U.K. stock markets to the Japanese market. Lin et al. (1994) study the Tokyo and New York stock markets and observe reciprocal interdependence in returns and volatilities between one market's daytime returns and the other market's overnight returns using a signal-extraction model with GARCH processes. On the other hand, Susmel and Engle (1994) undertake a univariate GARCH analysis of the interrelationship between the New York and London stock markets and are unable to find strong evidence of either mean or volatility spillovers between the two markets.

Some studies adopt a bivariate GARCH framework in testing for the existence of volatility spillovers. This approach permits the modeling of not only the conditional variance in each market, but also the conditional covariances between markets. Karolyi (1995) employs such a technique in analyzing the New York and Toronto stock markets. Karolyi finds that there are short-lived price spillovers between the two markets, although the impact of shocks originating in New York on Toronto stock returns has decreased in the latter part of the 1980s. Theodossiou and Lee (1993) analyze the relationship between the U.S., U.K., Canadian, German, and Japanese stock markets using a multivariate GARCH-in-mean model, and find statistically significant mean and volatility spillovers between some of those markets.

Past studies on the volatility dynamics of individual asset markets document evidence of asymmetry in the response of conditional variances to the type of news revealed to the markets. In particular, negative shocks raise volatility by a greater

and the second is called the quoted currency. The quotes refer to the number of units of the quoted currency per unit of the base currency.

amount than do positive innovations. This phenomenon, which Black (1976) and Christie (1982) attribute, in the context of equity returns, to financial and operating leverage effects, is captured by the exponential GARCH (EGARCH) model of Nelson (1991).

Recent research on volatility spillovers across markets employs this EGARCH specification to examine whether news in one market has an asymmetric influence on volatility in another market. In their study of linkages between the New York, Tokyo, and London stock markets, Koutmos and Booth (1995) demonstrate that the volatility transmission process is asymmetric: bad news in one market increases volatilities in other markets more than does good news in the originating market. Kanas (1998) tests for volatility spillovers across the London, Frankfurt, and Paris stock markets using a bivariate EGARCH model and concludes that there are reciprocal spillovers between London and Paris, and Paris and Frankfurt, together with unidirectional spillovers from London to Frankfurt. In most cases, these spillovers are asymmetric. Booth et al. (1997) discover price and volatility spillovers among the Swedish, Danish, Norwegian, and Finnish stock markets over a seven-year period. Using a multivariate EGARCH model to investigate volatility spillovers between three European monetary system (EMS) and three non-EMS exchange rates, Laopodis (1998) observes an asymmetric transmission in the volatilities of exchange rates before German reunification.

Volatility spillovers in the fixed-income cash and derivatives markets have also been analyzed in the literature. Tse and Booth (1996) study the relationship between U.S. Treasury bill and Eurodollar futures while Tse (1998) focuses on the connection between Euroyen and Eurodollar futures. In a study of Australian domestic and offshore interest rates, Ann and Alles (2000) note significant volatility spillover effects between the two markets. Fleming et al. (1998) investigate volatility linkages between stock, bond, and money markets using generalized method of moments (GMM) estimation of a simple trading model, and they find evidence of strong connections between those three markets.

This paper also studies the transmission of information across markets of different asset classes. Specifically, using data on U.S. dollar/Canadian dollar (USD/CAD), U.S. dollar/Deutsche mark (USD/DEM), and USD/JPY daily exchange rate returns together with returns on 90-day Eurodollar, Euro Canada, Euromark, and Euroyen deposits, the paper examines whether there are price and volatility spillovers between each exchange rate return and the two related Eurocurrency money market returns.

The analysis uses a trivariate GARCH model in which the conditional covariance matrix follows the positive-definite parameterization of Baba, Engle, Kraft, and Kroner (BEKK) delineated in Engle and Kroner (1995). The potential for asymmetric responses of the conditional variances and covariances to different types of news within individual markets and from other markets is also incorporated in the specification.

This study contributes to the literature in two principal ways. First, it examines the form and efficiency of information transmission across different asset classes involving foreign exchange and money markets, rather than the movement of news between markets in each asset class. One way that the interdependence between foreign exchange and money markets can be motivated is through interest rate parity conditions. Uncovered interest rate parity states that the interest rate differential between two countries is equal to the difference between expected future spot and current spot exchange rates, while covered interest rate parity indicates that this interest rate differential equals the forward exchange rate less the current spot exchange rate. These parity conditions suggest theoretical reasons for contemporaneous correlations between spot exchange rates and domestic and foreign interest rates. Given the interdependence between these markets, it is useful to examine the extent to which information in one market influences returns and volatilities in other markets. As long as news about fundamentals is serially uncorrelated, there should not be a relationship between *lagged* returns or innovations in one market and returns or volatilities in another. Indeed, any such relationship would imply a lack of weak-form informational efficiency in these markets. If the fundamental relationship between the foreign exchange and money markets is weak, the presence of spillovers is less likely to imply a transmission of information between markets, but could be suggestive of the market contagion hypothesis of Ito and Lin (1994). According to that hypothesis, agents who observe price declines in one market become more risk-averse and reduce their positions—thereby effecting price decreases—in the other market.

Second, this paper adds to the literature on volatility spillovers by jointly modeling returns in three markets in a manner that permits correlations between markets to be time-varying. The specification also allows for asymmetries in the responses of conditional variances and covariances to news from other markets. Other multivariate models in the volatility spillover literature typically assume that correlations between markets are constant over time. To the extent that correlations are time-varying, the more flexible parameterization employed in this paper avoids potential misspecification problems.

The paper finds strong evidence of price and volatility spillovers in all three models, and some volatility spillovers are found to be asymmetric. Although the volatilities of some innovations share common features, pairwise contemporaneous correlations between innovations in the three models are low. These results suggest either that common factors between markets are small, with investors in one market processing information from other markets gradually or that the spillovers are the result of market contagion effects. The paper also shows that while volatility spillovers from Eurocurrency to foreign exchange markets are small, the volatility in the Euro Canada market is more susceptible to exchange rate shocks than are Euromark and Euroyen volatilities in their respective models.

The rest of this paper is organized as follows. The next section describes the data used in this study. Section 3 outlines the trivariate GARCH model used to study price and volatility spillovers between the foreign exchange and money markets. The subsequent section provides the estimation results, and Section 5 concludes.

2 Data

This study uses daily data on the USD/CAD, USD/DEM, and USD/JPY exchange rates between 4 January 1988 and 31 December 1998. The USD/DEM and USD/JPY series were recorded by Reuters at noon Eastern time and are mid rates calculated by taking averages of the bid and ask rates. The USD/CAD data were obtained from the Bank of Canada and are recorded at noon Eastern time using a weighted average of mid rate quotes obtained from foreign exchange brokers. In addition, 90-day Eurodollar, Euro Canada, Euromark, and Euroyen interest rates are compiled on a daily basis over the same sample period. These data are the bid rates as recorded by Reuters at noon Eastern time. The quoted rates, y_t, are add-on interest rates that are first restated as discount rates, $y_t/(1+y_t)$, following the convention in the Treasury bill market, and then converted to prices, p_t, as follows:

$$p_t = 100 - 100(y_t/(1+y_t))(90/360).$$

Then, daily returns are computed from the exchange rate and the Eurocurrency price series by forming log differences of the data. In the case of the Eurocurrency series, for example, the daily return, r_t, is given by:

$$r_t = \log p_t - \log p_{t-1}.$$

A holiday in either the market for a particular exchange rate or the two associated money markets results in that day being excluded from the creation of the series. Data for weekends are also excluded.

Table 1 presents the summary statistics for the daily USD/CAD, USD/DEM, and USD/JPY exchange rate returns, as well as for the daily Eurodollar, Euro Canada, Euromark, and Euroyen 90-day deposit returns. The exchange rate returns exhibit a number of properties commonly associated with financial time series. The USD/CAD daily returns are slightly positively skewed, while the USD/DEM and USD/JPY returns exhibit negative skewness. All the exchange rate returns are leptokurtic. Consequently, Jarque-Bera (1980) statistics indicate rejections of the null hypotheses that the exchange rate returns are normally distributed. Ljung-Box (1978) portmanteau statistics to test for serial correlation in the data series up to lags 2, 5, and 20 are computed for the returns ($Q_l,\ l = 2, 5, 20$) and squared returns ($Q_l^2,\ l = 2, 5, 20$). For the exchange rates, it is not possible to reject the null hypothesis of zero autocorrelations in returns for each case at the 1 per cent significance level. However, there is significant persistence in squared returns; indeed, the null hypothesis that squared daily exchange rate returns are uncorrelated is rejected in all cases at the 1 per cent significance level. This persistence in squared returns is indicative of the volatility clustering commonly observed with financial data.

The 90-day Eurodollar and Euroyen daily returns are slightly positively skewed, while Euromark returns demonstrate slight negative skewness. On the other hand, Euro Canada returns exhibit strong negative skewness. The kurtosis coefficients of the four Eurocurrency series are higher than those of the three exchange rates. As a result, the Jarque-Bera tests provide overwhelming evidence against the null hypotheses that the returns are normally distributed. The results of the Ljung-Box tests applied to the Eurocurrency returns are also qualitatively different from those applied to the exchange rates. Specifically, the null hypothesis of zero autocorrelations up to lags 2, 5, and 20 for the Eurocurrency daily returns is rejected at the 1 per cent significance level in all cases. Thus, unlike the exchange rate returns, there is serial correlation in the Eurocurrency returns series. In addition, there is persistence in the Eurocurrency squared returns series, with p-values for the Ljung-Box tests of about zero in all cases.

Daily returns of the USD/CAD, USD/DEM, and USD/JPY exchange rates are illustrated in Figures 1–3, and returns of the 90-day Eurodollar, Euro Canada, Euromark, and Euroyen deposits are shown in Figures 4–7. The large skewness and kurtosis statistics of Euro Canada returns appear to be strongly influenced by a few observations. In particular, political events relating to the Charlottetown Accord and Quebec referenda in Canada were responsible for the negative spike in September 1992 and the positive spike in October 1995.[2]

3 Model Development

It is possible to estimate the set of the U.S. dollar exchange rate return, the money market return associated with one currency in the pair, and the U.S. money market return jointly in models for Canada, Germany, and Japan labeled $i = cad$, dem, and jpy. Let r^x_{it} be the daily exchange rate return at time t, where $x = uc$, ud, and uj represents USD/CAD, USD/DEM, and USD/JPY, respectively. Daily money market returns at time t consist of r^{ed}_{it}, which represents 90-day Eurodollar deposits, and r^j_{it}, where $j = ec$, em, and ey implies 90-day Euro Canada, Euromark, and Euroyen deposits, respectively. The system of equations is given by:

$$\begin{aligned}
r^x_{it} &= \gamma^x_{i0} + \gamma^x_{i1}\, r^x_{i,t-1} + \gamma^x_{i2}\, r^j_{i,t-1} + \gamma^x_{i3}\, r^{ed}_{i,t-1} + \gamma^x_{i4}\, \mathrm{WKND}_t + \gamma^x_{i5}\, \mathrm{HOL}_t + \epsilon^x_{it} && (1)\\
r^j_{it} &= \gamma^j_{i0} + \gamma^j_{i1}\, r^x_{i,t-1} + \gamma^j_{i2}\, r^j_{i,t-1} + \gamma^j_{i3}\, r^{ed}_{t-1} + \gamma^j_{i4}\, \mathrm{WKND}_t + \gamma^j_{i5}\, \mathrm{HOL}_t + \epsilon^j_{it} && (2)\\
r^{ed}_{t} &= \gamma^{ed}_{i0} + \gamma^{ed}_{i1}\, r^x_{i,t-1} + \gamma^{ed}_{i2}\, r^j_{i,t-1} + \gamma^{ed}_{i3}\, r^{ed}_{i,t-1} + \gamma^{ed}_{i4}\, \mathrm{WKND}_t + \gamma^{ed}_{i5}\, \mathrm{HOL}_t + \epsilon^{ed}_{it} && (3)
\end{aligned}$$

$$\boldsymbol{\epsilon}_{it}|\, I_{t-1} \equiv \begin{bmatrix} \epsilon^x_{it} \\ \epsilon^j_{it} \\ \epsilon^{ed}_{it} \end{bmatrix} |\, I_{t-1} \sim N(\mathbf{0}, \boldsymbol{H}_{it})$$

where I_{t-1} is the information set at time $t-1$, and

$$\boldsymbol{H}_{it} \equiv \begin{bmatrix} h^x_{it} & h^{x,j}_{it} & h^{x,ed}_{it} \\ h^{x,j}_{it} & h^j_{it} & h^{j,ed}_{it} \\ h^{x,ed}_{it} & h^{j,ed}_{it} & h^{ed}_{it} \end{bmatrix}$$

[2]See Clinton and Zelmer (1997) for a chronology of events affecting Canadian financial markets during this period.

is the conditional covariance matrix at time t. WKND_t is a dummy variable designed to capture weekend effects, and is equal to one for Mondays and zero otherwise. HOL_t is a dummy variable that is equal to one for any day following a holiday and zero otherwise. These dummy variables are included in the modeling of the conditional covariance dynamics to allow for weekend or holiday effects. The specification for the conditional mean allows for price spillovers by permitting the returns in each market to depend on the last period's returns in the other markets. Own lagged returns are also included as explanatory variables to account for persistence in daily returns.

The conditional covariance matrix dynamics can be described by a trivariate GARCH(1,1) process using the positive-definite parameterization of Baba, Engle, Kraft, and Kroner (BEKK) of Engle and Kroner (1995):

$$\begin{aligned} \boldsymbol{H}_{it} &= \boldsymbol{C}_i{}'\boldsymbol{C}_i + \boldsymbol{A}_i{}'\boldsymbol{\epsilon}_{i,t-1}\boldsymbol{\epsilon}'{}_{i,t-1}\boldsymbol{A}_i + \boldsymbol{B}_i{}'\boldsymbol{H}_{i,t-1}\boldsymbol{B}_i + \boldsymbol{G}_i{}'\boldsymbol{u}_{i,t-1}\boldsymbol{u}'{}_{i,t-1}\boldsymbol{G}_i \\ &+ \boldsymbol{S}_i{}'\boldsymbol{\psi}_{i,t-1}\boldsymbol{\psi}'{}_{i,t-1}\boldsymbol{S}_i + \boldsymbol{P}_i{}'\boldsymbol{\xi}_{i,t-1}\boldsymbol{\xi}'{}_{i,t-1}\boldsymbol{P}_i + \boldsymbol{T}_i{}'\boldsymbol{\eta}_{i,t-1}\boldsymbol{\eta}'{}_{i,t-1}\boldsymbol{T}_i \\ &+ \boldsymbol{Q}_i{}'\boldsymbol{\zeta}_{i,t-1}\boldsymbol{\zeta}'{}_{i,t-1}\boldsymbol{Q}_i + \boldsymbol{V}_{1i}{}'\boldsymbol{V}_{1i}\,\text{WKND}_t + \boldsymbol{V}_{2i}{}'\boldsymbol{V}_{2i}\,\text{HOL}_t \end{aligned} \tag{4}$$

where $\boldsymbol{C}_i$, $\boldsymbol{V}_{1i}$, and $\boldsymbol{V}_{2i}$ are upper triangular matrices whose general form, $\boldsymbol{M}_i$, is characterized as:

$$\boldsymbol{M}_i \equiv \begin{bmatrix} m_i^{11} & m_i^{12} & m_i^{13} \\ 0 & m_i^{22} & m_i^{23} \\ 0 & 0 & m_i^{33} \end{bmatrix}.$$

Meanwhile, $\boldsymbol{A}_i$, $\boldsymbol{B}_i$, $\boldsymbol{G}_i$, $\boldsymbol{S}_i$, $\boldsymbol{P}_i$, $\boldsymbol{T}_i$, and $\boldsymbol{Q}_i$ are diagonal matrices whose general form, $\boldsymbol{N}_i$, is given by:

$$\boldsymbol{N}_i \equiv \begin{bmatrix} n_i^x & 0 & 0 \\ 0 & n_i^j & 0 \\ 0 & 0 & n_i^{ed} \end{bmatrix}.$$

The 3×1 vector, $\boldsymbol{u}_{i,t-1}$, captures the asymmetric impact that the vector of past innovations has on the conditional covariance matrix in a manner similar to that of Glosten et al. (1993), and is defined as:

$$\boldsymbol{u}_{i,t-1} \equiv \begin{bmatrix} \min(\epsilon_{i,t-1}^x, 0) \\ \min(\epsilon_{i,t-1}^j, 0) \\ \min(\epsilon_{i,t-1}^{ed}, 0) \end{bmatrix}.$$

The effects of past shocks of other markets on a market's conditional variance or conditional covariances are gauged in this model by using the vectors $\boldsymbol{\psi}_{i,t-1}$ and $\boldsymbol{\xi}_{i,t-1}$, which are as follows:

$$\boldsymbol{\psi}_{i,t-1} \equiv \begin{bmatrix} \epsilon^{j}_{i,t-1} \\ \epsilon^{ed}_{i,t-1} \\ \epsilon^{x}_{i,t-1} \end{bmatrix} \qquad \boldsymbol{\xi}_{i,t-1} \equiv \begin{bmatrix} \epsilon^{ed}_{i,t-1} \\ \epsilon^{x}_{i,t-1} \\ \epsilon^{j}_{i,t-1} \end{bmatrix}.$$

A number of papers in the literature demonstrate that volatility spillovers between markets are asymmetric, in that negative innovations in a market increase volatilities in other markets more than do positive innovations in that market. This asymmetry is taken into account using the vectors $\boldsymbol{\eta}_{i,t-1}$ and $\boldsymbol{\zeta}_{i,t-1}$, given by:

$$\boldsymbol{\eta}_{i,t-1} \equiv \begin{bmatrix} \min(\epsilon^{j}_{i,t-1}, 0) \\ \min(\epsilon^{ed}_{i,t-1}, 0) \\ \min(\epsilon^{x}_{i,t-1}, 0) \end{bmatrix} \qquad \boldsymbol{\zeta}_{i,t-1} \equiv \begin{bmatrix} \min(\epsilon^{ed}_{i,t-1}, 0) \\ \min(\epsilon^{x}_{i,t-1}, 0) \\ \min(\epsilon^{j}_{i,t-1}, 0) \end{bmatrix}.$$

For example, the conditional variance of exchange rate returns, h^{x}_{it} , depends on past shocks in the non-U.S. Eurocurrency market, $\epsilon^{j}_{i,t-1}$, through the parameter, s^{x}_{i}, and on past shocks in the Eurodollar market, $\epsilon^{ed}_{i,t-1}$, through the parameter, p^{x}_{i}. This conditional variance also depends on past negative shocks in the non-U.S. Eurocurrency market through the parameter, t^{x}_{i}, and on past negative shocks in the Eurodollar market through the parameter, q^{x}_{i}. Here, these parameters measure the incremental amounts by which bad news in the Eurodollar and non-U.S. Eurocurrency markets at time $t-1$ affect the conditional variance of the exchange rate return at time t.

The parameterization of the conditional covariance matrix can therefore be viewed as an extension of the diagonal BEKK representation of Engle and Kroner (1995) that allows for past shocks from other markets to influence conditional variances and covariances, for asymmetries in the impacts of these shocks, and for seasonal and holiday effects. This representation of the conditional covariance matrix differs from the most general BEKK form in that conditional variances are not permitted to depend on cross-products of lagged shocks, lagged conditional variances of other markets, and lagged conditional covariances with other markets. Similarly, conditional covariances are not influenced by lagged squared shocks and lagged conditional variances in other markets. The formulation presented here facilitates testing of the null hypothesis of no volatility spillover effects against the alternative that conditional variances depend on other markets only through their past squared shocks. The BEKK parameterization is selected over other multivariate GARCH specifications because it guarantees that the covariance matrix is positive-definite, and it enables estimated correlations between asset returns to be time-varying. The complete model of daily returns requires the estimation of 57 parameters.

Let $\boldsymbol{r}_{it}$ be the 3×1 vector of returns, T be the number of observations, and $\boldsymbol{\Theta}$ be a vector of unknown parameters. It is then possible to write the conditional density of $\boldsymbol{r}_{it}$ as:

$$f(\boldsymbol{r}_{it}|I_{t-1};\boldsymbol{\Theta}) = (2\pi)^{-1}\,|\boldsymbol{H}_{it}|^{-1/2}\,\exp(-\boldsymbol{\epsilon'}_{it}\,\boldsymbol{H}_{it}^{-1}\,\boldsymbol{\epsilon}_{it}/2). \tag{5}$$

The log likelihood function

$$\ell = \sum_{t=1}^{T} \log f(\boldsymbol{r}_{it}|I_{t-1};\boldsymbol{\Theta}) \tag{6}$$

is then maximized numerically with respect to the population parameters using the Broyden, Fletcher, Goldfarb, and Shanno algorithm to yield maximum likelihood estimates. Standard errors are calculated using the quasi-maximum likelihood method of Bollerslev and Wooldridge (1992), which is robust to the distribution of the disturbance term.

4 Results and Analysis

4.1 Price and Volatility Spillovers

The estimated conditional variances for the exchange rate return, the non-U.S. Eurocurrency return, and the Eurodollar return are illustrated in Figures 8–10 for the USD/CAD, USD/DEM, and USD/JPY models, respectively. A comparison of the exchange rate return conditional variances for these three models reveals that both the USD/DEM and USD/JPY exchange rate conditional variances are higher than the USD/CAD exchange rate conditional variance throughout the sample period. The estimated Eurodollar conditional variances display similar patterns in all three models. It is also interesting to note the large spikes in the Euro Canada conditional variance around the times of the Canadian referenda in 1992 and 1995. In contrast, estimated Euromark and Euroyen conditional variances are generally lower in the USD/DEM and USD/JPY models.

Table 2 presents the quasi-maximum likelihood estimates for the model involving USD/CAD, Euro Canada, and Eurodollar returns. Euro Canada and Eurodollar returns exhibit autoregressive behaviour. The data also exhibit evidence of price spillovers. Specifically, current USD/CAD returns are positively affected by lagged Euro Canada returns, while current Euro Canada returns are negatively affected by lagged exchange rate returns. Current Eurodollar returns do not depend on either lagged USD/CAD returns or lagged Euro Canada returns.

USD/CAD, Eurodollar, and Euro Canada conditional variances are all asymmetrically influenced by their own lagged shocks. Volatility spillovers are also present in the data. In particular, the Euro Canada conditional variance depends positively on lagged shocks in the USD/CAD and the Eurodollar markets, while lagged innovations in the Euro Canada market increase the USD/CAD conditional variance. There are asymmetries in the volatility spillovers across markets as observed in other studies in the literature. Indeed, the conditional variance of USD/CAD returns increases following a negative shock in the Euro Canada market. Euro Canada and Eurodollar conditional variances are also affected to some extent by bad news in the Eurodollar and USD/CAD markets, respectively.

In order to assess the sensitivity of the spillover relationships to the two Canadian referenda in 1992 and 1995, the sample was divided into one set consisting of data from 4 January 1988 to 31 October 31 1995, and a second set consisting of data from 1 November 1995 to 31 December 1998. The models were estimated for each data segment. The results are qualitatively similar across the two periods, although the price spillover from the Euro Canada market to the USD/CAD market is present in the first period but absent from the post-referenda period. In the second period, past Eurodollar shocks do not affect the Euro Canada conditional variance as they do in the first period and in the full sample. As well, negative Euro Canada shocks exert a much stronger influence on the USD/CAD conditional variance in the post-referenda period compared with the first period.

Table 3 provides the estimated parameters for the USD/DEM, Euromark, and Eurodollar model. Again, there is evidence of autoregressive behaviour in the two Eurocurrency returns. There are also price spillovers between these markets; in fact, current Eurodollar returns are affected by lagged Euromark returns, while current Euromark returns are influenced by lagged Eurodollar returns. The conditional variances of USD/DEM and Euromark returns are higher following bad rather than good news in their respective markets. Volatility spillovers are also present in the USD/DEM model. The conditional variance of the Euromark return is higher following shocks in the USD/DEM and the Eurodollar markets. Furthermore, the large estimated value of the t^{ud}_{dem} parameter demonstrates that there are volatility spillovers into the USD/DEM market following bad Euromark news.

The quasi-maximum likelihood estimates for the set of USD/JPY, Euroyen, and Eurodollar returns are given in Table 4. The returns display autoregressive behaviour. Price spillovers occur from the USD/JPY and Eurodollar markets to the Euroyen market, and from the USD/JPY market to the Eurodollar market. An analysis of estimated parameters of the conditional covariance matrix reveals that negative innovations to USD/JPY and Eurodollar returns lead to higher volatilities in those markets than do positive innovations. The GARCH(1,1) model also illustrates the existence of weak volatility spillovers from the USD/JPY and Eurodollar markets to the Euroyen market. A stronger spillover occurs from the Euroyen market to the Eurodollar market.

Table 5 summarizes the spillover effects that are evident in the three models. There are no price spillovers to any exchange rate, except for those from Euro Canada returns to USD/CAD returns.

To assess the fit of the three estimated models, Ljung-Box portmanteau tests are performed on standardized residuals, squared standardized residuals, and cross-products of standardized residuals. The vector of standardized residuals at time t, $\hat{\boldsymbol{z}}_{it}$, is formulated by undertaking a Cholesky decomposition of the inverse of the conditional covariance matrix, $\boldsymbol{W}_{it}\boldsymbol{W'}_{it} = \boldsymbol{H}^{-1}_{it}$, and transforming the vector of raw residuals, $\hat{\boldsymbol{\epsilon}}_{it}$, to yield $\hat{\boldsymbol{z}}_{it} = \boldsymbol{W'}_{it}\hat{\boldsymbol{\epsilon}}_{it}$. Statistics are computed for each model and are listed in Table 6. The three sets of statistics test for serial correlation in up to 16 lags of the standardized residuals, squared standardized residuals, and cross-products of standardized residuals, respectively.

The results indicate that the models are fairly well specified, although the null hypothesis of no autocorrelation is rejected in six cases at the 1 per cent significance level of the 27 tests performed. The tests do, however, indicate that the GARCH(1,1) models are effective in accounting for the persistence in squared returns and cross-products of returns in the data.

Hypothesis testing is performed on the models using likelihood ratio tests. The outcomes of these tests are portrayed in Table 7. The joint hypothesis of no price or volatility spillovers is strongly rejected in all three models. Separate joint hypotheses that the trivariate models contain no spillovers in the conditional means or in the conditional variances are also rejected at conventional significance levels in all models. Volatility spillovers are asymmetric only in the USD/CAD model. Indeed, the joint hypothesis of no asymmetry in all spillovers cannot be rejected for the USD/DEM and USD/JPY models. The individual findings of asymmetry in the three models implies that negative shocks in one market increase volatilities in other markets more than do positive shocks in that market. These observations are similar to those in equity-market studies such as Koutmos and Booth (1995), Kanas (1998), and Booth et al. (1997).

There is also evidence of day-of-the-week and holiday effects in the conditional covariance matrices; the null hypothesis of no weekend or holiday effects is rejected for all models. However, it is not possible to reject the null hypothesis of no weekend/holiday effects in the conditional mean vectors of the USD/CAD and USD/DEM models at conventional significance levels. Weekend and holiday effects in the conditional means only manifest themselves in the USD/JPY model.

4.2 Impulse Response Analysis

In order to gauge the amount by which shocks from one market change conditional variances in other markets, an impulse response analysis is conducted. First, sample standard deviations of residuals are calculated for each series in the USD/CAD, USD/DEM, and USD/JPY models over the entire sample period. Next, to examine the response of a return's conditional variance on a typical day to a shock as well as the shock's propagation through time, sample averages of the estimated conditional variances for each series are computed as follows:

$$\tilde{h}_{i0}^{x} = (1/T)\sum_{t=1}^{T} h_{it}^{x}$$

$$\tilde{h}_{i0}^{j} = (1/T)\sum_{t=1}^{T} h_{it}^{j}$$

$$\tilde{h}_{i0}^{ed} = (1/T)\sum_{t=1}^{T} h_{it}^{ed}.$$

These amounts are used as initial values to obtain series of conditional variances assuming zero innovations up to 20 periods in advance: $\{\tilde{h}_{ik}^{x}\}_{k=1}^{20}$, $\{\tilde{h}_{ik}^{j}\}_{k=1}^{20}$, and

$\{\tilde{h}_{ik}^{ed}\}_{k=1}^{20}$.

Next, simulated conditional variances are computed for each of the series assuming a positive or negative one standard deviation shock in a market in the initial period. All other innovations are set to zero for up to 20 periods in advance. The percentage increases in conditional variances following the shock relative to the series that assumes zero innovations are then calculated. For example, suppose that the series assuming a positive one standard deviation shock of the exchange rate innovation at time 0 are given by $\{\hat{h}_{ik}^{x}\}_{k=1}^{20}$, $\{\hat{h}_{ik}^{j}\}_{k=1}^{20}$, and $\{\hat{h}_{ik}^{ed}\}_{k=1}^{20}$. Then, the percentage responses to the shock are formed as:

$$\left\{\frac{\hat{h}_{ik}^{x}}{\tilde{h}_{ik}^{x}} - 1\right\}_{k=1}^{20}$$

$$\left\{\frac{\hat{h}_{ik}^{j}}{\tilde{h}_{ik}^{j}} - 1\right\}_{k=1}^{20}$$

$$\left\{\frac{\hat{h}_{ik}^{ed}}{\tilde{h}_{ik}^{ed}} - 1\right\}_{k=1}^{20}$$

These percentage responses are graphed for the USD/CAD model, the USD/DEM model, and the USD/JPY model in Figures 11–13. The results for all three models demonstrate that shocks from Eurocurrency markets have small quantitative effects on foreign exchange markets; the only noticeable responses in exchange rate conditional variances occur as a result of shocks originating in their own markets. Thus, even though Euro Canada shocks and negative Euromark shocks raise USD/CAD and USD/DEM exchange rate volatilities, respectively, these increases are not economically significant. On the other hand, a positive one standard deviation shock in the USD/CAD of 0.29 per cent initially increases the conditional variance in the Euro Canada market by about 6.3 per cent, with this effect decreasing to about 1 per cent in 16 days. Furthermore, volatility in the Euro Canada market is more susceptible to foreign exchange market shocks than are Eurocurrency volatilities in other models. In the Euro Canada market, a negative one standard deviation shock of 0.03 per cent (corresponding to an increase in interest rates) initially raises volatility in this market by about 30 per cent, with this level falling to 1.4 per cent after 20 days. This increase in volatility is substantially greater than the change effected by a positive Euro Canada shock. Finally, a one standard deviation innovation of 0.02 per cent in the Eurodollar market has only a small effect on the Euro Canada market. While the Eurodollar conditional variance rises appreciably in response to positive and negative shocks in its own market in each model, only Euroyen innovations and bad news relating to the USD/CAD and USD/JPY exchange rates produce visible volatility spillover effects into the Eurodollar market.

4.3 Information Transmission Between Markets

The results described in Section 4.2 demonstrate that there are significant spillovers in the conditional means and variances of foreign exchange and money market returns. The data sampling times selected in this analysis may contribute to the observation of a spillover effect if one market is less liquid than another at that specific time of day. For example, if Eurocurrency markets are less active at noon Eastern time compared to other times of the day, then the release of news pertinent to both the foreign exchange and Eurocurrency markets may not be fully incorporated in the Eurocurrency market until the following day, leading to the appearance of a spillover effect. Such an issue is unlikely to be important in the USD/CAD model, in which all assets are actively traded in the same time zone.

The spillover results suggest that all three markets share common fundamentals and that news about the fundamentals in any one market is useful to investors in the other markets. The presence of spillovers could then imply that information transmission between markets occurs gradually and that the markets do not process news efficiently.

Alternatively, following the market contagion hypothesis of Ito and Lin (1994), it may be the case that the foreign exchange and money markets do not share common fundamentals, and the observed spillover effects are the result of changes in the risk-aversion of agents. According to this hypothesis, agents in one market who observe a price decrease in another market could become more risk-averse. Prices would fall in other markets on the following day, providing the appearance of a spillover effect. This market contagion hypothesis would therefore lead to an observationally equivalent outcome as the hypothesis that markets are weak-form inefficient.

One possible nexus between foreign exchange market and money market fundamentals stems from the interest rate parity conditions. Those conditions link the difference between domestic and foreign interest rates to the current spot exchange rate and either the current forward exchange rate (covered interest rate parity) or the expected future spot exchange rate (uncovered interest rate parity). Although this paper does not test those hypotheses, which involve the contemporaneous relationships between markets, the conditions point out avenues along which information transmission between markets could occur.[3] For example, suppose that the Federal Reserve Board unexpectedly decides to raise short-term interest rates while Canadian interest rates remain unchanged. Then, in order for covered interest rate parity to hold, either current spot or forward USD/CAD exchange rates (or both) would have to adjust following this unanticipated event. To the extent that there is an adjustment in current spot exchange rates as a result of the unexpected increase in U.S. interest rates, information will be transmitted between markets.

One way to ascertain whether there are common features in the news of each market is to examine contemporaneous correlations between the residuals, ϵ_{it}^{x}, ϵ_{it}^{j}, ϵ_{it}^{ed}, obtained from the models estimated in Section 4.2.[4] Table 8 lists these correlation coefficients, denoted by $\rho(\cdot,\cdot)$. Contemporaneous correlations between innovations are not high. In fact, six of the nine correlations are less than 0.1 in absolute value. The highest correlation (in absolute value) is that between the USD/CAD and Euro Canada return innovations and has a value of -0.1621. Similar results are obtained for contemporaneous correlations between squared residuals: seven correlations have absolute values less than 0.1, and the highest correlation is between squared USD/JPY and Euroyen innovations. Based on these results, there do not appear to be strong linkages between the news about fundamentals in each market. However, the information that is common to the pairs of markets could represent a small portion of the news revealed in each market, or there could be a non-linear relationship between the news in each market.

Another way to determine whether there are common features in the innovations of the three series is to use the Engle and Kozicki (1993) common volatility tests. These tests for common ARCH gauge whether two series follow a similar volatility process. If two series share a significant common factor, then it should be possible to construct a linear combination of the two that does not exhibit a time-varying variance.

First, each series is tested for the presence of ARCH(4) using Engle's (1982) test, and for the presence of multivariate ARCH (MARCH(2)) using a test that employs a multivariate information set as described in Engle and Susmel (1993). The former test statistic is the $T \times R^2$ from regressing squared residuals against four lags, and the

[3]For tests of risk premia in deviations from the uncovered interest rate parity condition using spot foreign exchange rates and Eurocurrency interest rates, see McCurdy and Morgan (1991).

[4]An analysis of contemporaneous correlations between returns in each market yields substantially similar results.

latter test statistic is the $T \times R^2$ from regressing squared residuals from a particular series against two lags of own squared residuals, as well as two lags of squared residuals from each of the other two series. The results of these tests are shown in Table 9, and they provide overwhelming evidence against the null hypothesis of no ARCH for all series. Thus, all series exhibit volatility clustering.

Next, for any two series, x_t and y_t, the linear combination $y_t - \tau x_t$ is formed and regressed on four lagged squares of x_t and y_t, four lagged cross-products, and a constant. The test statistic is the smallest $T \times R^2$ found by minimizing over the parameter τ. This statistic is distributed as χ^2 with 11 degrees of freedom. Table 9 lists the results. The null hypothesis of no ARCH in the linear combinations of series is rejected in all three cases of the USD/JPY model and in one case of the USD/DEM model at the 1 per cent significance level. In all cases, there is no evidence that innovations have a strong common volatility component. It is not possible to reject the null hypotheses of no ARCH in the linear combinations at the 1 per cent significance level for the exchange rate–Euromark and exchange rate–Eurodollar pairs in the USD/DEM model. Also, it is not possible to reject the null hypothesis at this level for all pairs in the USD/CAD model. These results indicate that innovations in USD/CAD, Euro Canada, and Eurodollar returns share common volatility processes. Thus, the clustering of news follows similar patterns in all three markets. These results imply that the volatilities in U.S. and Canadian foreign exchange and money markets are influenced by similar news. The Eurodollar and Euro Canada markets follow a common ARCH process, but the Eurodollar market does not experience volatility behaviour similar to that of the Euromark or the Euroyen markets.

While all markets in the USD/CAD model and some markets in the USD/DEM model share common volatility processes, the findings from the contemporaneous correlations of innovations in all models, as well as the results of the common ARCH tests, indicate that the news in the foreign exchange and money markets are not strongly related to each other. However, it could be that there is a small common factor that is dominated by larger idiosyncratic components in each market, or that more dominant market microstructure factors reduce computed correlations. Furthermore, the information that relates to the common component is disseminated gradually across markets, inducing spillover effects. This hypothesis implies that the foreign exchange and money markets are not efficient in processing pertinent information revealed in other markets.

Alternatively, the finding of low contemporaneous correlations between innovations in each market could follow from the market contagion hypothesis described by Ito and Lin (1994). For example, following an unexpected increase in U.S. interest rates, investors in the Japanese money market could become more risk-averse and decide to sell instruments in that market. As a result, the news in the U.S. money market would affect the Japanese money market the next day, even though there might not be fundamental reasons for such a relationship.

4.4 Discussion

The results presented above are interesting from a Canadian perspective for a number of reasons. First, the results show that the USD/CAD exchange rate volatility responds very little to unanticipated U.S. and Canadian interest rate changes as manifest in the Eurodollar and Euro Canada markets. The finding that the exchange rate volatility is not substantially affected by Eurocurrency shocks is similar to observations in the USD/DEM and USD/JPY models. On the other hand, exchange rate shocks increase the volatility of Euro Canada returns, and the difference between the Euro Canada conditional variance following a shock and the conditional variance in the absence of a shock falls below 1 per cent only after about 15 days. The effect of exchange rate shocks on the volatility of Euro Canada returns is also markedly greater than the impact that exchange rate shocks have on Euromark and Euroyen volatilities in their respective models. Thus, the Bank of Canada may, in the past, have reacted to USD/CAD shocks in the foreign exchange market by changing interest rates, or participants in the Euro Canada market may have responded to shocks by demanding greater risk premia. Either of these factors would contribute to increases in Euro Canada volatility following exchange rate shocks.

In the asset return equations, the exchange rate return depends positively on the lagged Euro Canada returns. Thus, an increase in the short-term Canadian interest rate in the Euro Canada market at time $t-1$ leads to an appreciation in the Canadian dollar against the U.S. dollar at time t. In the Euro Canada return equation, the coefficient on the lagged exchange rate return is small but significantly negative. Hence, a lagged depreciation of the Canadian dollar against the U.S. dollar is followed by a slight increase in the interest rate in the Euro Canada market.

The fact that exchange rate shocks can cause persistent increases in the volatility of short-term interest rates suggests that the Bank of Canada might wish to take policy actions following a large exchange rate shock should it want to mitigate the higher interest rate volatility. However, while a large depreciation in the Canadian dollar that is met with a substantial increase in short-term interest rates could curb the currency depreciation, it would further raise the volatility of short-term interest rates. Thus, an attempt to stabilize the exchange rate through a change in short-term interest rates will often heighten volatility in the latter market for some time.

5 Conclusions

This paper uses trivariate GARCH models to investigate information transmission between the foreign exchange and associated money markets. Three models are estimated for USD/CAD, USD/DEM, and USD/JPY exchange rate returns together with associated 90-day Eurocurrency market returns in order to determine whether price and volatility spillovers exist between the markets. The paper finds strong evidence of price and volatility spillovers in all three models, and some volatility spillovers are found to be asymmetric.

The results of significant spillover effects can be rationalized in terms of a gradual processing of news about common fundamentals in one market by investors in the other markets. Indeed, the interest rate parity conditions suggest channels through which the three markets might be linked. Although the Engle and Kozicki (1993) tests provide some evidence to support the existence of common features in the volatilities of innovations in the USD/CAD and USD/DEM models, contemporaneous correlations between pairs of innovations are low. Thus, if there are fundamental linkages between these markets, the variation in these common factors likely represents a small proportion of the total variation in the innovations.

It is also possible that the spillovers are caused by market contagion effects, whereby agents experience shifts in their risk-aversion after observing price changes in other markets. These movements in risk-aversion permit price changes to be transmitted across markets, leading to spillover effects even though markets are not contemporaneously correlated and do not share common fundamentals.

Whether spillovers are caused by the gradual dissemination of information about fundamentals across markets or by market contagion is worthy of further study. The low correlations between pairs of innovations could be related to the fact that the data being studied are sampled at the daily frequency in which idiosyncratic components of returns dominate the common factors. The estimation of these models using data sampled at lower frequencies should result in higher correlations between innovations as the influence of idiosyncratic components is reduced.

The Canadian experience in the foreign exchange and short-term interest rate markets over the past ten years has been characterized by a number of large shocks. It would be interesting to apply tools such as Markov-switching ARCH models to gauge volatility spillovers between markets, and to compare the forecasting performance of such models with that of the multivariate GARCH model described in this paper. It would also be interesting to study whether price and volatility spillovers exist between foreign exchange and stock or bond markets. These issues await future research.

Table 1: Summary statistics of returns

	USD/ CAD	USD/ DEM	USD/ JPY	Euro-dollar	Euro Canada	Euro-mark	Euro-yen
Obs.	2738	2709	2665	2738	2738	2709	2665
Mean	0.0060	0.0019	-0.0025	0.0002	0.0003	-0.0000	0.0004
Std. dev.	0.2916	0.6785	0.7328	0.0215	0.0281	0.0170	0.0271
Skewness	0.0551	-0.0240	-0.4725	0.1492	-2.0870	-0.2446	0.2175
Kurtosis	6.1734	5.2942	7.7347	29.306	33.859	8.8360	17.579
Q_2	4.70 [0.1734]	3.63 [0.1628]	7.29 [0.0261]	287.71 [0.0000]	66.48 [0.0000]	158.20 [0.0000]	417.79 [0.0000]
Q_5	5.42 [0.4626]	6.71 [0.2432]	12.18 [0.0324]	305.37 [0.0000]	70.16 [0.0000]	162.93 [0.0000]	419.17 [0.0000]
Q_{20}	22.35 [0.4714]	17.45 [0.6235]	34.05 [0.0258]	417.63 [0.0000]	97.87 [0.0000]	186.36 [0.0000]	491.62 [0.0000]
Q_2^2	108.28 [0.0000]	61.62 [0.0000]	181.71 [0.0000]	496.03 [0.0000]	61.10 [0.0000]	184.84 [0.0000]	598.83 [0.0000]
Q_5^2	216.25 [0.0000]	102.74 [0.0000]	273.37 [0.0000]	500.34 [0.0000]	74.78 [0.0000]	241.41 [0.0000]	889.82 [0.0000]
Q_{20}^2	619.14 [0.0000]	314.59 [0.0000]	531.05 [0.0000]	548.60 [0.0000]	139.00 [0.0000]	310.68 [0.0000]	2071.79 [0.0000]
Jarque-Bera	386.89 [0.0000]	246.13 [0.0000]	315.76 [0.0000]	3066.9 [0.0000]	2566.3 [0.0000]	543.32 [0.0000]	1714.8 [0.0000]

Note: The Ljung-Box (1978) statistic, Q_l or Q_l^2, for l lags is asymptotically distributed as χ^2 with l degrees of freedom, and the Jarque-Bera (1980) statistic is asymptotically distributed as χ^2 with 2 degrees of freedom (p-values are given in parentheses).

Table 2: USD/CAD GARCH(1,1) model estimates

Parameter	Est./t-stat.	Parameter	Est./t-stat.	Parameter	Est./t-stat.
$\gamma^{uc}_{cad,0}$	-0.0000 [-0.74]	c^{11}_{cad}	0.0002 [8.03]*	p^{ed}_{cad}	0.0155 [0.70]
$\gamma^{uc}_{cad,1}$	0.0256 [1.45]	c^{12}_{cad}	0.0000 [15.88]*	t^{uc}_{cad}	0.5704 [3.21]*
$\gamma^{uc}_{cad,2}$	0.6765 [3.95]*	c^{13}_{cad}	0.0000 [13.16]*	t^{ec}_{cad}	0.1155 [3.43]*
$\gamma^{uc}_{cad,3}$	-0.2629 [-1.14]	c^{22}_{cad}	0.0000 [3.43]*	t^{ed}_{cad}	0.0166 [54.53]*
$\gamma^{uc}_{cad,4}$	0.0001 [0.87]	c^{23}_{cad}	0.0001 [119.6]*	q^{uc}_{cad}	0.0000 [0.00]
$\gamma^{uc}_{cad,5}$	0.0008 [3.35]*	c^{33}_{cad}	0.0000 [23.67]*	q^{ec}_{cad}	0.0000 [0.00]
$\gamma^{ec}_{cad,0}$	0.0000 [1.62]	a^{uc}_{cad}	0.2132 [64.52]*	q^{ed}_{cad}	0.0000 [0.00]
$\gamma^{ec}_{cad,1}$	-0.0131 [-9.08]*	a^{ec}_{cad}	0.2609 [35.89]*	$v^{11}_{1,cad}$	0.0004 [8.00]*
$\gamma^{ec}_{cad,2}$	-0.2249 [-13.41]*	a^{ed}_{cad}	0.5179 [113.1]*	$v^{12}_{1,cad}$	0.0000 [2.96]*
$\gamma^{ec}_{cad,3}$	-0.0083 [-0.43]	b^{uc}_{cad}	0.9664 [1645.1]*	$v^{13}_{1,cad}$	0.0000 [1.66]
$\gamma^{ec}_{cad,4}$	0.0000 [2.64]*	b^{ec}_{cad}	0.8669 [452.4]*	$v^{22}_{1,cad}$	0.0000 [13.47]*
$\gamma^{ec}_{cad,5}$	0.0000 [1.65]	b^{ed}_{cad}	0.7407 [448.4]*	$v^{23}_{1,cad}$	0.0000 [50.63]*
$\gamma^{ed}_{cad,0}$	-0.0000 [-0.47]	g^{uc}_{cad}	0.0947 [6.66]*	$v^{33}_{1,cad}$	0.0000 [0.00]
$\gamma^{ed}_{cad,1}$	-0.0006 [-0.74]	g^{ec}_{cad}	0.4272 [53.39]*	$v^{11}_{2,cad}$	0.0013 [18.55]*
$\gamma^{ed}_{cad,2}$	0.0040 [0.63]	g^{ed}_{cad}	0.1961 [6.12]*	$v^{12}_{2,cad}$	0.0000 [1.08]
$\gamma^{ed}_{cad,3}$	-0.2029 [-20.46]*	s^{uc}_{cad}	0.3544 [2.41]*	$v^{13}_{2,cad}$	0.0000 [0.65]
$\gamma^{ed}_{cad,4}$	0.0000 [1.99]*	s^{ec}_{cad}	0.0839 [3.99]*	$v^{22}_{2,cad}$	0.0000 [2.78]*
$\gamma^{ed}_{cad,5}$	0.0000 [1.08]	s^{ed}_{cad}	0.0006 [0.11]	$v^{23}_{2,cad}$	0.0001 [15.73]*
Obs.	2736	p^{uc}_{cad}	0.0153 [0.03]	$v^{33}_{2,cad}$	0.0000 [0.00]
Log likelihood	56086.72	p^{ec}_{cad}	0.0217 [55.86]*	Note: *Indicates significance at the 5 per cent level.	

Table 3: USD/DEM GARCH(1,1) model estimates

Parameter	Est./t-stat.	Parameter	Est./t-stat.	Parameter	Est./t-stat.
$\gamma^{ud}_{dem,0}$	0.0000 [0.07]	c^{11}_{dem}	0.0005 [15.34]*	p^{ed}_{dem}	0.0165 [0.25]
$\gamma^{ud}_{dem,1}$	0.0212 [1.15]	c^{12}_{dem}	0.0000 [5.18]*	t^{ud}_{dem}	2.2773 [4.75]*
$\gamma^{ud}_{dem,2}$	-1.1235 [-1.65]	c^{13}_{dem}	0.0000 [17.08]*	t^{em}_{dem}	0.0672 [2.69]*
$\gamma^{ud}_{dem,3}$	0.3782 [0.70]	c^{22}_{dem}	0.0000 [47.47]*	t^{ed}_{dem}	0.0002 [0.02]
$\gamma^{ud}_{dem,4}$	-0.0003 [-1.23]	c^{23}_{dem}	0.0000 [2.51]*	q^{ud}_{dem}	0.1485 [0.04]
$\gamma^{ud}_{dem,5}$	0.0003 [0.61]	c^{33}_{dem}	0.0001 [189.6]*	q^{em}_{dem}	0.0001 [0.00]
$\gamma^{em}_{dem,0}$	0.0000 [0.99]	a^{ud}_{dem}	0.1750 [56.17]*	q^{ed}_{dem}	0.0003 [0.00]
$\gamma^{em}_{dem,1}$	0.0001 [0.19]	a^{em}_{dem}	0.3556 [49.42]*	$v^{11}_{1,dem}$	0.0002 [0.53]
$\gamma^{em}_{dem,2}$	-0.2628 [-14.40]*	a^{ed}_{dem}	0.4648 [88.27]*	$v^{12}_{1,dem}$	0.0000 [0.76]
$\gamma^{em}_{dem,3}$	0.0264 [2.05]*	b^{ud}_{dem}	0.9751 [1951.2]*	$v^{13}_{1,dem}$	0.0000 [4.40]*
$\gamma^{em}_{dem,4}$	-0.0000 [-0.79]	b^{em}_{dem}	0.8613 [414.3]*	$v^{22}_{1,dem}$	0.0000 [7.46]*
$\gamma^{em}_{dem,5}$	-0.0000 [-1.14]	b^{ed}_{dem}	0.7584 [468.7]*	$v^{23}_{1,dem}$	0.0001 [35.01]*
$\gamma^{ed}_{dem,0}$	-0.0000 [-0.22]	g^{ud}_{dem}	0.1171 [13.03]*	$v^{33}_{1,dem}$	0.0000 [2.63]*
$\gamma^{ed}_{dem,1}$	-0.0010 [-1.93]	g^{em}_{dem}	0.2573 [13.27]*	$v^{11}_{2,dem}$	0.0018 [12.29]*
$\gamma^{ed}_{dem,2}$	0.0509 [3.19]*	g^{ed}_{dem}	0.0404 [0.91]	$v^{12}_{2,dem}$	0.0000 [2.91]*
$\gamma^{ed}_{dem,3}$	-0.2415 [-17.08]*	s^{ud}_{dem}	0.3421 [0.22]	$v^{13}_{2,dem}$	0.0000 [0.17]
$\gamma^{ed}_{dem,4}$	0.0000 [0.11]	s^{em}_{dem}	0.0744 [6.00]*	$v^{22}_{2,dem}$	0.0000 [4.06]*
$\gamma^{ed}_{dem,5}$	0.0000 [0.43]	s^{ed}_{dem}	0.0001 [0.02]	$v^{23}_{2,dem}$	0.0001 [11.65]*
Obs.	2706	p^{ud}_{dem}	0.0262 [0.01]	$v^{33}_{2,dem}$	0.0000 [0.00]
Log likelihood	54331.90	p^{em}_{dem}	0.0031 [19.44]*	Note: *Indicates significance at the 5 per cent level.	

Table 4: USD/JPY GARCH(1,1) model estimates

Parameter	Est./t-stat.	Parameter	Est./t-stat.	Parameter	Est./t-stat.
$\gamma^{uj}_{jpy,0}$	-0.0001 [-0.67]	c^{11}_{jpy}	0.0010 [40.63]*	p^{ed}_{jpy}	0.1561 [45.99]*
$\gamma^{uj}_{jpy,1}$	0.0471 [2.51]*	c^{12}_{jpy}	0.0000 [0.26]	t^{uj}_{jpy}	0.0068 [0.00]
$\gamma^{uj}_{jpy,2}$	-0.1976 [-0.42]	c^{13}_{jpy}	0.0000 [0.90]	t^{ey}_{jpy}	0.0916 [10.30]*
$\gamma^{uj}_{jpy,3}$	-0.3952 [-0.57]	c^{22}_{jpy}	0.0000 [0.16]	t^{ed}_{jpy}	0.0062 [39.12]*
$\gamma^{uj}_{jpy,4}$	-0.0002 [-0.78]	c^{23}_{jpy}	0.0000 [16.46]*	q^{uj}_{jpy}	0.2019 [0.01]
$\gamma^{uj}_{jpy,5}$	0.0014 [3.11]*	c^{33}_{jpy}	0.0000 [20.66]*	q^{ey}_{jpy}	0.0001 [0.01]
$\gamma^{ey}_{jpy,0}$	-0.0000 [-1.07]	a^{uj}_{jpy}	0.1667 [44.39]*	q^{ed}_{jpy}	0.0142 [0.20]
$\gamma^{ey}_{jpy,1}$	-0.0016 [-3.46]*	a^{ey}_{jpy}	0.2882 [78.79]*	$v^{11}_{1,jpy}$	0.0005 [2.42]*
$\gamma^{ey}_{jpy,2}$	-0.3023 [-20.19]*	a^{ed}_{jpy}	0.5653 [136.3]*	$v^{12}_{1,jpy}$	0.0000 [2.85]*
$\gamma^{ey}_{jpy,3}$	0.0548 [3.30]*	b^{uj}_{jpy}	0.9647 [1599.4]*	$v^{13}_{1,jpy}$	0.0001 [65.08]*
$\gamma^{ey}_{jpy,4}$	0.0000 [4.64]*	b^{ey}_{jpy}	0.9309 [1520.8]*	$v^{22}_{1,jpy}$	0.0001 [85.70]*
$\gamma^{ey}_{jpy,5}$	-0.0000 [-0.17]	b^{ed}_{jpy}	0.7457 [441.7]*	$v^{23}_{1,jpy}$	0.0000 [1.50]
$\gamma^{ed}_{jpy,0}$	0.0000 [0.27]	g^{uj}_{jpy}	0.1723 [24.38]*	$v^{33}_{1,jpy}$	0.0000 [1.51]
$\gamma^{ed}_{jpy,1}$	-0.0007 [-2.04]*	g^{ey}_{jpy}	0.0343 [1.02]	$v^{11}_{2,jpy}$	0.0022 [14.26]*
$\gamma^{ed}_{jpy,2}$	0.0122 [1.16]	g^{ed}_{jpy}	0.2559 [9.64]*	$v^{12}_{2,jpy}$	0.0000 [4.19]*
$\gamma^{ed}_{jpy,3}$	-0.1908 [-18.77]*	s^{uj}_{jpy}	0.0449 [0.02]	$v^{13}_{2,jpy}$	0.0000 [0.07]
$\gamma^{ed}_{jpy,4}$	0.0000 [0.05]	s^{ey}_{jpy}	0.0684 [9.88]*	$v^{22}_{2,jpy}$	0.0000 [47.70]*
$\gamma^{ed}_{jpy,5}$	0.0000 [1.03]	s^{ed}_{jpy}	0.0005 [0.28]	$v^{23}_{2,jpy}$	0.0001 [1.00]
Obs.	2663	p^{uj}_{jpy}	0.0371 [0.02]	$v^{33}_{2,jpy}$	0.0000 [43.51]*
Log likelihood	52681.07	p^{ey}_{jpy}	0.0015 [6.95]*	Note: *Indicates significance at the 5 per cent level.	

Table 5: Summary of spillover effects

Panel A – Conditional means

	$r^{x}_{i,t-1}$	$r^{j}_{i,t-1}$	$r^{ed}_{i,t-1}$
USD/CAD model			
$r^{uc}_{cad,t}$	—	*	
$r^{ec}_{cad,t}$	*	—	
$r^{ed}_{cad,t}$			—
USD/DEM model			
$r^{ud}_{dem,t}$	—		
$r^{em}_{dem,t}$		—	*
$r^{ed}_{dem,t}$		*	—
USD/JPY model			
$r^{uj}_{jpy,t}$	—		
$r^{ey}_{jpy,t}$	*	—	*
$r^{ed}_{jpy,t}$	*		—

Panel B – Conditional variances

	All innovations			Negative innovations		
	x	j	ed	x	j	ed
USD/CAD model						
$h^{uc}_{cad,t}$	—	*		—	*	
$h^{ec}_{cad,t}$	*	—	*		—	*
$h^{ed}_{cad,t}$			—	*		—
USD/DEM model						
$h^{ud}_{dem,t}$	—			—	*	
$h^{em}_{dem,t}$	*	—	*		—	*
$h^{ed}_{dem,t}$			—			—
USD/JPY model						
$h^{uj}_{jpy,t}$	—			—		
$h^{ey}_{jpy,t}$	*	—	*		—	*
$h^{ed}_{jpy,t}$		*	—	*		—

Note: The table indicates effects of past returns on current returns (Panel A) and the effects of past shocks on current conditional variances (Panel B). Asterisks indicate parameters that are significant at the 5 per cent level.

Table 6: Ljung-Box diagnostic tests

Model	Q_{16}^{x}	Q_{16}^{j}	Q_{16}^{ed}
USD/CAD	21.23 [0.1698]	25.70 [0.0584]	52.43 [0.0000]
USD/DEM	17.07 [0.3811]	35.70 [0.0032]	34.46 [0.0047]
USD/JPY	19.80 [0.2294]	63.62 [0.0000]	25.32 [0.0644]
Model	$Q_{16}^{x^2}$	$Q_{16}^{j^2}$	$Q_{16}^{(ed)^2}$
USD/CAD	28.69 [0.0261]	30.80 [0.0143]	33.56 [0.0062]
USD/DEM	12.12 [0.7357]	11.97 [0.7460]	3.35 [0.9996]
USD/JPY	18.44 [0.2988]	10.53 [0.8375]	7.95 [0.9503]
Model	$Q_{16}^{x,j}$	$Q_{16}^{x,ed}$	$Q_{16}^{j,ed}$
USD/CAD	52.25 [0.0000]	24.26 [0.0840]	19.11 [0.2630]
USD/DEM	26.12 [0.0524]	17.02 [0.3843]	18.41 [0.3004]
USD/JPY	21.82 [0.1491]	21.07 [0.1758]	16.54 [0.4159]

Note: Ljung-Box (1978) statistics for 16 lags are asymptotically distributed as χ^2 with 16 degrees of freedom (p-values are given in parentheses).

Table 7: Likelihood ratio tests

Test	USD/CAD	USD/DEM	USD/JPY
No spillovers $H_0: \gamma_{i2}^x = \gamma_{i3}^x = \gamma_{i1}^j = \gamma_{i3}^j = \gamma_{i1}^{ed} = \gamma_{i2}^{ed} =$ $s_i^x = s_i^j = s_i^{ed} = p_i^x = p_i^j = p_i^{ed} =$ $t_i^x = t_i^j = t_i^{ed} = q_i^x = q_i^j = q_i^{ed} = 0$	171.46 [0.0000]	43.65 [0.0006]	190.03 [0.0000]
No price spillovers $H_0: \gamma_{i2}^x = \gamma_{i3}^x = \gamma_{i1}^j = \gamma_{i3}^j = \gamma_{i1}^{ed} = \gamma_{i2}^{ed} = 0$	40.62 [0.0000]	18.40 [0.0053]	39.83 [0.0000]
No volatility spillovers $H_0: s_i^x = s_i^j = s_i^{ed} = p_i^x = p_i^j = p_i^{ed} =$ $t_i^x = t_i^j = t_i^{ed} = q_i^x = q_i^j = q_i^{ed} = 0$	122.03 [0.0000]	24.77 [0.0160]	161.37 [0.0000]
No asymmetry in volatility spillovers $H_0: t_i^x = t_i^j = t_i^{ed} = q_i^x = q_i^j = q_i^{ed} = 0$	18.02 [0.0062]	0.88 [0.9898]	8.59 [0.1980]
No weekend/holiday effects $H_0: \gamma_{i4}^x = \gamma_{i5}^x = \gamma_{i4}^j = \gamma_{i5}^j = \gamma_{i4}^{ed} = \gamma_{i5}^{ed} =$ $v_{1i}^{11} = v_{1i}^{12} = v_{1i}^{13} = v_{1i}^{22} = v_{1i}^{23} = v_{1i}^{33} =$ $v_{2i}^{11} = v_{2i}^{12} = v_{2i}^{13} = v_{2i}^{22} = v_{2i}^{23} = v_{2i}^{33} = 0$	61.87 [0.0000]	106.08 [0.0000]	317.78 [0.0000]
No wknd./hol. effects in cond. mean vector $H_0: \gamma_{i4}^x = \gamma_{i5}^x = \gamma_{i4}^{dj} = \gamma_{i5}^{dj} = \gamma_{i4}^{d4} = \gamma_{i5}^{d4} = 0$	9.77 [0.1348]	4.80 [0.5710]	23.99 [0.0005]
No wknd./hol. effects in cond. cov. matrix $H_0: v_{1i}^{11} = v_{1i}^{12} = v_{1i}^{13} = v_{1i}^{22} = v_{1i}^{23} = v_{1i}^{33} =$ $v_{2i}^{11} = v_{2i}^{12} = v_{2i}^{13} = v_{2i}^{22} = v_{2i}^{23} = v_{2i}^{33} = 0$	49.83 [0.0000]	33.62 [0.0008]	158.80 [0.0000]

Note: Likelihood ratio test statistics are distributed as χ^2, with the number of degrees of freedom equal to the number of restrictions (p-values are given in parentheses).

Table 8: Correlations of residuals and squared residuals

Model	$\rho(\epsilon_{it}^{x}, \epsilon_{it}^{j})$	$\rho(\epsilon_{it}^{x}, \epsilon_{it}^{ed})$	$\rho(\epsilon_{it}^{j}, \epsilon_{it}^{ed})$
USD/CAD	-0.1621	-0.0126	0.1543
USD/DEM	-0.0184	-0.0398	0.1438
USD/JPY	-0.0178	-0.0327	0.0019
Model	$\rho((\epsilon_{it}^{x})^2, (\epsilon_{it}^{j})^2)$	$\rho((\epsilon_{it}^{x})^2, (\epsilon_{it}^{ed})^2)$	$\rho((\epsilon_{it}^{j})^2, (\epsilon_{it}^{ed})^2)$
USD/CAD	0.1270	-0.0057	0.0079
USD/DEM	0.0646	0.0012	0.0701
USD/JPY	0.1419	0.0036	0.0922

Table 9: Common ARCH tests

Model	ϵ_{it}^{x}	ϵ_{it}^{j}	ϵ_{it}^{ed}
ARCH tests	ARCH(4)	ARCH(4)	ARCH(4)
USD/CAD	395.76 [0.0000]	66.12 [0.0000]	495.41 [0.0000]
USD/DEM	410.86 [0.0000]	410.30 [0.0000]	439.97 [0.0000]
USD/JPY	385.76 [0.0000]	533.16 [0.0000]	487.76 [0.0000]
MARCH tests	MARCH(2)	MARCH(2)	MARCH(2)
USD/CAD	521.58 [0.0000]	120.79 [0.0000]	525.52 [0.0000]
USD/DEM	559.09 [0.0000]	488.33 [0.0000]	467.58 [0.0000]
USD/JPY	503.41 [0.0000]	578.94 [0.0000]	525.03 [0.0000]
EK test parameters, τ	$\epsilon_{it}^{x}, \epsilon_{it}^{j}$	$\epsilon_{it}^{x}, \epsilon_{it}^{ed}$	$\epsilon_{it}^{j}, \epsilon_{it}^{ed}$
USD/CAD	-8.22	-8.31	1.05
USD/DEM	-4.08	-10.29	-0.59
USD/JPY	-8.82	41.00	-16.34
EK test statistics	$\epsilon_{it}^{x}, \epsilon_{it}^{j}$	$\epsilon_{it}^{x}, \epsilon_{it}^{ed}$	$\epsilon_{it}^{j}, \epsilon_{it}^{ed}$
USD/CAD	21.76 [0.0263]	17.35 [0.0979]	17.35 [0.0980]
USD/DEM	22.86 [0.0185]	13.06 [0.2892]	39.63 [0.0000]
USD/JPY	52.73 [0.0000]	29.17 [0.0021]	33.98 [0.0004]

Note: ARCH(4) test statistics are distributed as χ^2 with 4 degrees of freedom. MARCH(2) test statistics are distributed as χ^2 with 6 degrees of freedom. Engle and Kozicki (1993) test statistics are distributed as χ^2 with 11 degrees of freedom. In all cases, p-values are given in parentheses.

Figure 1: USD/CAD Daily Returns

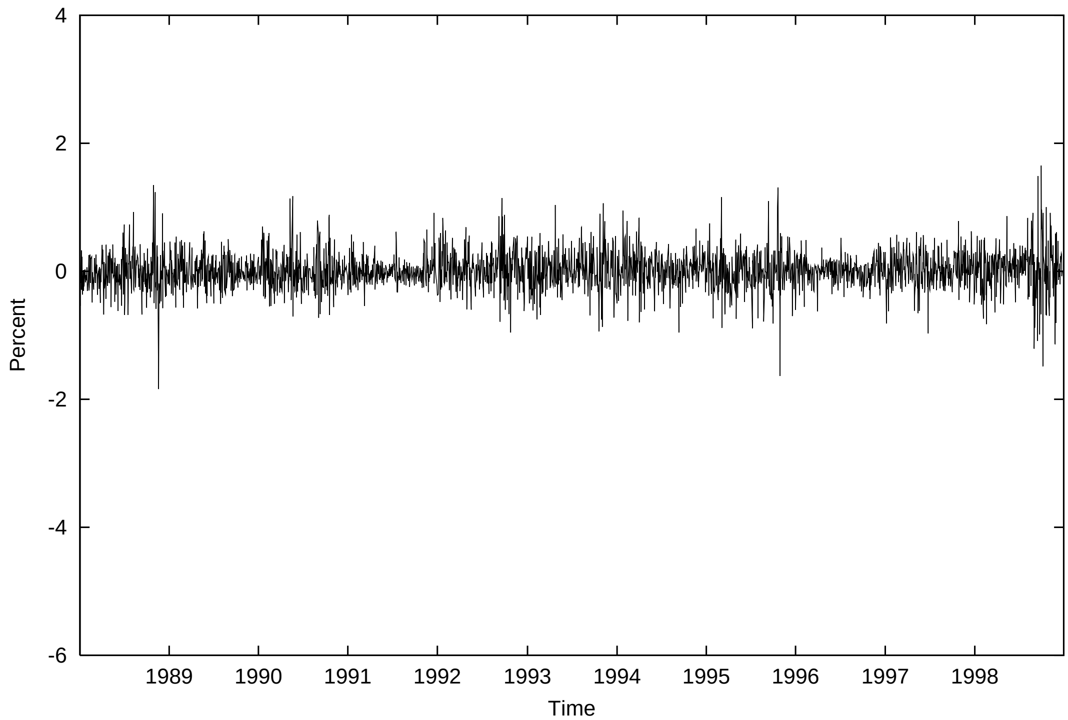


Figure 2: USD/DEM Daily Returns

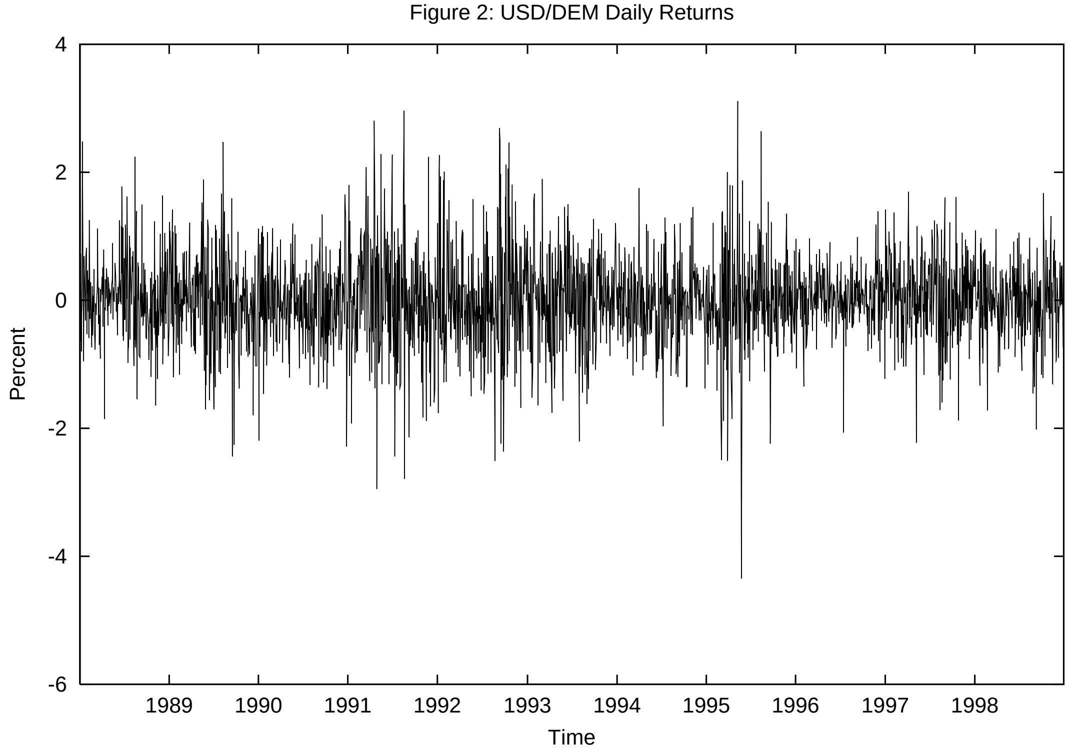


Figure 3: USD/JPY Daily Returns

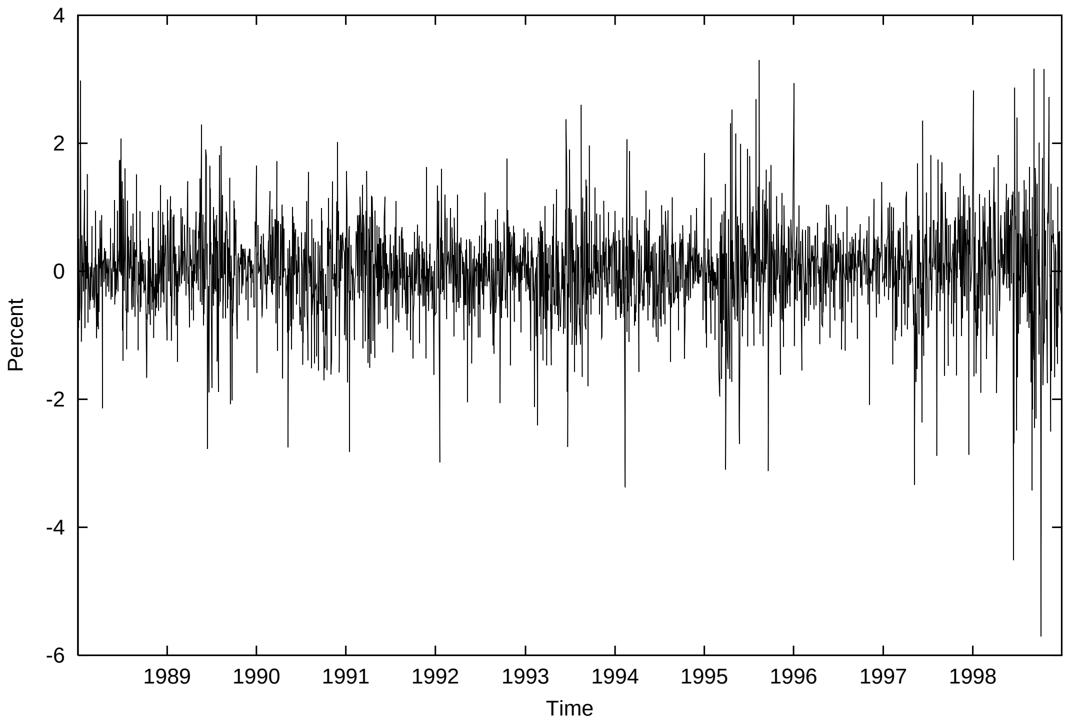


Figure 4: 90-Day Eurodollar Deposit Daily Returns

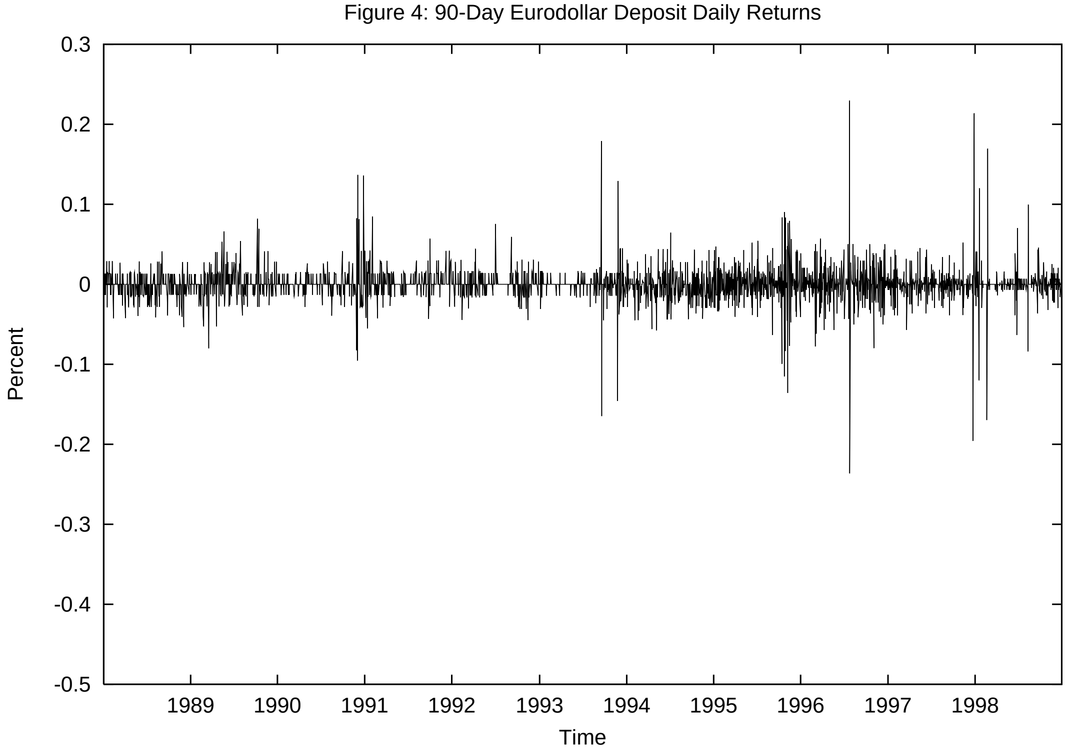


Figure 5: 90-Day Euro Canada Deposit Daily Returns

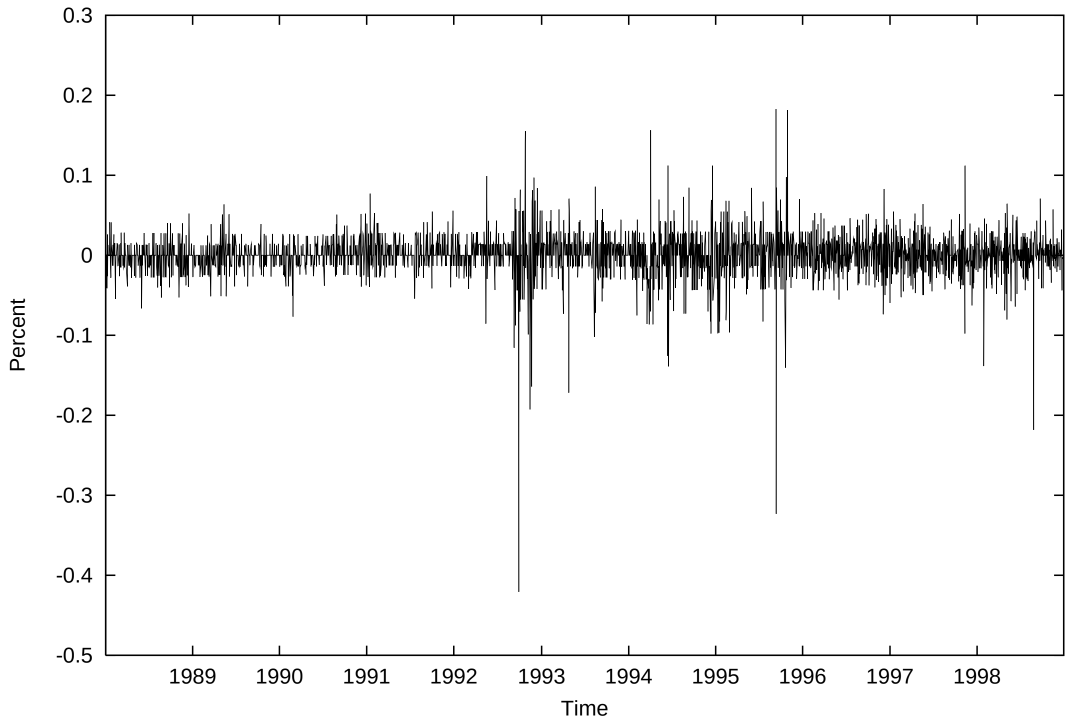


Figure 6: 90-Day Euromark Deposit Daily Returns

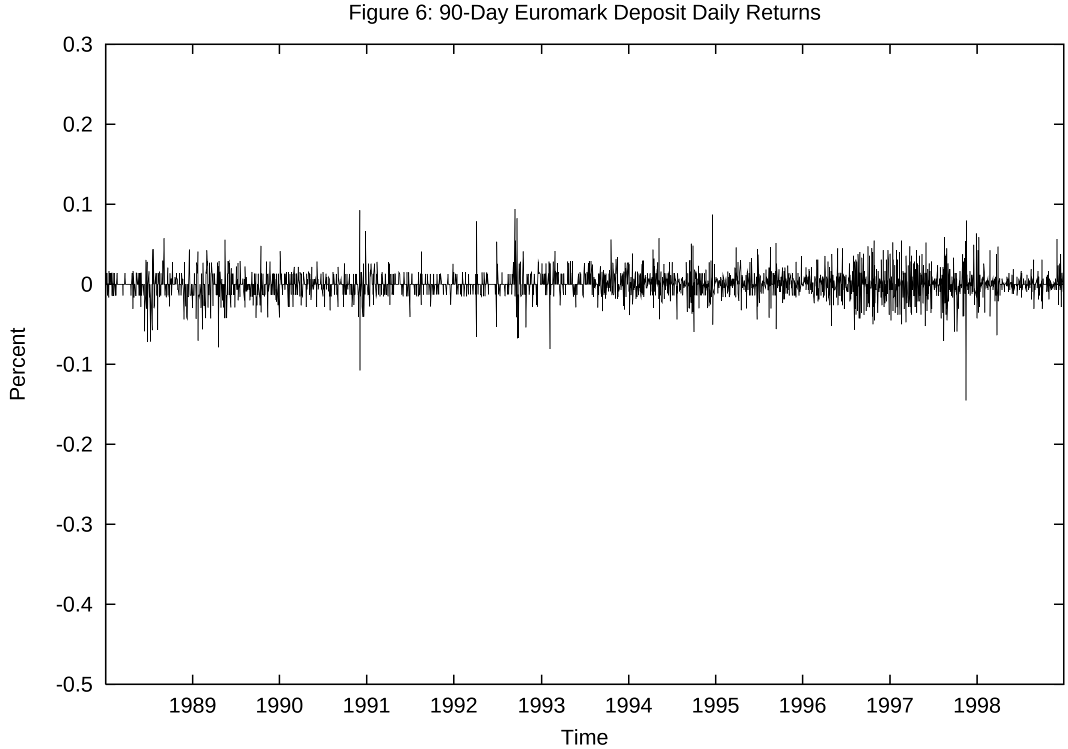
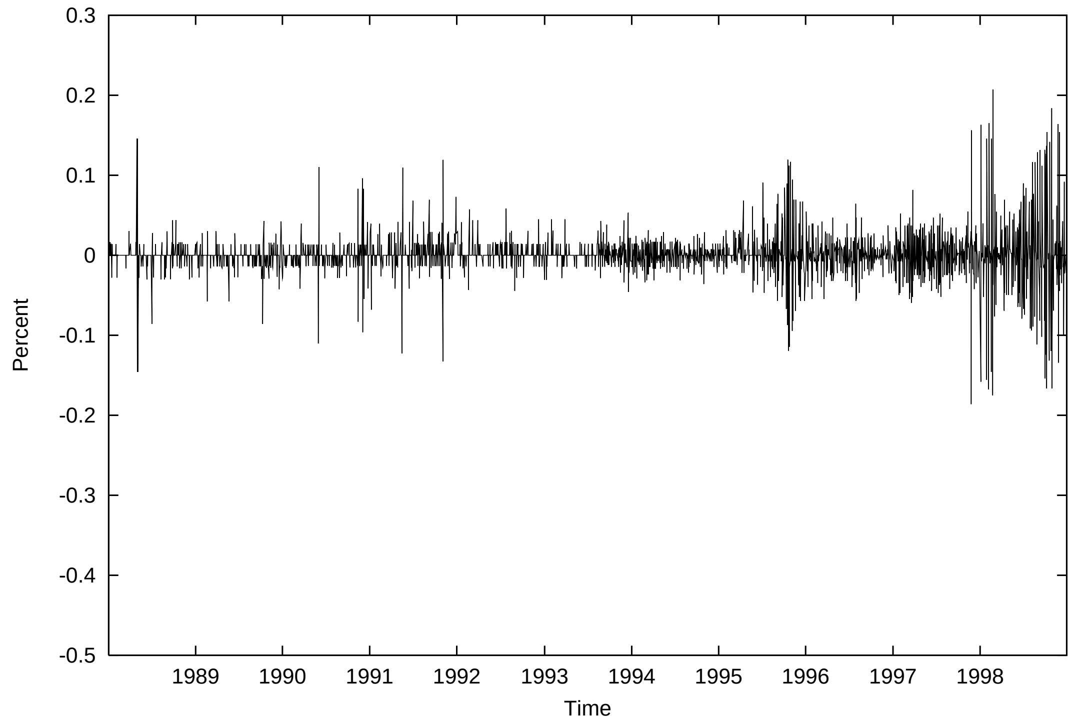


Figure 7: 90-Day Euroyen Deposit Daily Returns



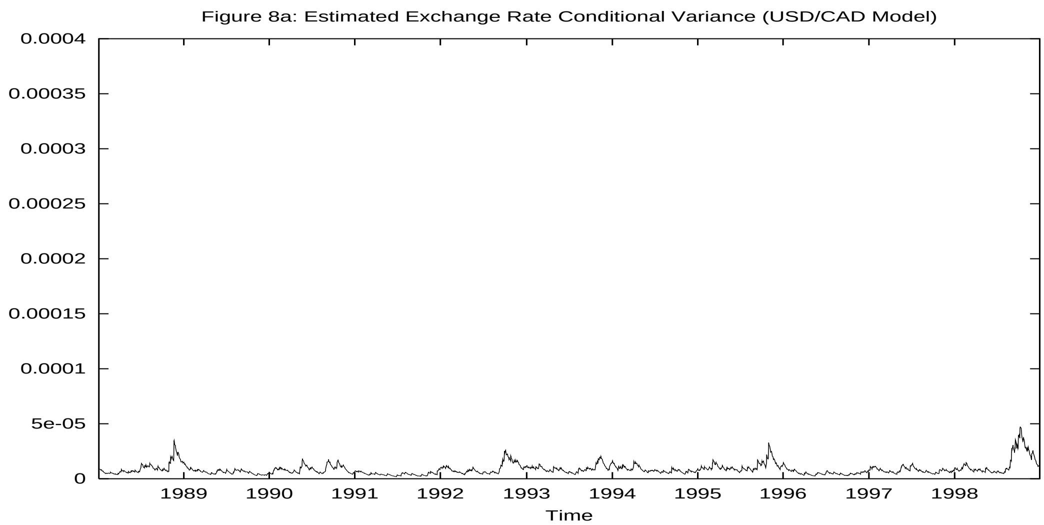


Figure 8a: Estimated Exchange Rate Conditional Variance (USD/CAD Model)
0.0004
0.00035
0.0003
0.00025
0.0002
0.00015
0.0001
5e-05
0
1989 1990 1991 1992 1993 1994 1995 1996 1997 1998
Time

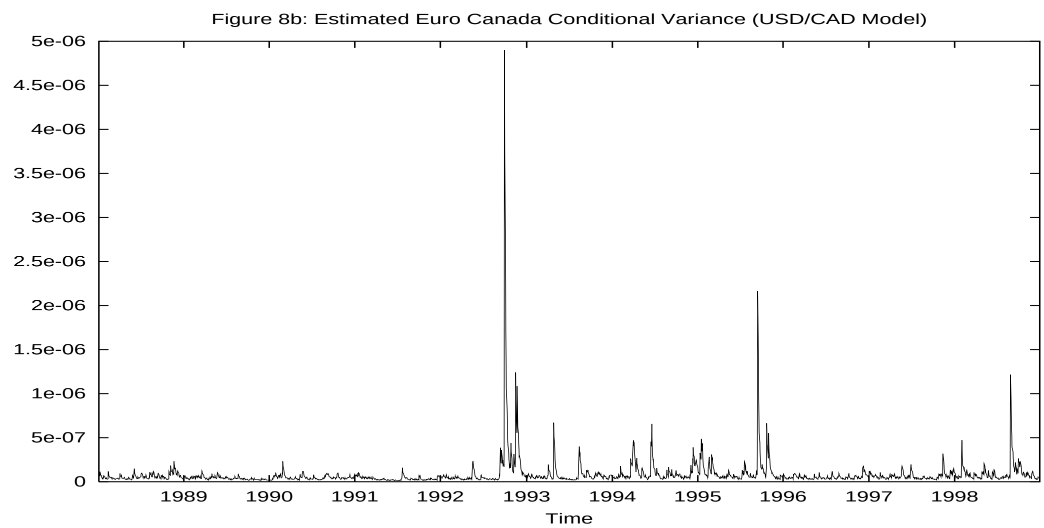


Figure 8b: Estimated Euro Canada Conditional Variance (USD/CAD Model)
5e-06
4.5e-06
4e-06
3.5e-06
3e-06
2.5e-06
2e-06
1.5e-06
1e-06
5e-07
0
1989 1990 1991 1992 1993 1994 1995 1996 1997 1998
Time

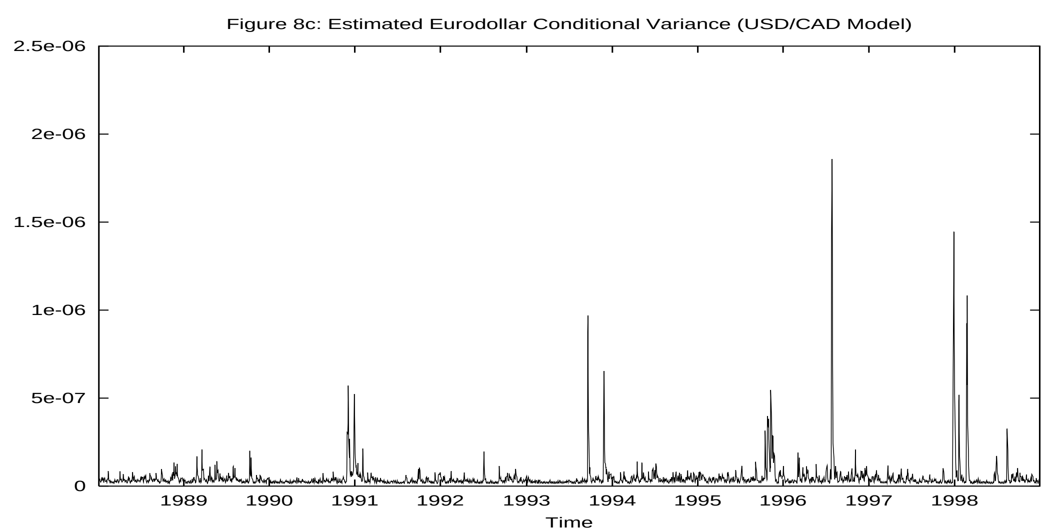


Figure 8c: Estimated Eurodollar Conditional Variance (USD/CAD Model)
2.5e-06
2e-06
1.5e-06
1e-06
5e-07
0
1989 1990 1991 1992 1993 1994 1995 1996 1997 1998
Time

Figure 9a: Estimated Exchange Rate Conditional Variance (USD/DEM Model)

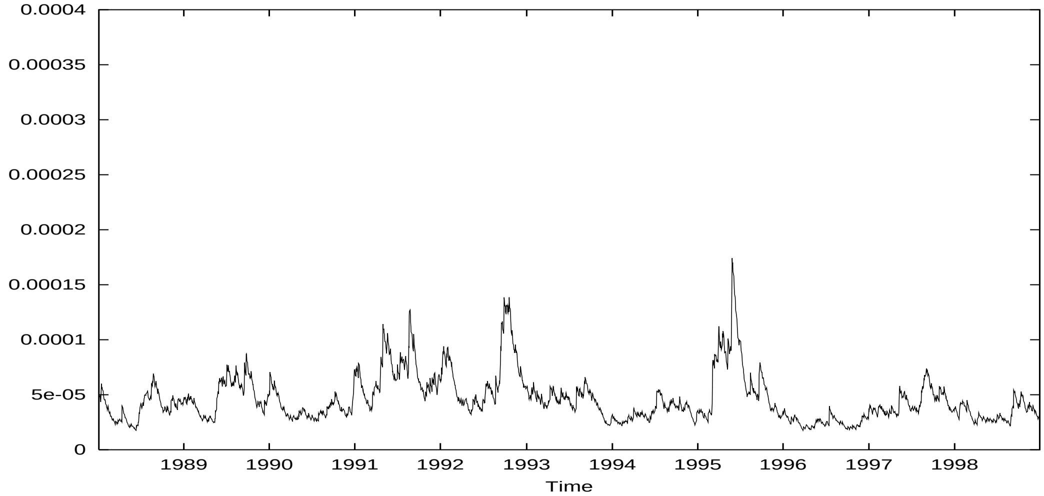


Figure 9b: Estimated Euromark Conditional Variance (USD/DEM Model)

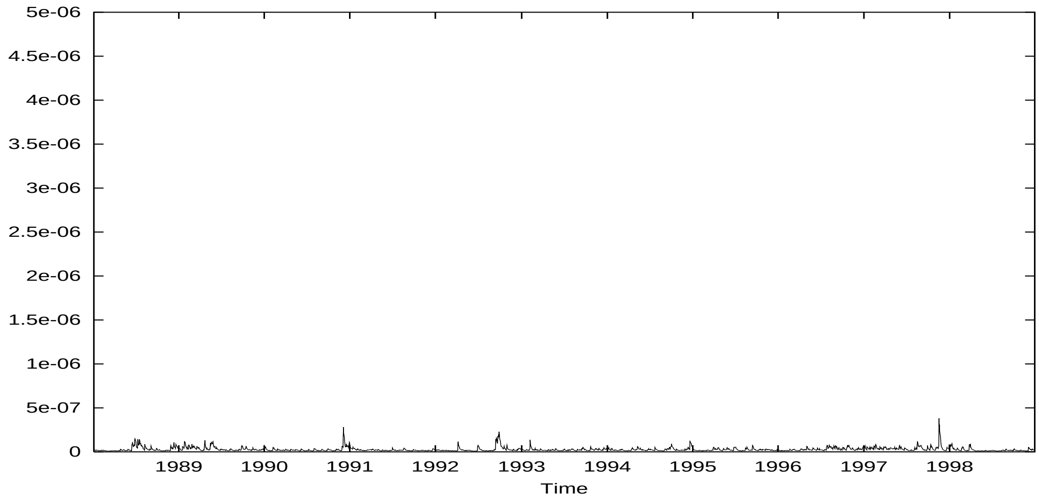


Figure 9c: Estimated Eurodollar Conditional Variance (USD/DEM Model)

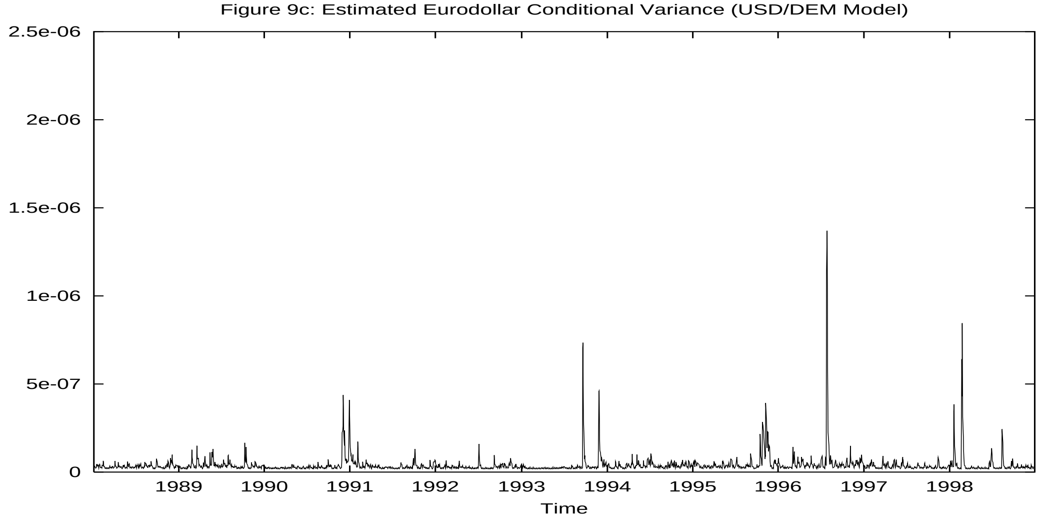


Figure 10a: Estimated Exchange Rate Conditional Variance (USD/JPY Model)

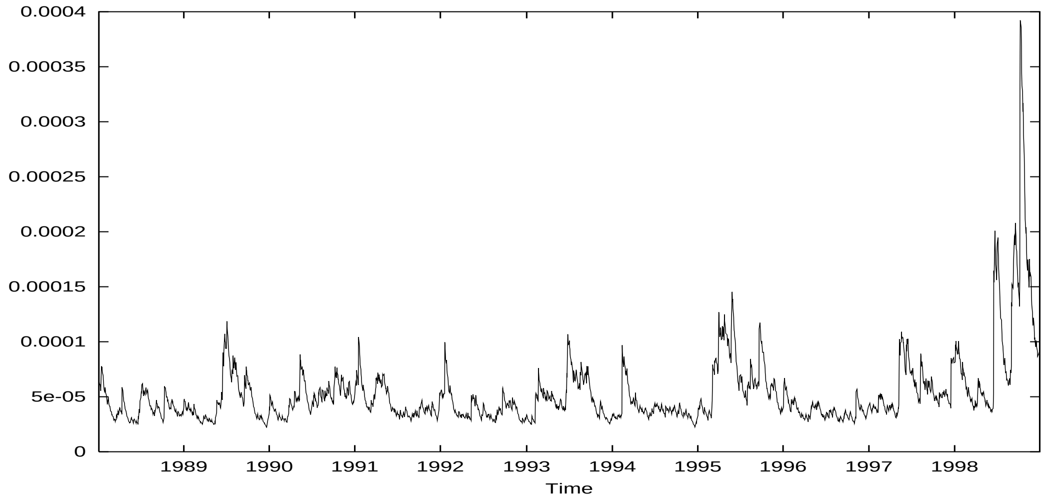


Figure 10b: Estimated Euroyen Conditional Variance (USD/JPY Model)

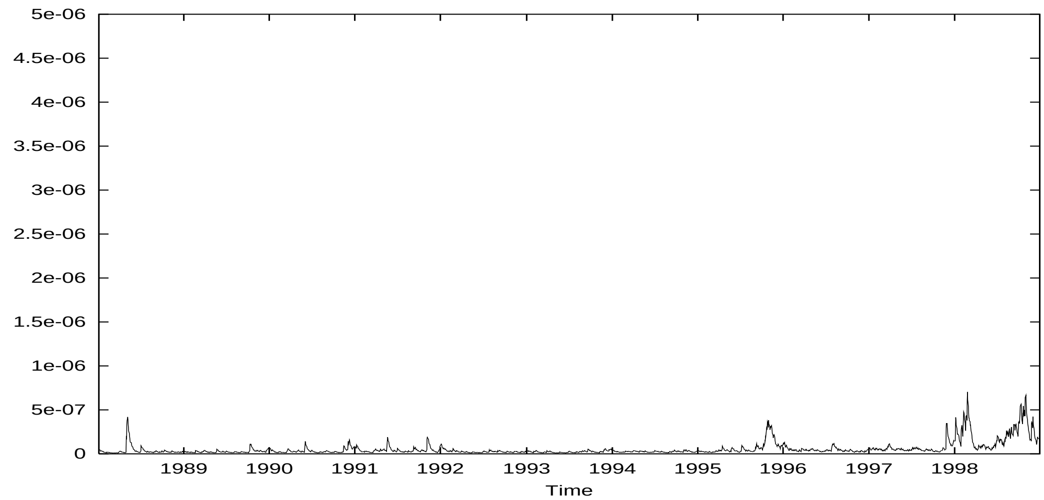


Figure 10c: Estimated Eurodollar Conditional Variance (USD/JPY Model)

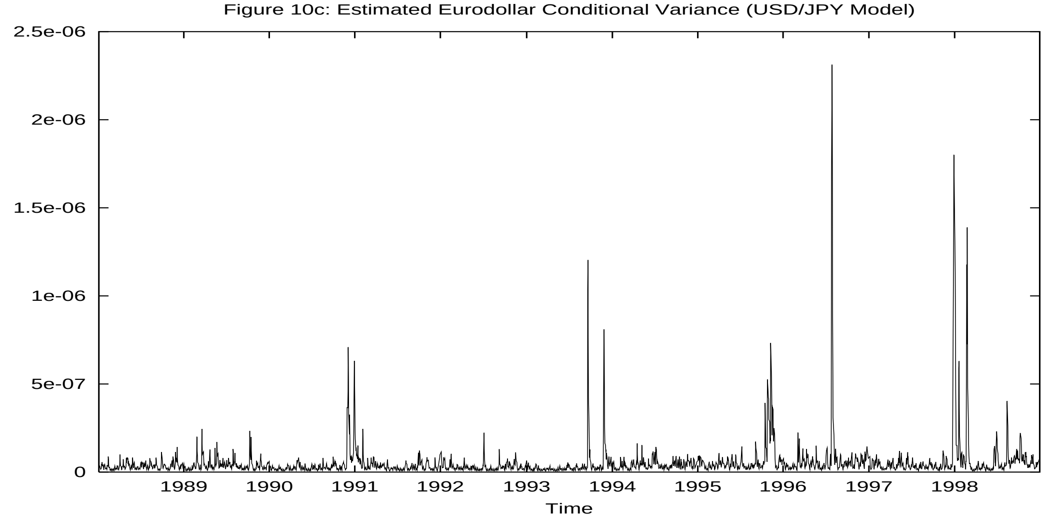


Fig. 11a: Response of USD/CAD Conditional Variance to Positive Shocks

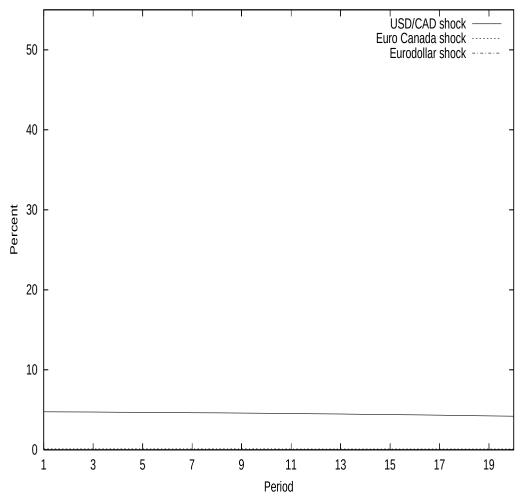


Fig. 11d: Response of USD/CAD Conditional Variance to Negative Shocks

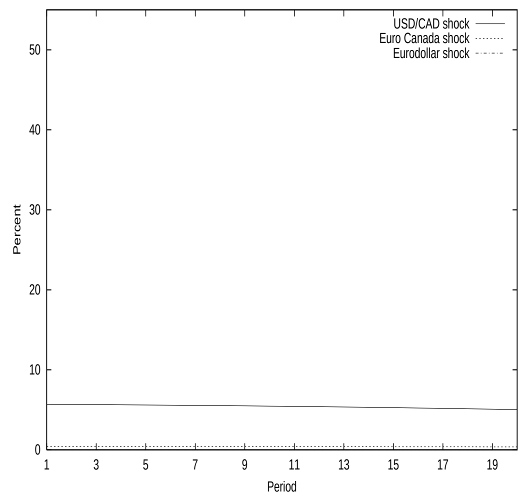


Fig. 11b: Response of Euro Canada Conditional Variance to Positive Shocks

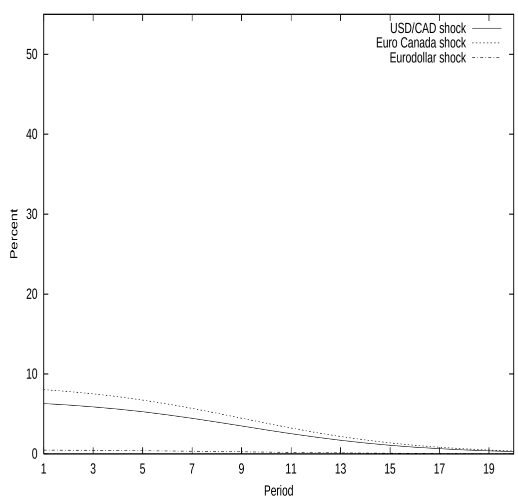


Fig. 11e: Response of Euro Canada Conditional Variance to Negative Shocks

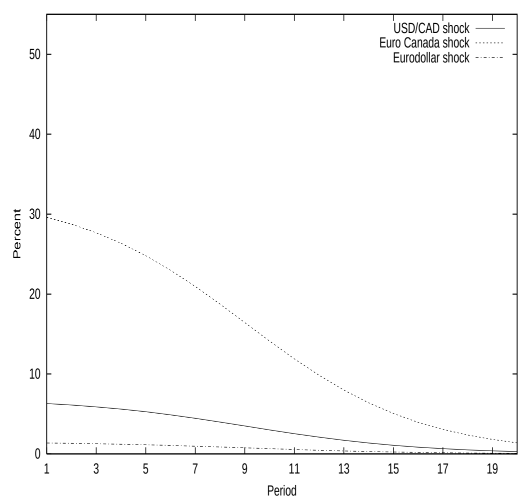


Fig. 11c: Response of Eurodollar Conditional Variance to Positive Shocks

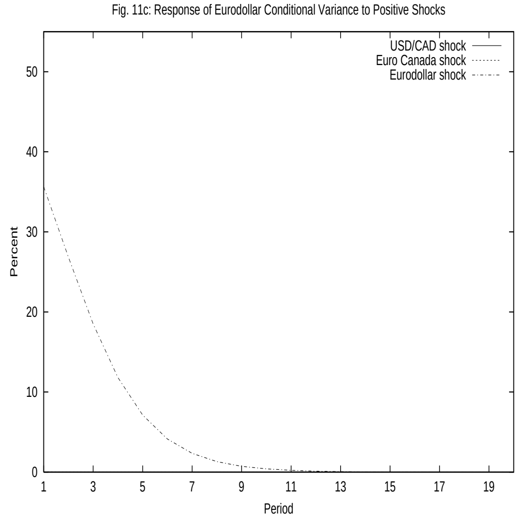


Fig. 11f: Response of Eurodollar Conditional Variance to Negative Shocks

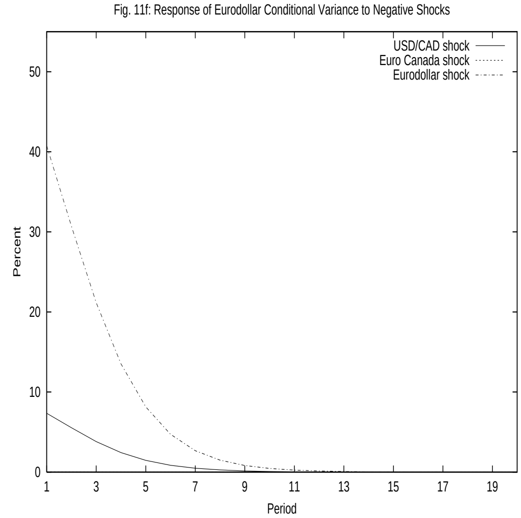


Fig. 12a: Response of USD/DEM Conditional Variance to Positive Shocks

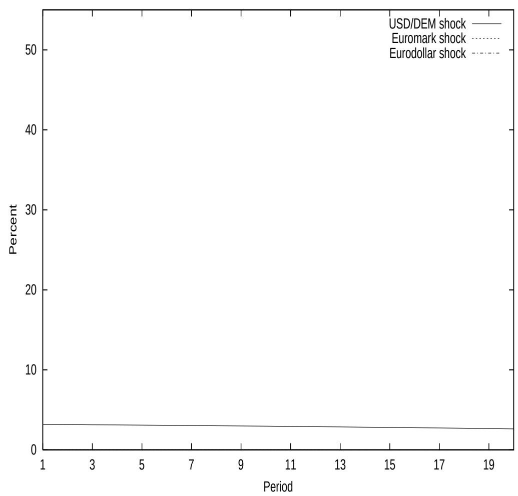


Fig. 12d: Response of USD/DEM Conditional Variance to Negative Shocks

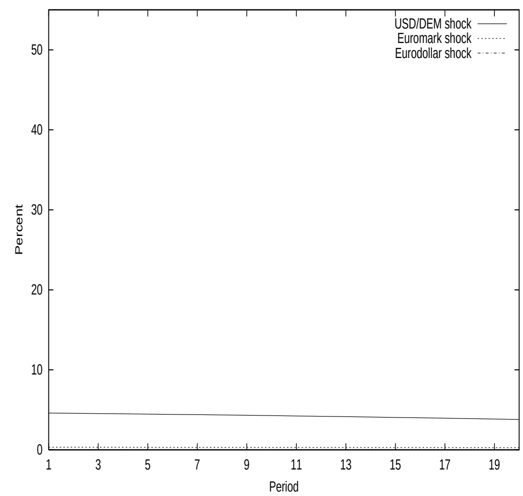


Fig. 12b: Response of Euromark Conditional Variance to Positive Shocks

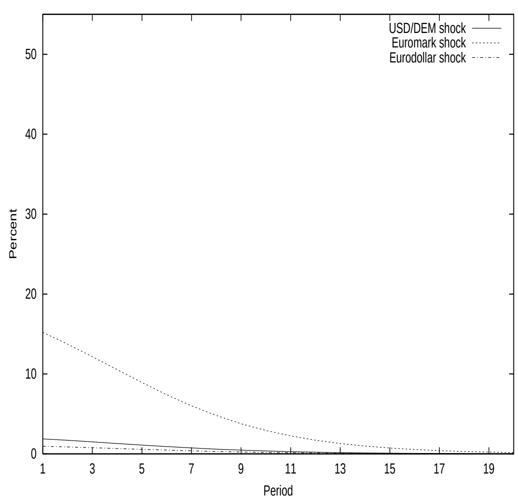


Fig. 12e: Response of Euromark Conditional Variance to Negative Shocks

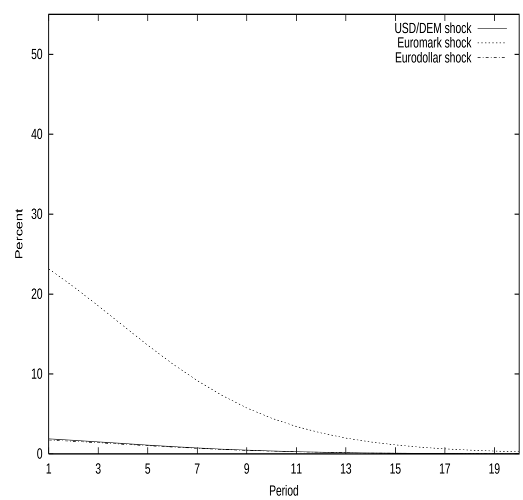


Fig. 12c: Response of Eurodollar Conditional Variance to Positive Shocks

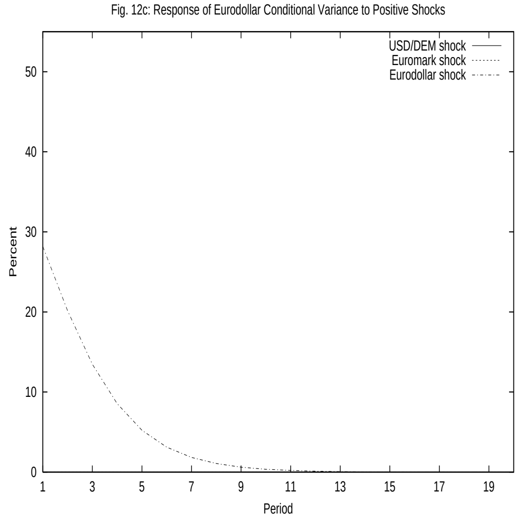


Fig. 12f: Response of Eurodollar Conditional Variance to Negative Shocks

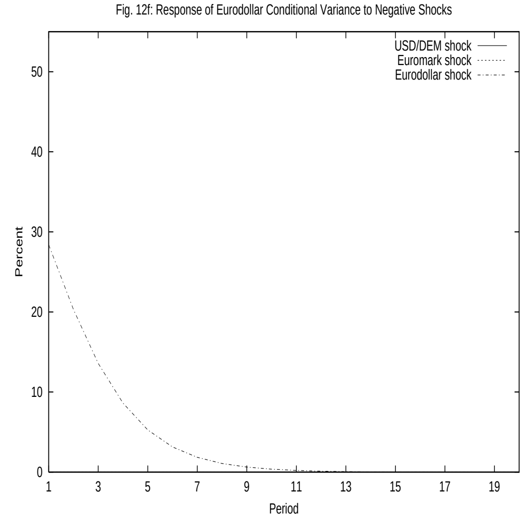


Fig. 13a: Response of USD/JPY Conditional Variance to Positive Shocks

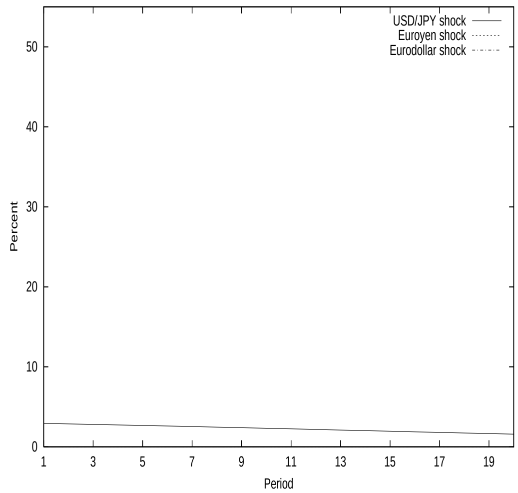


Fig. 13d: Response of USD/JPY Conditional Variance to Negative Shocks

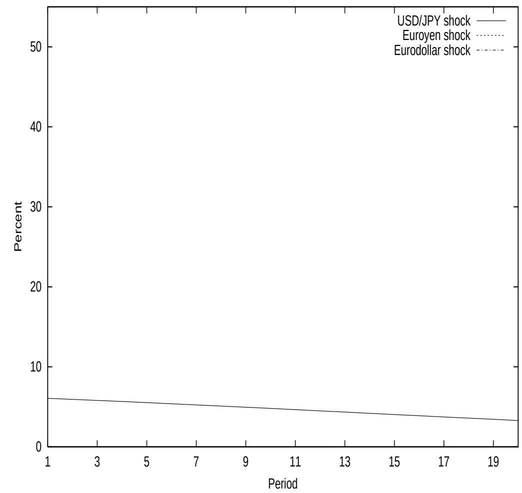


Fig. 13b: Response of Euroyen Conditional Variance to Positive Shocks

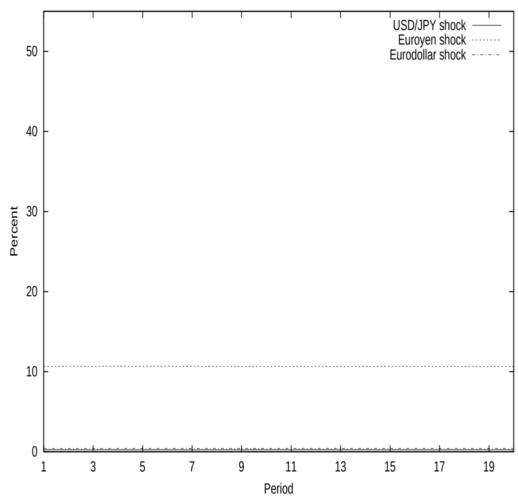


Fig. 13e: Response of Euroyen Conditional Variance to Negative Shocks

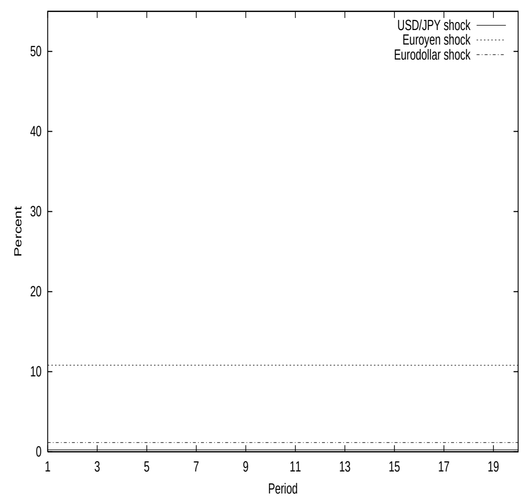


Fig. 13c: Response of Eurodollar Conditional Variance to Positive Shocks

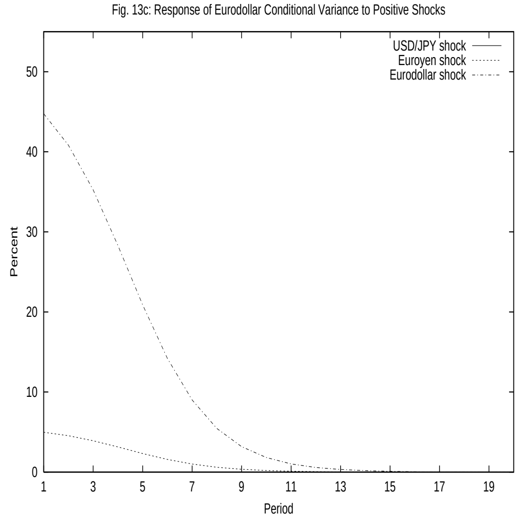
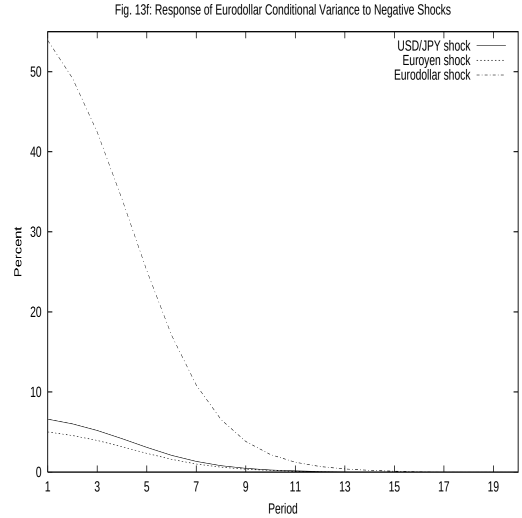


Fig. 13f: Response of Eurodollar Conditional Variance to Negative Shocks



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