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ALONG THE YIELD CURVE

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Interest Rate Transmission and Volatility Transmission along the Yield Curve

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Abstract

In order to analyse the interest rate transmission mechanism, we study daily Euro-rates term structure for the US, Germany, and the UK between 1983 and 1997. We estimate multivariate VECM-GARCH models, which take into account most of the usual features of financial data (non-stationarity, cointegration, heteroskedasticity, asymmetric effects). The estimates of these models, allows us to study interest rate transmission as well as volatility transmission along the yield curve. Due to the huge number of the parameters it is quite difficult to interpret the empirical results. To avoid this problem we use the impulse responses framework to examine the transmission mechanism along both the yield and volatility curves.

Résumé

Afin d'analyser les mécanismes de transmission sur les marchés monétaires de trois pays industrialisés (Etats-Unis, Allemagne et Royaume-Uni), nous étudions, en fréquence quotidienne, la structure par terme des euro-taux sur la période 1983-1997. Cette analyse est réalisée dans le cadre de modèles multivariés (VECM-GARCH), permettant de tenir compte des propriétés des séries financières (non-stationnarité, cointégration, hétéroscédasticité, effets de levier). Dans ce cadre, les mécanismes de transmission transitent aussi bien par les rendements que par les volatilités. Pour contourner les problèmes d'interprétation liés au nombre élevé de paramètres estimés, nous avons aussi estimé les fonctions de réponse pour évaluer l'impact d'un choc affectant un compartiment de la courbe sur les autres.

Key words: Term structure, volatility spillovers, impulse response analysis.

JEL classification: E43, G12.

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1 Introduction

An prominent literature focused on the expectations hypothesis (EH) of the term structure of interest rates. Most of this work concluded that the EH is not supported by US data (*e.g.*, Campbell and Shiller, 1991, Campbell, 1995), but it is not rejected for other countries (Hardouvelis, 1994, Gerlach and Smets, 1997). One of the reasons why the EH has been extensively studied lies in its implications in terms of transmission mechanisms. Indeed the EH states that interest rates are determined simultaneously and therefore a positive shock on the term spread —that is the spread between a long-term and a short-term rates— should result in an increase in the long-term rate as well as in the short-term rate (the latter increase being larger than the former).

As far as money markets are concerned, this point is of particular interest, since it is related to the following question: if the EH has to be rejected, which are the leading rates, the shortest-term rates (which reflect monetary policy) or the longest-term rates (which are more related to market activity)? Some work answered that the long-term rates are the leader rates in the long run (Hall et al., 1992, Engsted and Tanggaard, 1994). However causal feature in the short-run dynamics remains an opened question.

More recently, the causal links between interest rates volatilities has been questioned. Considering money market interest rates for four European countries (Germany, France, the UK, and Spain), Ayuso, Haldan and Restoy (1997) measure the effect of overnight rates on other domestic short-term rates (from 1 to 12 months) at the mean level as well as at the volatility level. However this study has two main drawbacks: first Ayuso et al. estimate univariate models and therefore they do not take into account the possible correlation between innovations associated to the different maturities. Second the causal links –from the overnight rate toward longer-term rates, without feedbacks– are imposed rather than tested.

This paper contributes to the debate about interest rate transmission and volatility transmission. Our contribution is twofold. First we estimate an econometric model that is large enough to take into account most of the statistical properties characterizing interest rates series. The cointegration links between interest rates are directly introduced by modelling the mean equation as a vector error-correcting model (VECM). The volatilities are described in a multivariate GARCH framework, in which the asymmetric behavior of the conditional variance is captured by a GJR component (Glosten, Jagannathan and Runkle, 1993).

Second we study in a multivariate framework interest rates and volatility spillovers, that is first-moment and second-moment interdependencies. We provide new evidence on the maturities which mainly contribute to interest rates and volatilities fluctuations. In particular we test whether these fluctuations mainly come from monetary policy or from market activity. The use of a multivariate GARCH model to identify the data generating process eliminates the two-step procedure, in which residuals of other maturities are previously estimated. It also improves the efficiency of the estimates and the tests for cross-maturity spillovers, avoiding problems associated with estimated regressors. Spillovers effects are introduced in the conditional volatility equation of an interest rate through the squared residuals of the other interest rates. The use of GARCH-based volatility series (rather than, *e.g.*, option-based volatility series) allows both homogenous data (volatilities are estimated in a single framework) and a large sample.

The remainder of the paper is organized as follows: Section 2 outlines the methodology adopted in the paper. In Section 3 we discuss the data and their statistical properties. In Section 4 we present the estimates of GARCH models. Section 5 deals with impulse responses analysis. Section 6 is devoted to the concluding remarks.

2 Methodology

To take into account the statistical properties of financial series (especially their non-stationarity), we use a well-known VECM framework to represent the interest rates. $r_t^{(m_i)}$ denotes the interest rate at time t for maturity m_i, $i = 1, ..., N$. $S_t^{(m_i,m_j)} = r_t^{(m_j)} - r_t^{(m_i)}$ denotes the term spread between interest rates of maturities m_j and m_i. Campbell and Shiller (1987, 1988) showed that if the short-term interest rate is difference-stationary ($I(1)$) then the expectations hypothesis implies that all the other rates are $I(1)$ and that the spreads are stationary. Most of the studies on the EH in a multivariate framework (Hall et al., 1992, Shea, 1992, Engsted and Tanggaard, 1994) found that the cointegration rank is generally $(N - 1)$ in a system of N interest rates. We have thus to take into account this property in our analysis. Therefore the dynamics of interest rates is written in a VECM framework, in which the spreads are the error-correcting terms.

It has been shown that asset returns conditional volatility is partially predictable (see, *e.g.*, Bollerslev et al., 1992, for a survey). The most popular approach of modelling volatility is the class of autoregressive conditional heteroskedasticity models (ARCH), proposed by Engle (1982) and generalized (GARCH) by Bollerslev (1986). However ARCH and GARCH models cannot capture some important features of financial data, such as asymmetric effect. More recent research explored some refinements of the approach, taking into account these empirical features.

First returns are generally asymmetric (Black, 1976, Christie, 1982, French et al., 1987, Engle and Ng, 1993). Indeed a negative shock on conditional return (bad news) is usually followed by a larger increase in volatility than a positive shock (good news). Asymmetric or leverage effects can be captured, for example, by Exponential GARCH (Nelson, 1991), Threshold GARCH (Zakoïan, 1994) or GJR (Glosten et al., 1993) models.

Second returns display interactions in terms of both first and second moments. Most of the recent literature on this topic concerns stock market indices and exchange rates. Several papers studied transmission mechanisms, that is how shocks on a market are transmitted to another one (Baillie and Bollerslev, 1990, Hamao et al., 1990, Susmel and Engle, 1994, Koutmos and Booth, 1995, Booth et al., 1997). However there is little work on volatility transmission along the term structure, except the work by Ayuso et al. (1997). They study the effect on the money market rates volatility of shocks on the overnight rate, between 1988 and 1993. They first estimate the conditional volatility of the overnight rate, using an EGARCH model. They then estimate the conditional volatility of the money market rates, using EGARCH models again, but introducing the volatility of the overnight rate estimated in the first step. However this study is a univariate one, preventing from analyzing feedbacks from market toward monetary policy. They find that volatility transmission are quite large in France and Spain, less significant in the UK, but surprisingly negative in Germany.

Our goal is to take into account both the statistical properties and the empirical features of the various markets. We therefore adopt a quite general model, allowing transmission mechanisms parameters both on conditional mean and variance. It appears that the interpretation of the empirical results —namely the meaning of the parameters— will be difficult.

So we adopt a multivariate GARCH specification, in which correlations between innovations are supposed constant over time (Bollerslev, 1990). This assumption allows to reduce dramatically the number of unknown parameters. Furthermore the correlation coefficients can be directly interpreted as measuring contemporaneous relationships between innovations of different maturities. Asymmetric effects are introduced as in the GJR model (Glosten et al., 1993): the effect on the conditional variance of the squared innovation is different whether the innovation is positive or negative.

The general VECM-GJR model with volatility spillovers is thus formulated as follows:

$$\Delta r_t^{(m_i)} = a_{i0} + \sum_{j=1}^{N} a_{ij} \Delta r_{t-1}^{(m_j)} + \sum_{j=1}^{N-1} b_{ij} S_{t-1}^{(m_j, m_{j+1})} + \varepsilon_t^{(m_i)} \qquad i = 1, ..., N \qquad (1)$$

$$\sigma_t^{(m_i)2} = \alpha_{i0} + \beta_{ii} \sigma_{t-1}^{(m_i)2} + \sum_{j=1}^{N} \alpha_{ij} \varepsilon_{t-1}^{(m_j)2} + \gamma_i \Pi_{i,t-1}^{-} \varepsilon_{t-1}^{(m_i)2} \qquad i = 1, ..., N \qquad (2)$$

$$\sigma_t^{(m_i, m_j)} = \rho^{(m_i, m_j)} \sqrt{\sigma_t^{(m_i)2} \sigma_t^{(m_j)2}} \qquad j \neq i \qquad (3)$$

where $\sigma_t^{(m_i)2} \equiv \sigma_t^{(m_i,m_i)}$ and $\sigma_t^{(m_i,m_j)}$ denote the conditional variance and the conditional covariance respectively. $\Pi_{i,t-1}^{-}$ equals 1 if $\varepsilon_{t-1}^{(m_i)} < 0$, 0 otherwise. $\varepsilon_t^{(m_i)} = \Delta r_t^{(m_i)} - E_{t-1} \Delta r_t^{(m_i)}$ is the innovation of the process and $\varepsilon_t = \left\{ \begin{array}{ccc} \varepsilon_t^{(m_1)} & \cdots & \varepsilon_t^{(m_N)} \end{array} \right\}$ is the (1xN) vector of innovations at time t. $\Sigma_t = \left\{ \sigma_t^{(m_i,m_j)} \right\}_{i,j}$ is the (N, N) time-varying conditional covariance matrix at time t, with diagonal element given by (2) and cross-diagonal element given by (3). Conditionally on the information set available at time t, the multivariate innovation ε_t is supposed to be normally distributed, with mean zero and variance-covariance matrix Σ_t.

Equation (1) describes the conditional mean for interest rates of various maturities in a VECM framework. The conditional mean of each change in rate is influenced by own past as well as by past change in other interest rates and by the lagged spreads.

The conditional variance is defined in (2) as an extended GJR model. Equation (2) simplifies to the standard GARCH model if $\gamma_i = \alpha_{ij} = 0$, $\forall i, j$, $j \neq i$. Asymmetric effects are captured by the term $\Pi_{i,t-1}^{-} \varepsilon_{t-1}^{(m_i)2}$, which allows to distinguish between positive and negative news: the impact of a positive shock on the conditional variance is α_{ii}, whereas the impact of a negative shock is $(\alpha_{ii} + \gamma_i)$. So a positive γ_i will be associated to a higher impact on the volatility of negative shocks than positive shocks.

Volatility transmissions along the yield curve are measured by α_{ij} for $i, j = 1, ..., N$, $j \neq i$. Such effects can be positive (volatility transmission, using the terminology of Ayuso et al., 1997) as well as negative (volatility transfer).

For positive conditional variance, it is sufficient that the parameters α_{i0}, β_{ii}, α_{ij} and $(\alpha_{ii} + \gamma_i)$, $\forall i, j$, are non-negative. In the general case, the multivariate Σ_t is weakly stationary if $\det(I_N - (B + A + \Gamma/2))$ has its roots outside the unit circle (see Hentschel, 1995, in the univariate case), where

$$B = \begin{bmatrix} \beta_{11} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \beta_{NN} \end{bmatrix}, \quad A = \begin{bmatrix} \alpha_{11} & \cdots & \alpha_{1N} \\ \vdots & \ddots & \vdots \\ \alpha_{N1} & \cdots & \alpha_{NN} \end{bmatrix} \quad \text{and} \quad \Gamma = \begin{bmatrix} \gamma_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \gamma_N \end{bmatrix}.$$

Equivalently, Σ_t is weakly stationary if all the eigenvalues of $(B + A + \Gamma/2)$ lie inside the unit circle. This result has been shown by Jeantheau (1998) in the case of the standard multivariate GARCH model.

The maximum likelihood estimates of the parameters are obtained numerically using the well-known Berndt et al. (1974) algorithm. The log-likelihood function can be written as:

$$L(\theta) = -\frac{1}{2} NT \ln(2\pi) - \frac{1}{2} \sum_{t=1}^{T} \left(\ln |\Sigma_t| + \varepsilon_t' \Sigma_t^{-1} \varepsilon_t \right)$$

where T is the number of observations and θ is the parameter vector to be estimated. The model presented in (1)–(3) has 66 unknown parameters (for $N = 4$). In the empirical analysis, we study at a first step a restricted, and rather uninteresting, model in which all cross maturity coefficients are set to zero (giving 28 unknown parameters). In the second step, we examine the more general model.

3 Data and Preliminary Analysis

We use daily Euro-rates at four maturities (one month, three months, six months, and one year, that is $m = \{1, 3, 6, 12\}$ in months) and for the US, Germany, and the UK. The sample covers the period January 3, 1983, to December 31, 1997 (3913 observations). The data are averages of bid and ask quotes (source: Datastream). Interest rates are expressed as continuously compounded zero-coupon rates, as recommended by McCulloch (1993) and Shea (1992). The starting point of the sample is intended to avoid the impact of the change in the monetary policy operating procedures by the Fed, which greatly disturbed the US term structure.

We do not include in the analysis overnight rates and 7-day rates, because they display for all the countries under study very marked shocks, due to currency turmoils (in the UK) or monetary operating procedures (in the US or in Germany). The 1-month rate is therefore considered as the main indicator of the monetary policy. Figure 1 displays the various interest rates series.

Table 1 presents some summary statistics on changes in Euro-rates over the period studied. The Ljung-Box statistics (LB), computed for the changes in returns, show that the null hypothesis of no correlation up to 20 lags is systematically rejected for all maturities and all countries. However, when the LB statistics are corrected to take into account the possible heteroskedasticity (LB_c), then the null hypothesis is almost never rejected, except for the 6-month US rate and for the 6-month and the 12-month German rates. The LB statistics for the squared changes in returns (LB_2) and the LM test statistics indicate that the null hypothesis of homoskedasticity is always clearly rejected.

Lastly the empirical skewness and the excess kurtosis clearly indicate that all series are not normally distributed. Indeed the series can be positively or negatively skewed, but all of them are heavy tailed with respect to the normal distribution. The excess kurtosis can be as high as 54.

4 Empirical Results

4.1 The Restricted Models

In order to simplify the estimates analysis, we first set to zero all cross-maturity coefficients in model (1)–(3). Thus the model is reduced to the following univariate AR-GJR models, for $i = 1, ..., N$:

$$\Delta r_t^{(m_i)} = a_{i0} + a_{ii}\Delta r_{t-1}^{(m_i)} + \varepsilon_t^{(m_i)} \tag{4}$$

$$\sigma_t^{(m_i)2} = \alpha_{i0} + \beta_{ii}\sigma_{t-1}^{(m_i)2} + \alpha_{ii}\varepsilon_{t-1}^{(m_i)2} + \gamma_i \Pi_{i,t-1}^{-}\varepsilon_{t-1}^{(m_i)2} \tag{5}$$

$$\rho^{(m_i,m_j)} = 0 \qquad j \neq i \tag{6}$$

where equation (5) is the usual GJR volatility specification.

The estimates of these restricted models are reported in Table 2. As far as the conditional mean equation is concerned, the autoregressive parameter a_{ii} is always negative, except for the 6-month French rate, in which case it is positive, but not significantly different from zero. This indicates that the root of the autoregressive process may be close to, but less than, one. The parameters are clearly less than one in Germany.

Concerning the conditional variance equation, the autoregressive component of the variance β_{ii} is large, but less than one. It is typically between 0.70 and 0.95. The impact of the squared innovation (measured by α_{ii}) is always positive and significantly different from zero. In particular, it is large (between 0.20 and 0.36) for the UK, and for the 1-month US rate ($\alpha_{ii} = 0.52$).

The necessary stationarity condition for volatilities ($\beta_{ii} + \alpha_{ii} + \gamma_i/2 < 1$) does not hold only for the US 1-month rate. Moreover the overall stationarity condition is not met for the US data.

The asymmetric effects (measured by γ_i) are surprisingly negative and significant for most of the maturities. So a positive innovation (an increase in the interest rate) will have a greater impact on volatility than a negative shock. These effects are very large for the 1-month rates, since the asymmetric effects are of the same magnitude (with opposite sign) than α_{ii}. This indicates that a negative shock on interest rate has basically no impact on volatility. This result is quite counterintuitive and could be explained by our assumption concerning the nullity of cross-maturity coefficients.

The test of the homoskedasticity hypothesis ($\beta_{ii} = \alpha_{ii} = \gamma_i = 0$, $\forall i$) is based on the likelihood ratio statistics (Table 3). For all countries we clearly reject the null hypothesis, the test statistics ranging from 2961 for the UK to 4435 for the US.

In most cases, LB statistics for residuals and squared residuals allow to reject both the serial correlation and heteroskedasticity hypotheses. Therefore except for the asymmetric effect, the ARCH specification appears to be well suited for the analysis of the term structure.

4.2 The Unrestricted Models

We turn now to the unrestricted models. Table 4 reports the estimates of these models, which correspond to equations (1)–(3).

4.2.1 The US

By reference to the impact of the changes in the euro-rates (or namely if we neglect the spread effects), it is worth noting that the 3-month and the 12-month rates have a leading role (i.e. all short-term rates are significantly influenced by the change in 3-month and 12-month rates on the US market) in the conditional mean equation. They have important effects on the other maturities. However, the 3-month rate is the only rate to affect significantly the 1-month rate. Conversely, the 1-month rate has no important effect on the other maturities.

Error-correcting terms are almost all significant and, in each equation, at least one error-correcting term is significant. The most significant terms are those which enter the 3-month equation ((1-3)-month and (3-6)-month spreads). So even if it has no effect in the short run, the 1-month rate is able to influence the yield curve in the long run.

As far as conditional volatility equations are concerned, the second part of Table 5 indicates eigenvalues of the matrix $(B + A + \Gamma/2)$. One notes that the global stationarity condition (that is, each eigenvalue of $(B + A + \Gamma/2)$ is less than 1) is satisfied. Asymmetric effects are quite large, especially for the shortest maturities: for the 1-month rate, α_{ii} and γ_i are very close in absolute value (0.188 and -0.182 respectively); this indicates that a positive shock of 100 basis points implies an increase in the volatility of the 1-month rate by 18.8 bp, whereas a negative shock of 100 bp implies an increase in the volatility of the 1-month rate by only 0.6 bp.

Concerning the volatility transmission mechanisms, the 3-month rate appears as the common causal variable of the four volatility equations. The 3-month rate seems to be a leader on the euro-dollar market, since it is the only one to have a significant impact on the 1-month rate.

Lastly we find a slight worsening of the statistical properties of residuals compared to the restricted model: residuals for maturities 3-month, 6-month and 12-month are serially correlated and residuals associated to the 12-month rate are heretoskedastic.

4.2.2 Germany

The conditional mean equations for German rates show a leading role of the 1-month and the 12-month rates. However, contrary to the US case, the (1-3)-month spread has a significant effect on the dynamics of the 1-month rate, but no effect on the dynamics of the 3-month rate; this indicates that the 3-month rate plays an important role in the long run.

Conditional volatilities are globally stationary. Asymmetric effects are never significant, so that a positive shock and a negative shock have basically the same impact on volatilities.

Moreover transmission mechanisms are very small. This point has been already highlighted by Ayuso et al. (1997), which found no significant effect of the overnight rate toward money market rates.

As for the US rates, the statistical properties of the residuals show a serial correlation and a residual heteroskedasticity for long maturities.

4.2.3 The UK

The transmission mechanisms between interest rates are abundant for the UK. First of all, the 1-month rate has a major impact on the other maturities. On the contrary, the 1-month rate is only influenced by the 3-month rate, but with a negative effect (-0.062). Lastly, the 12-month rate has a large effect on the 3-month and the 6-month rate, but it depends on no error-correcting term. Thus it can be considered as non-neutral in the long run.

Stationarity conditions for the volatility processes are satisfied. Asymmetric effects are all negative: the higher the maturity, the more significant the effect. Transmission mechanisms mainly come from the 6-month volatility, which has a large effect on the 1-month volatility. Once again, the 3-month volatility has a surprising negative effect on the 1-month rate. According to the definition by Ayuso et al. (1997), we observe a volatility transfer (rather than a volatility transmission) from the 3-month rate toward the 1-month rate. However, it appears quite difficult to find an economic explanation to this result.

The likelihood ratio test statistics to test the joint nullity of all cross-maturity parameters are highly significant (*i.e.*, the restricted versus the unrestricted models). The test statistics range from 4525 for Germany to 5233 for the UK.

Figure 2 shows the volatilities estimated using the unrestricted models. In all countries, the higher the maturity, the smaller the volatility, except for some very short period of time (*e.g.*, in 1985 in Germany). The volatilities look stationary, although in the US they seem to decrease over time.

This approach allows us to detect on each market the interest rate which has the most significant impact on the other ones. However, due to the large number of estimated parameters, interpreting parameter estimates appears quite difficult. From this point of view, studying transmission mechanisms in a VECM-GARCH framework using Granger-like causality is a failure. We therefore adopt in the following an alternative approach in which we are interested in the shocks transmission mechanisms only. This approach is based on the impulse response functions.

5 Impulse Response Analysis

A common tool for investigating the dynamics of variables in a linear, stationary system is the impulse response methodology proposed by Sims (1980) and developed by Doan et al. (1984). Impulse response analysis allows to examine the effect on the system of a small innovation shock. Lütkepohl and Reimers (1992) showed that this tool is also valuable for analyzing cointegrated systems. Similarly Engle et al. (1990) studied the effect of a squared innovation shock on subsequent volatility.

Since interest rates are highly correlated, it is necessary to orthogonalize the residuals before the impulse response analysis. However the standard approach — the Choleski decomposition— is largely arbitrary, since the results are affected by the reordering of the variables in the system. We thus consider an alternative approach recently proposed by Koop et al. (1996), the Generalized Impulse Responses (GIR).

The purpose of this section is twofold. First we study the effect on interest rates of a shock in the innovations of the system. This analysis allows to precise the transmission mechanisms between interest rates along the yield curve. Since the conditional mean equations are specified as a VECM, we adopt the methodology developed by Lütkepohl and Reimers (1992). Second we analyze the effect on volatility of a shock in the squared innovations, following the approach of Engle et al. (1990).

5.1 Impulse Responses of Interest Rates

The profiles of impulse responses of interest rates to an innovation shock are independent of the volatility dynamics (once parameters are estimated). Thus we focus on the conditional mean equations which are described with a VECM framework with $p-1$ lags:

$$A(L)\Delta r_t = \mu + BS_{t-1} + \varepsilon_t.$$

As shown in Lütkepohl and Reimers (1992), this representation can be rewritten as a VAR in level with p lags:

$$\Phi(L) r_t = \mu + \varepsilon_t \tag{7}$$

with some constraints on $\Phi(L)$.

Using this formulation, we compute the impulse responses —or dynamic multipliers—, as in the stationary case, as follows:

$$C(s) = \left[c_k^{(m_i)}(s)\right]_{i=1,\dots,N} = \sum_{j=1}^{s} C(s-j)\Phi_j \qquad s = 1, 2, \dots$$

with $C(0) = I_N$ and $c_k^{(m_i)}(s)$ denotes the response of variable $r_t^{(m_i)}$ to a unit shock in variable m_k, s periods ago.

When the (non-conditional) covariance matrix of residuals, Ω, is not diagonal, residuals are orthogonalized, using the triangular Choleski decomposition of Ω, that is $PP' = \Omega$ (Sims, 1981). In this case, the orthogonalized impulses are defined as:

$$Q(s) = \left[q_k^{(m_i)}(s)\right]_{i=1,\dots,N} = C(s)P \qquad s = 1, 2, \dots$$

where $q_k^{(m_i)}(s)$ denotes the response of variable $r_t^{(m_i)}$ to a one standard deviation impulse in variable m_k, s periods ago.

One important drawback of this approach is that orthogonalized impulses are affected by reordering of the variables in r_t. Koop et al. (1996) proposed an interesting alternative, in which the generalized impulse responses (GIR) are defined as:

$$\Theta(s) = \left[\theta_k^{(m_i)}(s)\right]_{i=1,\dots,N} \quad \text{where} \quad \theta_k^{(m_i)}(s) = C_s \eta_i e_k / \sigma_{ii} \qquad s = 1, 2, \dots \tag{8}$$

where e_k is the selection vector with its kth element equal to unity and zeros elsewhere; $\sigma_{ii}^2 = E\left(\varepsilon_{it}^2\right)$ and $\eta_i = E\left(\varepsilon_t \varepsilon_{it}\right)$ are respectively the (non-conditional) variance of ε_{it} and the (non-conditional) covariance between ε_t and ε_{it}.

These impulse responses take into account the dependence between the different shocks and reduce to the usual orthogonalized impulse responses $\Theta(s)$ only when the covariance matrix is diagonal. But contrary to the usual orthogonalized impulse responses, the GIR are unique and are not dependent on the reordering of the variables.[1]

The first part of Table 5 indicates eigenvalues of the long-term matrix $\Phi(1)$ defined in equation (7). The largest eigenvalue is, by definition, equal to unity, since the systems have only one common stochastic trend. The second largest eigenvalue is near unity (between 0.989 and 0.994). This indicates that, although we have concluded to

[1] The standard accumulated impulse responses are not considered here, since, as pointed out by Lütkepohl and Reimers (1992), they usually diverge to infinity for $s \to \infty$ in the non-stationary case.

three cointegration relationships, the whole long-run dynamics of the systems should be described by more than one common trend. The two last eigenvalues are less than one (between 0.85 and 0.90 for the third one and between 0.65 and 0.75 for the last one).

Table 6 allows to measure the impact on the system of a shock on a given rate. We study various types of impulse responses: impulse responses based on the canonical innovations, on orthogonalized innovations (using the Choleski decomposition, the series being ordered by maturity) and on GIR proposed by Koop et al. (1996), which are independent of the ordering of the series.

First of all, impulse responses based on canonical innovations are not suited to measure causal links in our systems. This can be seen considering the impact of a 100 bp shock on the 3-month US rate. Its final impact is a decrease by 60 bp of all interest rates. This result is clearly related to the fact that it does not take account of the correlation between innovations, whereas these correlations are very large for each country (between 0.4 and 0.8 depending on the maturities). We obtain the same kind of result for the 1-month and the 3-month German rates and for the 1-month UK rate.

Let's turn now to the two other types of impulse responses, which take explicitly account of the correlation between innovations. The main difference between the two approaches is rather easy to understand. The Choleski decomposition implies that we take account of all the correlations for the first shock, of all the correlations except those concerning the first series for the second shock, and so on. However, the correlation between the 1-month rate and the 3-month rate is very large (greater than 0.6). This implies to relatively low final impacts for shocks on the 3-month rates. For example, in the US, a 63 bp shock on the 3-month rate leads to an increase of the yield curve by only 28 bp.

On the contrary, the approach developed by Koop et al. (1996) works in the following way: each maturity is successively at the first place of the system, when one measures the impact of this maturity on the system. So, for each maturity, all the instantaneous correlations are taken into account, giving more 'natural' results: a 81 bp shock on the 3-month US rate implies an increase by 45 bp of the whole yield curve in the long run. The approach of Koop et al. (1996) allows to measure more precisely the relative impact of the various maturities on the yield curve. It does not bias the interpretation of the results. The difference between the orthogonalized impulse responses and the GIR is especially noticeable for the 12-month German rate and UK rate. If we use the Choleski decomposition, we obtain a final response of the system of respectively 84% and 81% of the initial shock on the 12-month rate. If we use the GIR, we obtain a final response of the system of respectively 98% and 108% of the initial shock.

Figure 3 shows impulse responses of interest rates for the GIR approach. For each figure, the impulse responses to a shock on the 1-month, 3-month, 6-month and 12-month maturity interest rates are plotted in graphs a to d respectively. The vertical axis represents the response of interest rates to an initial shock of one standard error on the interest rate of the maturity considered. The horizontal axis represents the days elapsed from the day of the shock.

As far as the GIR are concerned, one major conclusion should be noted: whatever the market, the 12-month rate has the largest impact on the system. Indeed, if one expresses the final impact as a percentage of the initial shock, one finds that for all countries the relative effect on the system increase with the maturity. This is particularly clear-cut for Germany: the 1-month rate has a final impact of 13% of the initial shock, whereas the 12-month rate has a final impact of 98%.

5.2 Impulse Responses of Volatility

In their study on the transmission mechanisms between stock markets, Engle et al. (1990) propose a methodology to measure effects on the volatilities of a shock on the return of a specific market. We adapt this approach to the GJR model. We define $\sigma_t^2 = \left(\sigma_t^{(m_1)2} \ \cdots \ \sigma_t^{(m_N)2} \right)'$ the vector of the conditional variance and $\eta_t = \left(\varepsilon_t^{(m_1)2} \ \cdots \ \varepsilon_t^{(m_N)2} \right)'$ the vector of the squared daily innovations derived from the equations presented previously. Equation (2) can thus be written as:

$$\sigma_{t+1}^2 = \alpha_0 + B\sigma_t^2 + A\eta_t + \Gamma\Pi_t^- \eta_t$$

where B, A and Γ have been already defined and

$$\Pi_t^- = \begin{bmatrix} \Pi_{1t}^- & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \Pi_{Nt}^- \end{bmatrix} \quad \text{and} \quad \alpha_0 = \begin{bmatrix} \alpha_{10} \\ \vdots \\ \alpha_{N0} \end{bmatrix}.$$

Taking expectations conditional to information available at time t, we obtain for a horizon $s \geq 2$:

$$E_t\left(\sigma_{t+s}^2\right) = \alpha_0 + BE_t\left(\sigma_{t+s-1}^2\right) + \left(A + \Gamma\Pi_{t+s-1}^-\right) E_t\left(\eta_{t+s-1}\right)$$

or, if one defines $\sigma_{t+s/t}^2 = E_t\left(\sigma_{t+s}^2\right)$:

$$\sigma_{t+s/t}^2 = \alpha_0 + \left(B + A + \Gamma\Pi_{t+s-1}^-\right) \sigma_{t+s-1/t}.$$

If the conditional variance process is stationary, then the non-conditional variance is given by $\sigma^2 = \lim_{s\to\infty} \sigma_{t+s/t}^2 = \left(I_N - B - A - \Gamma/2\right)^{-1} \alpha_0$.

Following Engle et al. (1990), we define the impulse response of daily volatility of maturity m_i to the squared innovation of maturity m_k as:

$$\psi_k^{(m_i)}(s) = \frac{\partial\sigma_{t+s/kt}^{(m_i)2}}{\partial\varepsilon_t^{(m_k)2}} \qquad i, k = 1, ..., N, s = 0, 1, ...$$

which is obtained recursively by solving the following relation:

$$\Psi_k(s) = \left[\psi_k^{(m_i)}(s)\right]_{i=1,...,N} = \left(B + A + \Gamma/2\right) \Psi_k(s-1) \qquad s = 2, 3, ... \tag{9}$$

For a stationary process, one has $\lim_{s\to\infty} \Psi_k(s) = 0$.

As for impulse responses of interest rate, we consider GIR of volatility based on

$$\tilde{\Xi}(s) = \left[\tilde{\xi}_k^{(m_i)}(s)\right]_{i=1,...,N} \quad \text{where} \quad \tilde{\xi}_k^{(m_i)}(s) = \psi_k^{(m_i)}(s)\frac{\tilde{\omega}_{ik}}{\sqrt{\tilde{\omega}_{ii}}} \qquad s = 1, 2, ... \tag{10}$$

where $\tilde{\Omega} = \left(\tilde{\omega}_{ik}\right)_{ij}$ is the (non-conditional) covariance matrix of $\left\{\varepsilon_t^2\right\}$.

The second part of Table 5 indicates eigenvalues of the matrix $(B + A + \Gamma/2)$ defined in equation (9). The first eigenvalue is general quite large (greater than 0.98 except for the UK). This shows that shocks may have transitory, but long-lasting effect.

Table 7 shows impulse responses in daily volatilities. Figure 4 displays the generalized impulse responses to a shock on the 1-month, 3-month, 6-month and 12-month maturity volatilities are plotted in graphs a to d respectively. The vertical axis represents the response of volatilities to an initial shock of one standard error on the volatility of the maturity considered. The horizontal axis represents the days elapsed from the day of the shock.

At a first glance, for each graph, the impulse responses exhibit short-run dynamics and die out after 100 days. The graphs allow to identify more precisely leader rates in terms of volatility. So a shock on a 'leader rate' should have a large and significant effect on the volatility of the other maturities. For example, in the case of the US, it is clear that shocks on the volatility of the 1-month, 6-month and 12-month rates have very low impact on other volatilities. Conversely, a shock on the 3-month rate volatility has a large effect on the volatility of other maturities, especially on the 1-month rate volatility.

The main causal variable in term of volatility is the 3-month rate in the US, in Germany and, to a lesser extent, in the UK. It is interesting to compare Germany and the UK. German volatilities display large persistence but small volatility spillovers. Conversely, the UK volatilities show very low persistence, since the impulse responses curves die out after only 20 to 30 days; but after a shock on the 6-month rate volatility they display significant spillovers: a increase by 10% in the 6-month volatility implies an transitory increase by 6% in the 1-month volatility after 10 days. This difference between German and UK volatilities can be seen in the eigenvalues of $(B + A + \Gamma/2)$. Indeed one notes that all eigenvalues are less than 1, since volatility processes are all stationary. But the German eigenvalues are all near 1 (between 0.98 and 0.91), whereas the UK eigenvalues are lower (between 0.94 and 0.79).

These results confirm the estimates of volatility spillovers parameters concerning the relative importance of volatility transmissions. It appears clearly that the 1-month rate volatility —which reflects the monetary policy the more accurately— has no impact on other volatilities. On the contrary, in all the countries, the 1-month volatility is the most impacted volatility by other volatility shocks.

6 Conclusion

In this paper, we study the interactions between the maturities of a same yield curve, at the conditional mean level as well as at the conditional volatility level. First of all, we obtain the usual statistical properties of interest rates at a daily frequency: returns independence, but heteroskedasticity and non-normality. These properties lead us to study the yield curve as multivariate GARCH models, which allow the volatility to vary over time. The representation adopted takes account of the mains characteristics of interest rates: non-stationarity and cointegration at the conditional mean level; heteroskedasticity, asymmetric effect and volatility transmissions at the conditional volatility level. The estimates give some empirical evidence: taking into account of the transmission mechanisms between interest rates and between volatilities markedly improve the estimation. Moreover these estimates show the crucial role of the 1-month rate in Germany and in the UK; of the 3-month and the 12-month rate in the US. The results are however difficult to interpret, because of the large number of parameters, and, more precisely, of the large number of significant parameters.

To solve this problem, we analyze the impulse responses of the yield curves to shocks on interest rates. We consider successively the impulse responses of interest rates and of volatilities after a shock on the innovation process. This impulse response analysis gives a slightly different interpretation as compared to the GARCH estimates: the impulse responses show that the yield curves are mostly lead by the 12-month rate at the conditional mean level, and by the 3-month rate at the conditional volatility level. The special role plaid by the 3-month rate in terms of volatility transmission mechanisms may be due to its use as underlying asset for futures and options contracts. The information flow may be transmitted from the futures and options markets to the spot euro-market through the 3-month maturity.

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Table 1: Summary statistics of daily changes in interest rates

The Table gives summary statistics on the changes in interest rates: σ denotes the standard deviation; LB denotes the Ljung-Box statistic associated to the null hypothesis of no serial correlation (up to 20 lags) of the change in rate; LB_c is the Ljung-Box statistic corrected for heterosckedasticity; LB_2 is the Ljung-Box statistic associated to the null hypothesis of no serial correlation (up to 20 lags) of the squared change in rate; LM is the TR^2 statistic associated to the null hypothesis of no ARCH effect (up to 20 lags). These four statistics are distributed as a χ^2 with 20 degrees of freedom. SK et EK denote the skewness and the excess kurtosis; under the null $SK/\sqrt{6/T}$ and $EK/\sqrt{24/T}$ are approximately distributed as a χ^2 with 1 degree of freedom.

country	σ	No serial correlation				Homoskedasticity				Normality			
maturity	(x1000)	LB		LB_c		LB_2		LM		SK		EK	
The US													
1-month	0.994	123.3	^{a}	24.1		267.9	^{a}	203.8	^{a}	0.10	^{b}	53.81	^{a}
3-month	0.775	51.4	^{a}	26.2		442.7	^{a}	218.5	^{a}	−0.53	^{a}	11.78	^{a}
6-month	0.801	43.5	^{a}	33.5	^{b}	257.9	^{a}	273.4	^{a}	−0.59	^{a}	14.19	^{a}
12-month	0.900	78.8	^{a}	30.7	^{c}	497.3	^{a}	428.8	^{a}	0.08	^{b}	17.46	^{a}
Germany													
1-month	0.845	105.7	^{a}	29.6	^{c}	422.5	^{a}	272.7	^{a}	−0.31	^{a}	18.85	^{a}
3-month	0.692	92.2	^{a}	30.5	^{c}	659.1	^{a}	446.8	^{a}	0.04		9.14	^{a}
6-month	0.688	140.6	^{a}	40.8	^{a}	688.4	^{a}	548.0	^{a}	−0.29	^{a}	12.84	^{a}
12-month	0.631	77.8	^{a}	47.1	^{a}	234.8	^{a}	193.9	^{a}	−0.28	^{a}	8.91	^{a}
The UK													
1-month	1.175	67.8	^{a}	21.4		496.7	^{a}	458.4	^{a}	2.65	^{a}	44.66	^{a}
3-month	1.067	81.8	^{a}	21.5		975.5	^{a}	709.9	^{a}	1.11	^{a}	35.76	^{a}
6-month	1.108	71.3	^{a}	19.2		1032.2	^{a}	563.6	^{a}	0.09	^{b}	22.62	^{a}
12-month	0.990	35.0	^{b}	16.0		507.5	^{a}	298.2	^{a}	−0.32	^{a}	18.47	^{a}

Table 2: Estimates of restricted univariate GARCH models

Standard errors in parentheses. SC denotes the stationarity condition $(\beta_{ii}+\alpha_{ii}+\gamma_i/2)$, and in parentheses, the global stationarity condition $\prod_{i=1}^{N}(\beta_{ii}+\alpha_{ii}+\gamma_i/2)$. It has to be less than 1 for the system to be globally stable. $LB(n)$ and $LB^2(n)$ are the Ljung-Box statistics for residuals and squared residuals respectively, distributed as χ^2 with n degrees of freedom.

	1-month		3-month		6-month		12-month	
The US								
a_{i0} (x100)	-0.037	(0.100)	0.011	(0.137)	-0.021	(0.184)	-0.147	(0.167)
a_{ii}	-0.064	(0.011)	-0.071	(0.020)	-0.049	(0.020)	-0.072	(0.021)
α_{i0} (x1000)	0.312	(0.011)	0.065	(0.006)	0.118	(0.011)	0.259	(0.019)
β_{ii}	0.761	(0.003)	0.924	(0.004)	0.939	(0.005)	0.884	(0.006)
α_{ii}	0.516	(0.011)	0.090	(0.006)	0.064	(0.005)	0.101	(0.008)
γ_i	-0.369	(0.015)	-0.044	(0.006)	-0.041	(0.005)	-0.028	(0.009)
SC: 1.020	1.093		0.992		0.983		0.957	
$LB(20)$	19.270	(0.504)	32.971	(0.034)	40.927	(0.004)	34.543	(0.023)
$LB_2(20)$	3.457	(0.999)	23.682	(0.257)	17.094	(0.647)	43.262	(0.002)
Germany								
a_{i0} (x100)	-0.004	(0.128)	-0.026	(0.126)	-0.047	(0.124)	-0.121	(0.116)
a_{ii}	-0.178	(0.018)	-0.142	(0.019)	-0.141	(0.017)	-0.111	(0.018)
α_{i0} (x1000)	0.156	(0.010)	0.157	(0.014)	0.086	(0.006)	0.181	(0.010)
β_{ii}	0.894	(0.003)	0.871	(0.007)	0.916	(0.002)	0.889	(0.004)
α_{ii}	0.130	(0.005)	0.118	(0.010)	0.080	(0.005)	0.072	(0.004)
γ_i	-0.080	(0.006)	-0.032	(0.012)	-0.023	(0.007)	-0.011	(0.007)
SC: 0.902	0.984		0.973		0.985		0.956	
$LB(20)$	25.887	(0.170)	24.110	(0.238)	32.581	(0.038)	46.113	(0.001)
$LB_2(20)$	13.319	(0.863)	12.155	(0.911)	31.644	(0.047)	31.752	(0.046)
The UK								
a_{i0} (x100)	-0.179	(0.163)	-0.001	(0.178)	0.080	(0.180)	0.084	(0.161)
a_{ii}	-0.091	(0.016)	-0.059	(0.023)	-0.018	(0.023)	-0.010	(0.023)
α_{i0} (x1000)	1.311	(0.039)	0.812	(0.042)	0.428	(0.031)	0.461	(0.034)
β_{ii}	0.705	(0.007)	0.740	(0.010)	0.817	(0.007)	0.787	(0.009)
α_{ii}	0.355	(0.020)	0.292	(0.022)	0.204	(0.014)	0.220	(0.016)
γ_i	-0.191	(0.024)	-0.163	(0.024)	-0.070	(0.019)	-0.076	(0.020)
SC: 0.877	0.965		0.951		0.986		0.969	
$LB(20)$	13.440	(0.858)	28.133	(0.106)	15.395	(0.753)	22.486	(0.315)
$LB_2(20)$	3.148	(0.999)	1.997	(0.999)	2.556	(0.999)	15.777	(0.730)

Table 3: Log-likelihood and likelihood ratio test

The first part of the Table indicates log-likelihood for various specifications of the model. The second part reports likelihood ratio test statistics for the null hypothesis of constant volatility and for restricted models. The degrees of freedom are in parentheses.

	The US	**Germany**	**The UK**
(1) constant volatility	4.137	4.943	3.217
(2) restricted model	4.691	5.343	3.974
(3) unrestricted model	5.845	6.182	5.312
(2)/(1): $\chi^2(16)$	4434.7	4227.5	2960.6
(3)/(2): $\chi^2(32)$	4873.1	4525.1	5232.9

Table 4: Estimates of unrestricted GARCH models

Standard errors in parentheses. $LB\,(n)$ and $LB^2\,(n)$ are the Ljung-Box statistics for residuals and squared residuals respectively distributed as χ^2 with n degrees of freedom.

The US	1-month		3-month		6-month		12-month	
a_{i0} (x100)	-0.382	(0.094)	-0.298	(0.081)	-0.701	(0.103)	-0.265	(0.121)
a_{i1} (1-month)	-0.201	(0.017)	0.034	(0.014)	0.045	(0.019)	0.024	(0.016)
a_{i2} (3-month)	0.126	(0.024)	-0.121	(0.019)	0.091	(0.020)	0.144	(0.023)
a_{i3} (6-month)	0.013	(0.020)	0.007	(0.017)	-0.182	(0.019)	0.124	(0.024)
a_{i4} (12-month)	0.029	(0.013)	0.071	(0.012)	0.066	(0.016)	-0.250	(0.019)
b_{i1} (3-1 m.)	-0.033	(0.007)	-0.172	(0.005)	-0.083	(0.007)	-0.059	(0.009)
b_{i2} (6-3 m.)	0.075	(0.010)	0.172	(0.006)	-0.035	(0.009)	0.078	(0.011)
b_{i3} (12-6 m.)	-0.006	(0.007)	-0.007	(0.004)	0.088	(0.006)	-0.018	(0.007)
α_{i0} (x1000)	0.098	(0.008)	0.133	(0.008)	0.148	(0.011)	0.256	(0.014)
β_{i1}	0.813	(0.003)	0.874	(0.004)	0.895	(0.005)	0.867	(0.005)
α_{i1} (1-month)	0.188	(0.006)	0.001	(0.002)	0.019	(0.001)	0.001	(0.001)
α_{i2} (3-month)	0.131	(0.005)	0.105	(0.007)	0.011	(0.003)	0.011	(0.003)
α_{i3} (6-month)	-0.002	(0.002)	0.017	(0.002)	0.063	(0.004)	0.032	(0.004)
α_{i4} (12-month)	-0.001	(0.001)	0.004	(0.002)	0.010	(0.002)	0.081	(0.006)
γ_i	-0.182	(0.007)	-0.072	(0.007)	-0.058	(0.005)	-0.032	(0.007)
ρ_{i1} (1-month)	—		0.642	(0.008)	0.542	(0.010)	0.477	(0.011)
ρ_{i2} (3-month)	—		—		0.748	(0.005)	0.624	(0.008)
ρ_{i3} (6-month)	—		—		—		0.687	(0.006)
$LB\,(20)$	25.598	(0.180)	294.664	(0.000)	117.054	(0.000)	54.824	(0.000)
$LB_2\,(20)$	17.735	(0.605)	12.726	(0.889)	13.808	(0.840)	45.288	(0.001)

Germany	1-month		3-month		6-month		12-month	
a_{i0} (x100)	-0.162	(0.097)	0.027	(0.090)	0.050	(0.090)	-0.162	(0.093)
a_{i1} (1-month)	-0.187	(0.020)	0.093	(0.015)	0.095	(0.014)	0.057	(0.014)
a_{i2} (3-month)	0.008	(0.023)	-0.228	(0.020)	0.049	(0.019)	0.089	(0.019)
a_{i3} (6-month)	0.092	(0.022)	-0.030	(0.021)	-0.241	(0.019)	0.062	(0.019)
a_{i4} (12-month)	0.061	(0.022)	0.081	(0.020)	0.06	(0.018)	-0.239	(0.019)
b_{i1} (3-1 m.)	0.137	(0.006)	-0.025	(0.007)	0.022	(0.007)	0.014	(0.006)
b_{i2} (6-3 m.)	-0.038	(0.007)	0.102	(0.007)	-0.037	(0.009)	0.046	(0.009)
b_{i3} (12-6 m.)	-0.025	(0.005)	-0.040	(0.006)	0.027	(0.006)	-0.037	(0.006)
α_{i0} (x1000)	0.133	(0.011)	0.122	(0.014)	0.064	(0.005)	0.182	(0.009)
β_{i1}	0.877	(0.005)	0.866	(0.008)	0.928	(0.002)	0.880	(0.005)
α_{i1} (1-month)	0.094	(0.005)	0.011	(0.002)	0.001	(0.001)	0.002	(0.001)
α_{i2} (3-month)	0.014	(0.004)	0.054	(0.006)	0.002	(0.002)	0.006	(0.002)
α_{i3} (6-month)	0.003	(0.002)	0.008	(0.003)	0.054	(0.004)	0.007	(0.002)
α_{i4} (12-month)	0.004	(0.003)	0.033	(0.003)	0.005	(0.002)	0.053	(0.003)
γ_i	0.001	(0.007)	0.006	(0.009)	-0.008	(0.004)	0.003	(0.006)
ρ_{i1} (1-month)	—		0.603	(0.007)	0.459	(0.010)	0.400	(0.011)
ρ_{i2} (3-month)	—		—		0.643	(0.006)	0.511	(0.010)
ρ_{i3} (6-month)	—		—		—		0.609	(0.007)
$LB\,(20)$	24.782	(0.210)	35.785	(0.016)	46.595	(0.001)	43.638	(0.002)
$LB_2\,(20)$	18.072	(0.583)	17.001	(0.653)	33.861	(0.027)	33.538	(0.029)

The UK	1-month		3-month		6-month		12-month	
a_{i0} (x100)	-0.630	(0.148)	-0.048	(0.129)	-0.586	(0.130)	-0.276	(0.132)
a_{i1} (1-month)	-0.057	(0.020)	0.147	(0.015)	0.126	(0.014)	0.057	(0.015)
a_{i2} (3-month)	-0.062	(0.026)	-0.289	(0.023)	-0.039	(0.023)	-0.003	(0.026)
a_{i3} (6-month)	0.031	(0.031)	0.072	(0.024)	-0.128	(0.024)	0.162	(0.026)
a_{i4} (12-month)	0.036	(0.026)	0.148	(0.019)	0.142	(0.019)	-0.161	(0.022)
b_{i1} (3-1 m.)	0.140	(0.009)	-0.027	(0.008)	0.054	(0.008)	0.016	(0.009)
b_{i2} (6-3 m.)	-0.089	(0.016)	0.069	(0.013)	-0.132	(0.013)	-0.005	(0.014)
b_{i3} (12-6 m.)	0.002	(0.008)	-0.024	(0.006)	0.063	(0.006)	-0.005	(0.006)
α_{i0} (x1000)	0.657	(0.023)	0.532	(0.026)	0.636	(0.028)	1.005	(0.057)
β_{i1}	0.764	(0.007)	0.779	(0.007)	0.807	(0.006)	0.694	(0.011)
α_{i1} (1-month)	0.133	(0.009)	0.025	(0.004)	0.004	(0.003)	0.004	(0.002)
α_{i2} (3-month)	-0.062	(0.006)	0.060	(0.010)	0.018	(0.007)	0.034	(0.008)
α_{i3} (6-month)	0.164	(0.007)	0.095	(0.007)	0.151	(0.009)	0.050	(0.010)
α_{i4} (12-month)	-0.020	(0.005)	-0.008	(0.004)	-0.003	(0.005)	0.112	(0.014)
γ_i	0.006	(0.012)	-0.026	(0.011)	-0.059	(0.009)	-0.041	(0.016)
ρ_{i1} (1-month)	—		0.668	(0.005)	0.511	(0.009)	0.445	(0.011)
ρ_{i2} (3-month)	—		—		0.786	(0.004)	0.682	(0.007)
ρ_{i3} (6-month)	—		—		—		0.757	(0.005)
$LB\,(20)$	18.932	(0.526)	19.051	(0.519)	34.493	(0.023)	19.901	(0.464)
$LB_2\,(20)$	2.678	(0.999)	1.456	(0.999)	1.519	(0.999)	8.914	(0.984)

Table 5: Eigenvalues associated the conditional mean equations and to the conditional variance equations

Eigenvalues associated to the conditional mean equations are eigenvalues of $\Phi(1)$ defined in equation (7). Eigenvalues associated to the conditional variance equations are eigenvalues of $(B + A + \Gamma/2)$ defined in equation (9).

	Conditional mean equation				Conditional variance equation			
	λ_1	λ_2	λ_3	λ_4	λ_1	λ_2	λ_3	λ_4
The US	1.000	0.989	0.865	0.694	0.981	0.934	0.899	0.899
Germany	1.000	0.991	0.895	0.750	0.981	0.973	0.939	0.911
The UK	1.000	0.994	0.908	0.664	0.947	0.852	0.852	0.789

Table 6: Initial shocks and final impacts, associated to impulse responses - conditional mean equations

The Table indicates the initial responses and the final impacts of the conditional mean to a shock on a given innovation. The first part of the Table is associated to canonical innovations (non-orthogonalized); the second part to the orthogonalized innovations (using the Choleski decomposition); the last part to the GIR (Koop et al., 1996). In the last two cases, initial shocks have been normalized, such that the shock on the first maturity is equal to unity. For orthogonalized innovations and GIR, the values of σ_{11} are 0.099, 0.083 and 0.160 for the US, Germany and the UK respectively.

	The US					**Germany**				
	Initial shocks				Final impact	Initial shocks				Final impact
Canonical innovations	1	0	0	0	0.091	1	0	0	0	-0.226
	0	1	0	0	-0.587	0	1	0	0	-0.246
	0	0	1	0	0.237	0	0	1	0	0.595
	0	0	0	1	1.321	0	0	0	1	0.845
Orthogon. innovations	1	0.502	0.413	0.363	0.374	1	0.503	0.378	0.305	0.132
	0	0.633	0.467	0.409	0.279	0	0.633	0.368	0.264	0.287
	0	0	0.529	0.277	0.491	0	0	0.603	0.267	0.585
	0	0	0	0.644	0.850	0	0	0	0.577	0.487
GIR	1	0.502	0.413	0.363	0.374	1	0.503	0.378	0.305	0.132
	0.621	0.808	0.622	0.546	0.451	0.622	0.809	0.523	0.396	0.307
	0.505	0.615	0.817	0.596	0.666	0.471	0.528	0.801	0.466	0.634
	0.409	0.497	0.548	0.889	1.050	0.405	0.426	0.496	0.753	0.735

	The UK				
	Initial shocks				Final impact
Canonical innovations	1	0	0	0	-0.150
	0	1	0	0	0.231
	0	0	1	0	0.203
	0	0	0	1	0.805
Orthogon. innovations	1	0.638	0.502	0.406	0.426
	0	0.642	0.559	0.441	0.617
	0	0	0.565	0.307	0.362
	0	0	0	0.509	0.410
GIR	1	0.638	0.502	0.406	0.426
	0.705	0.905	0.750	0.598	0.737
	0.534	0.722	0.940	0.664	0.812
	0.481	0.641	0.739	0.844	0.909

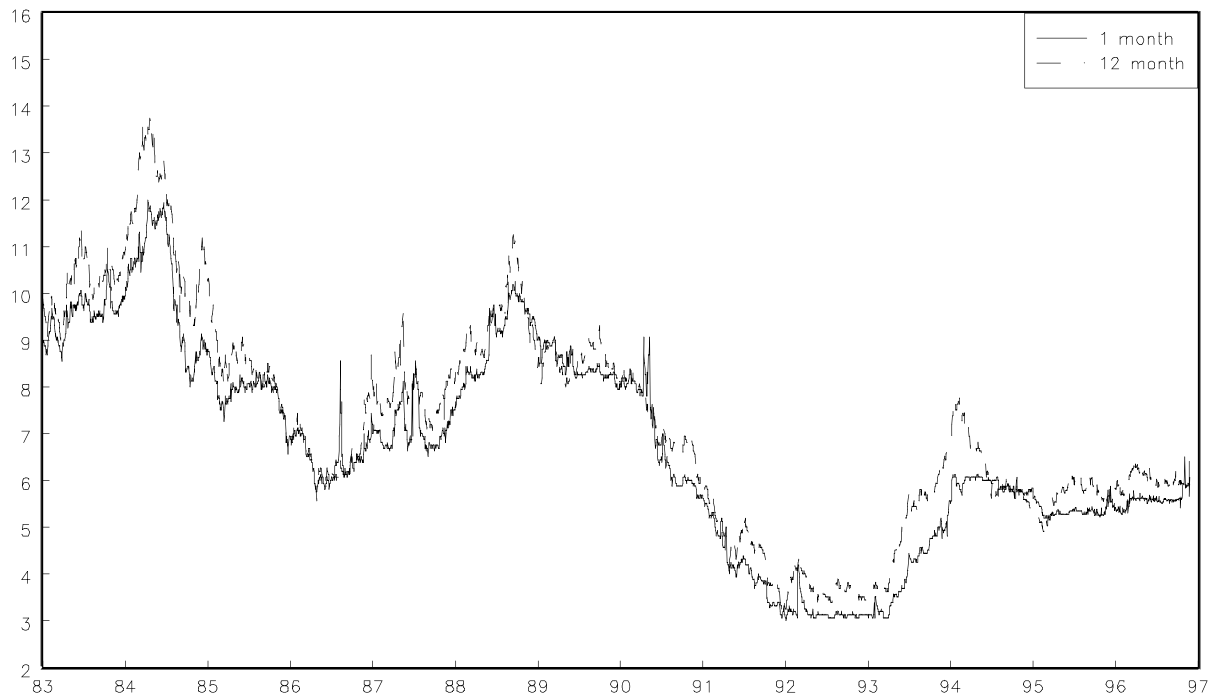
Table 7: Initial shocks, associated to impulse responses - conditional variance equations

The Table indicates the initial responses of the conditional mean to a shock on a given innovation (the final impacts are zero by construction). The first part of the Table is associated to canonical innovations (non-orthogonalized); the second part to the orthogonalized innovations (using the Choleski decomposition); the last part to the GIR (Koop et al., 1996). In the last two cases, initial shocks have been normalized, such that the shock on the first maturity is equal to unity. For orthogonalized innovations and GIR, the values of σ_{11} are 0.072, 0.031 and 0.094 for the US, Germany and the UK respectively.

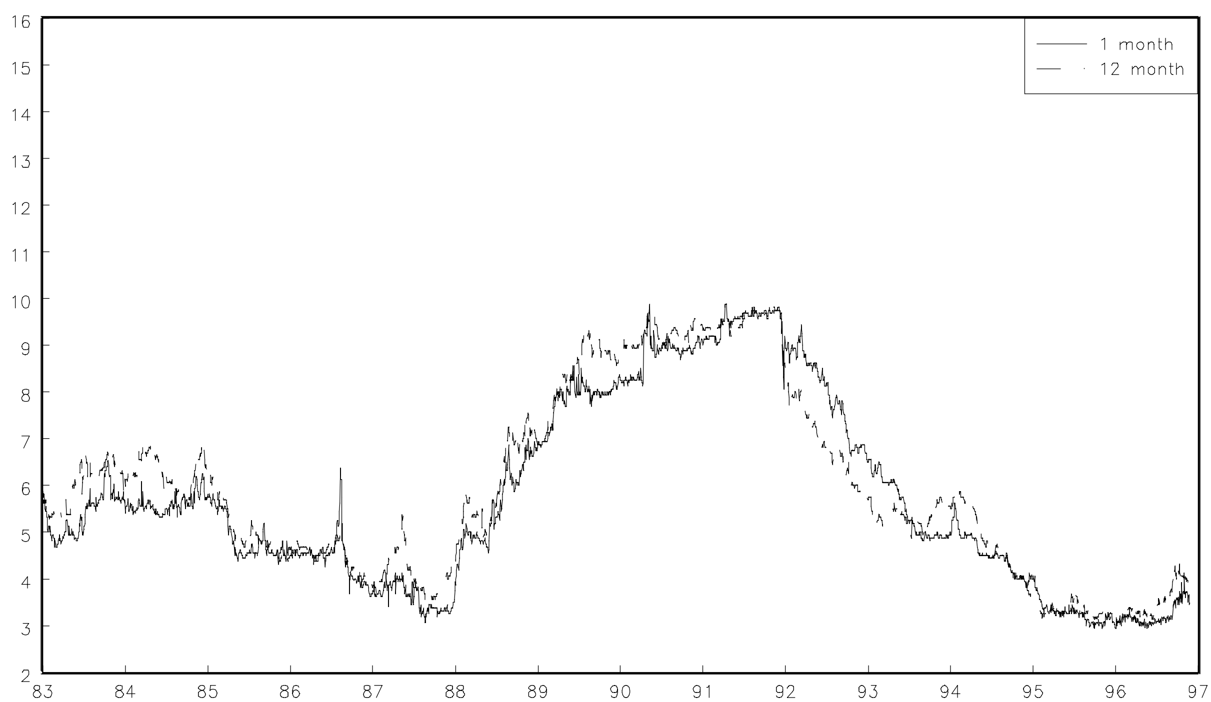
	The US				**Germany**			
Canonical	1	0	0	0	1	0	0	0
innovations	0	1	0	0	0	1	0	0
	0	0	1	0	0	0	1	0
	0	0	0	1	0	0	0	1
Orthogon.	1	0.133	0.049	0.025	1	0.209	0.144	0.090
innovations	0	0.265	0.175	0.146	0	0.412	0.251	0.113
	0	0	0.264	0.131	0	0	0.452	0.142
	0	0	0	0.356	0	0	0	0.375
GIR	1	0.133	0.049	0.025	1	0.209	0.144	0.090
	0.450	0.296	0.178	0.141	0.453	0.462	0.289	0.142
	0.152	0.164	0.320	0.191	0.268	0.248	0.537	0.197
	0.062	0.103	0.151	0.407	0.212	0.154	0.248	0.426

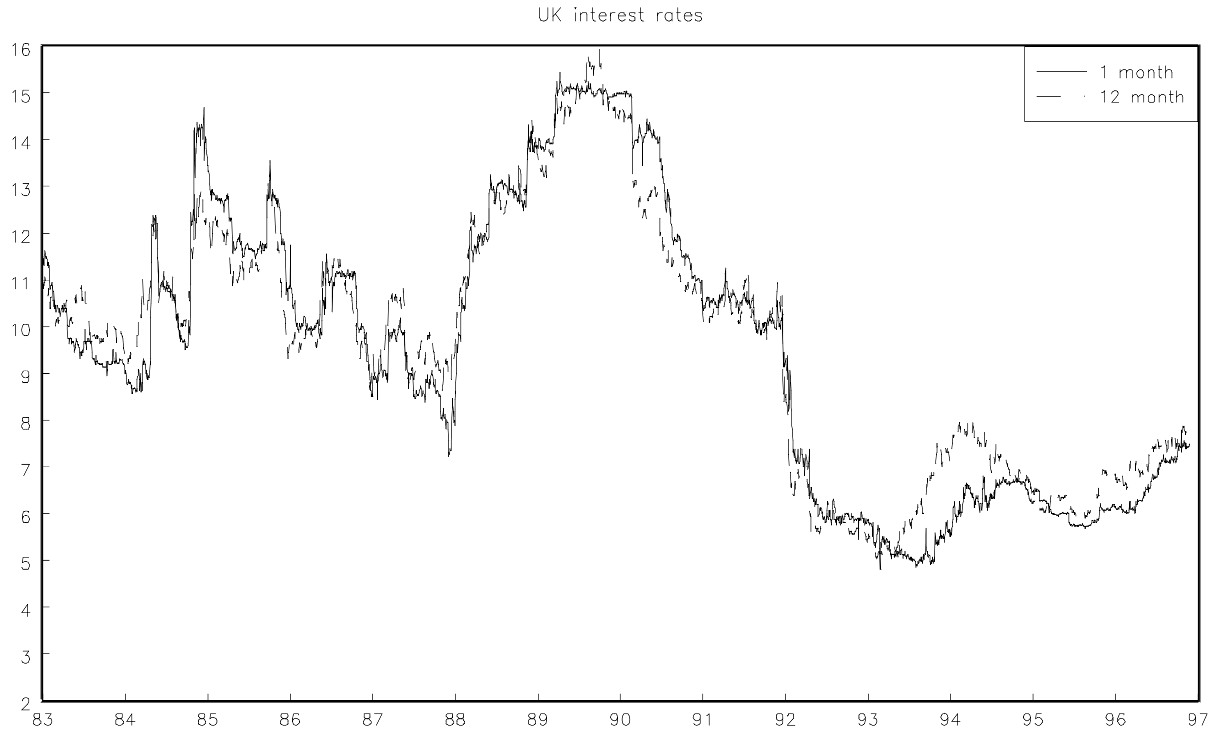
	The UK			
Canonical	1	0	0	0
innovations	0	1	0	0
	0	0	1	0
	0	0	0	1
Orthogon.	1	0.636	0.423	0.232
innovations	0	0.376	0.360	0.226
	0	0	0.284	0.156
	0	0	0	0.276
GIR	1	0.636	0.423	0.232
	0.861	0.739	0.547	0.315
	0.678	0.648	0.624	0.359
	0.512	0.513	0.494	0.454

US interest rates



German interest rates




UK interest rates
1 month
12 month
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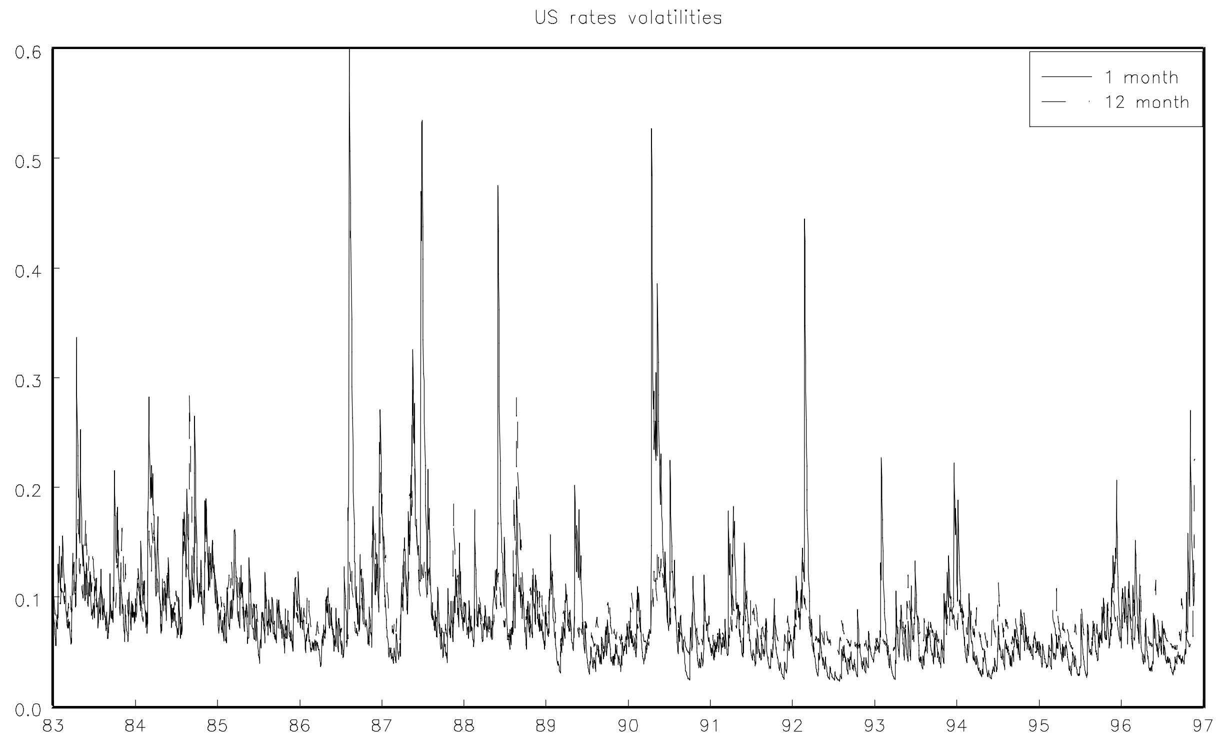
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12 month
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0.5
0.4
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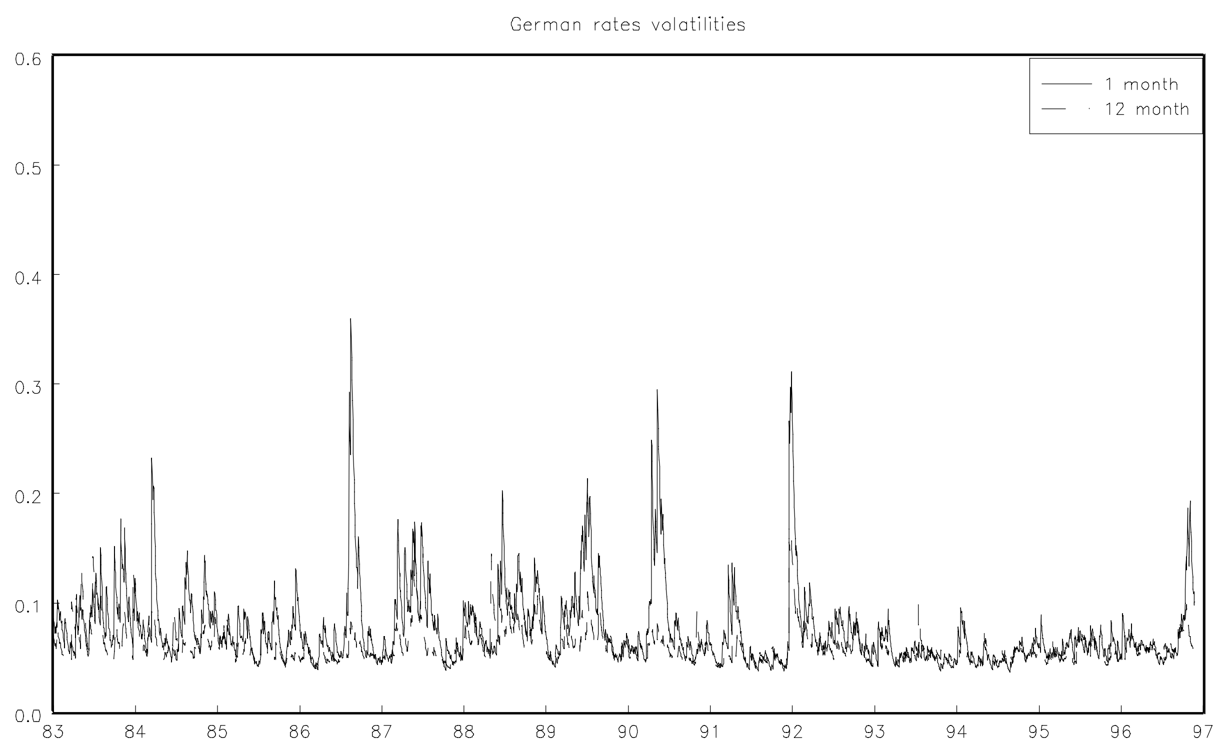
German rates volatilities
1 month
12 month
0.6
0.5
0.4
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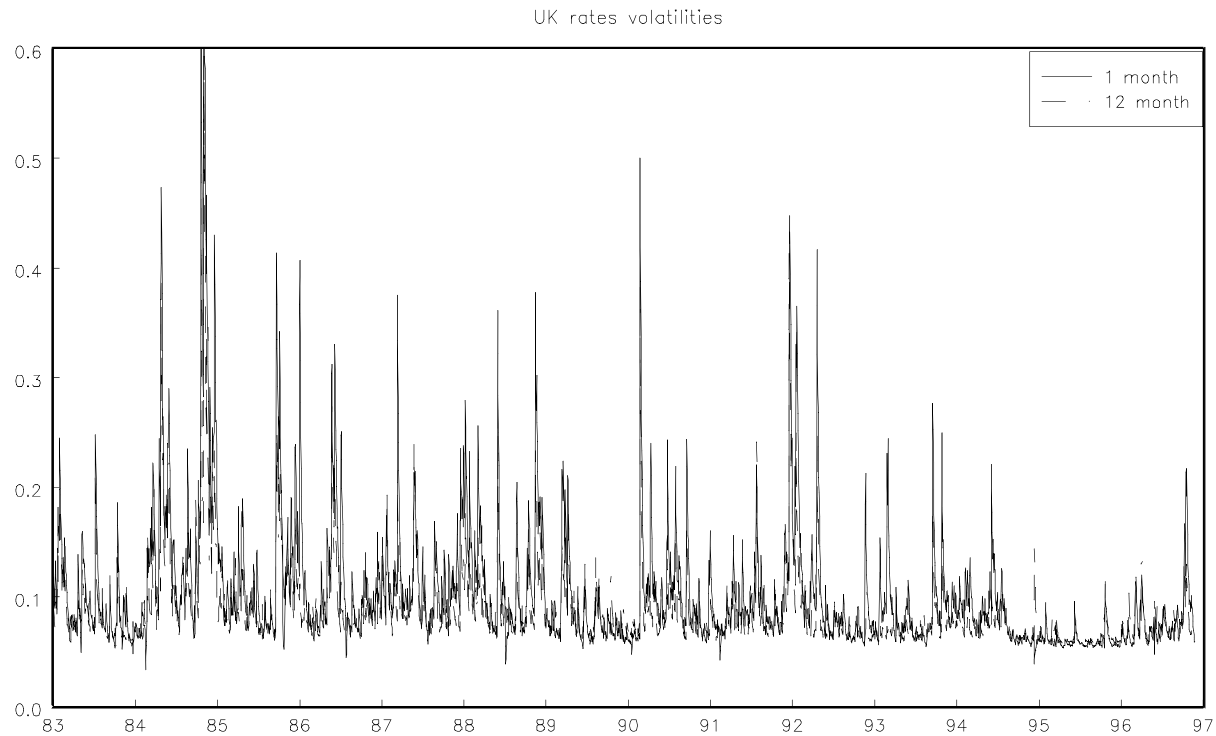
UK rates volatilities
1 month
12 month
0.6
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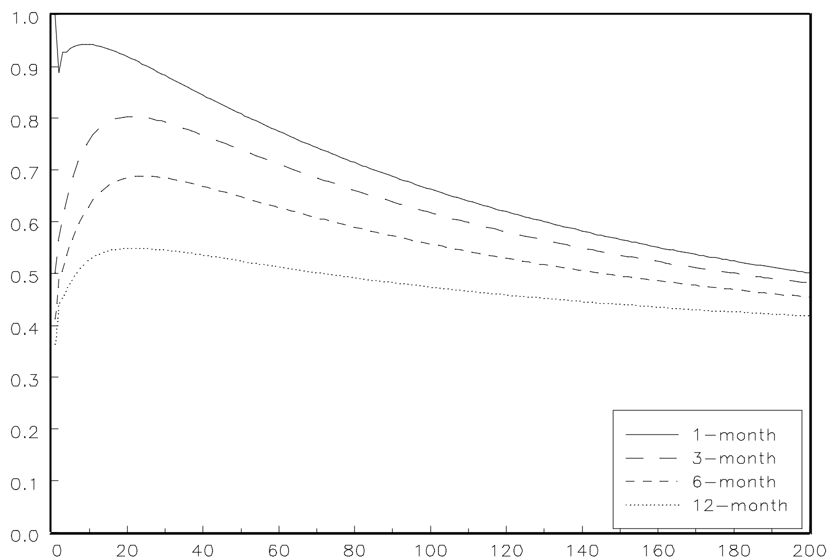
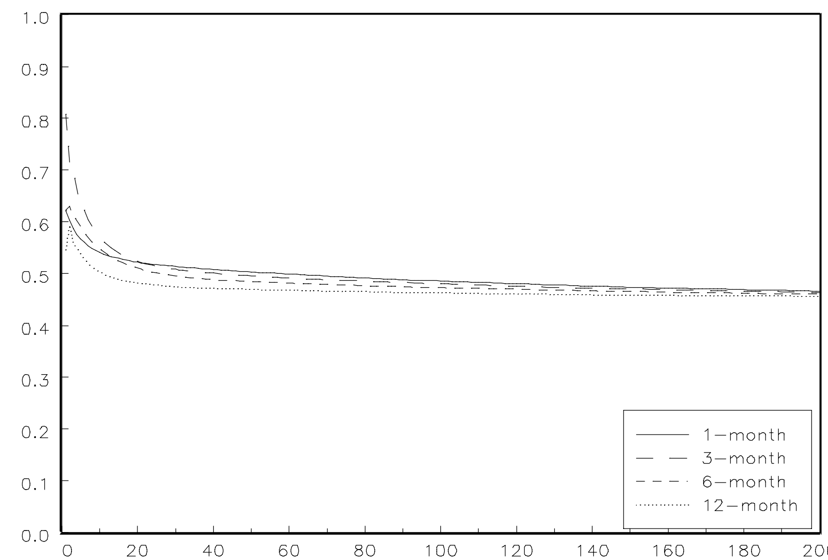
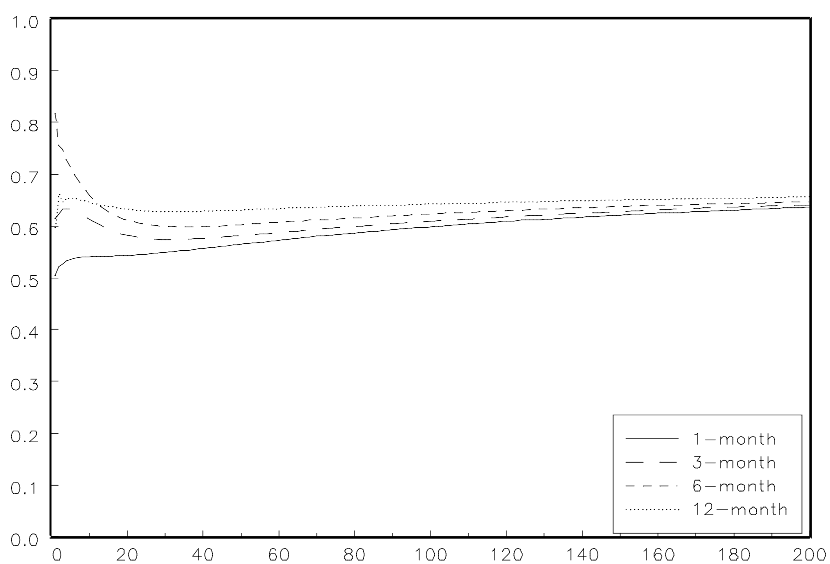
The US: response to an impulse on the 1-month rate



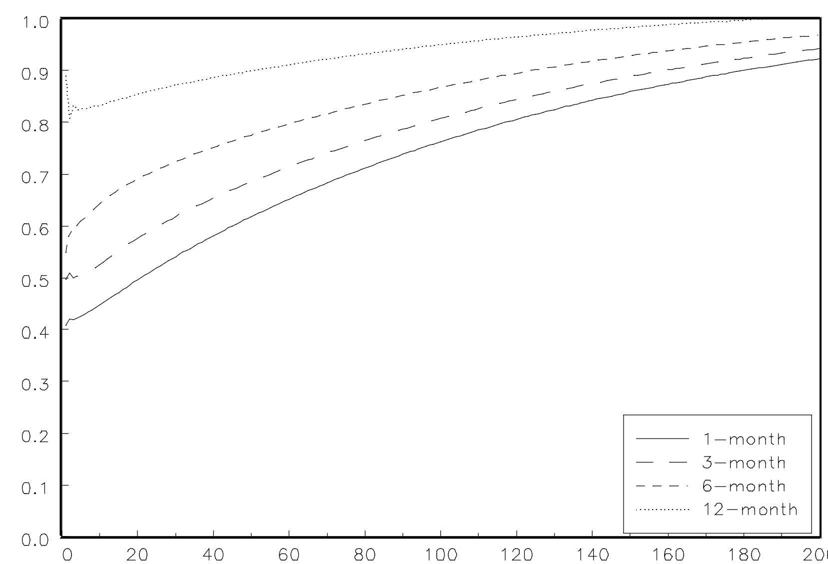
The US: response to an impulse on the 3-month rate



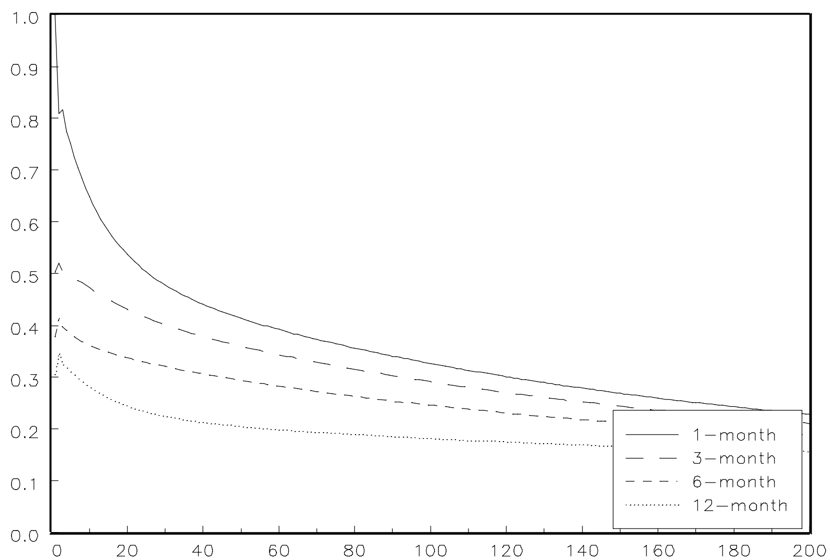
The US: response to an impulse on the 6-month rate



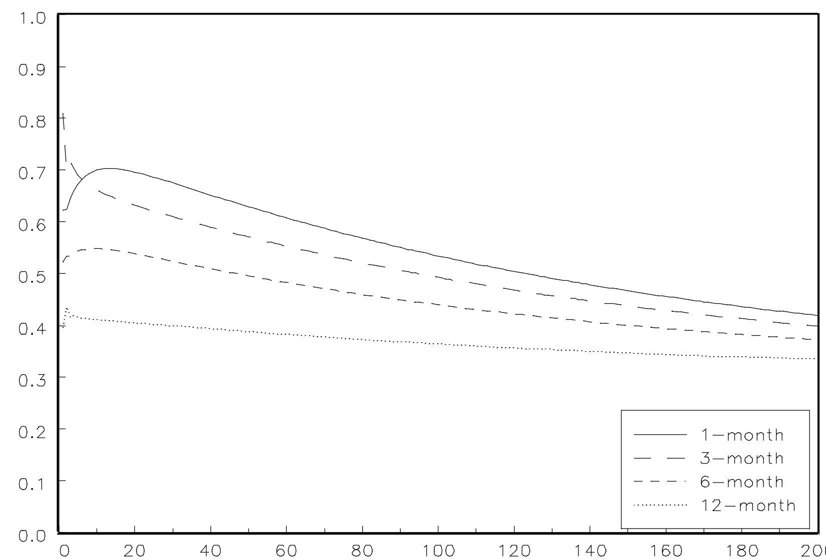
The US: response to an impulse on the 12-month rate



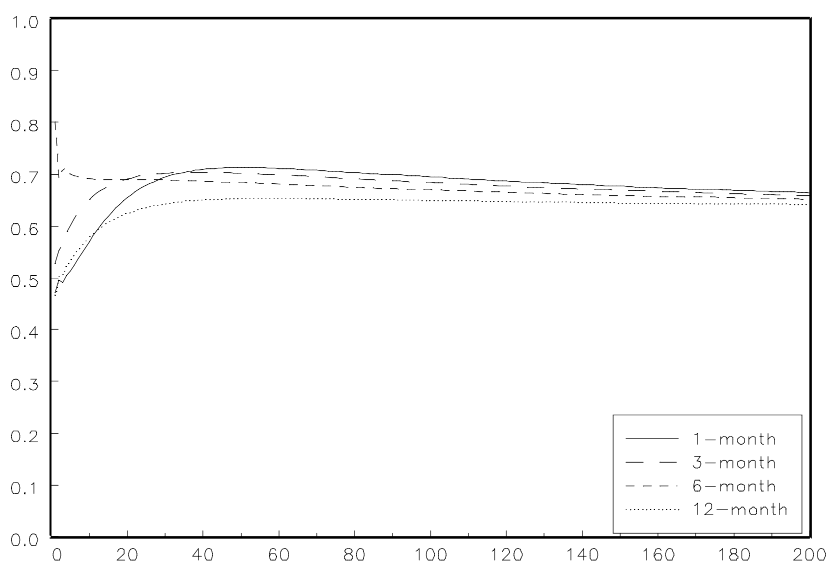
Germany: response to an impulse on the 1−month rate



Germany: response to an impulse on the 3−month rate



Germany: response to an impulse on the 6−month rate



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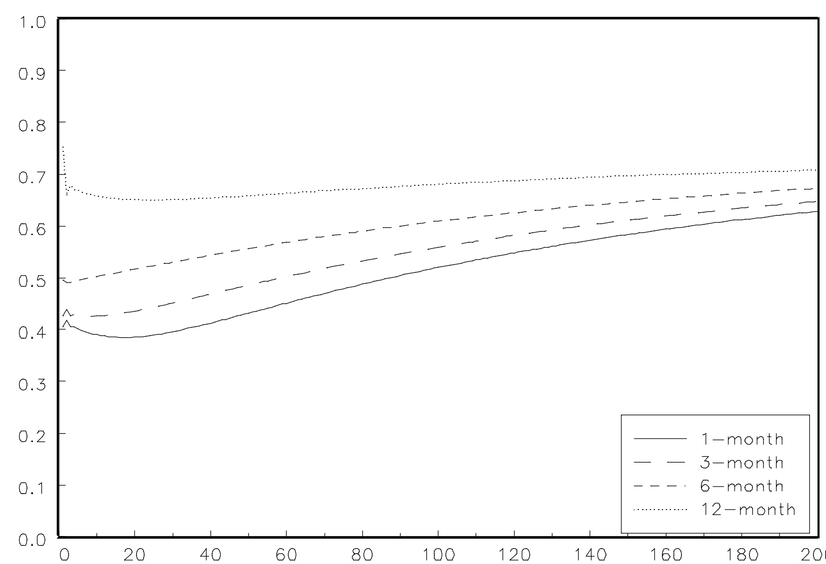

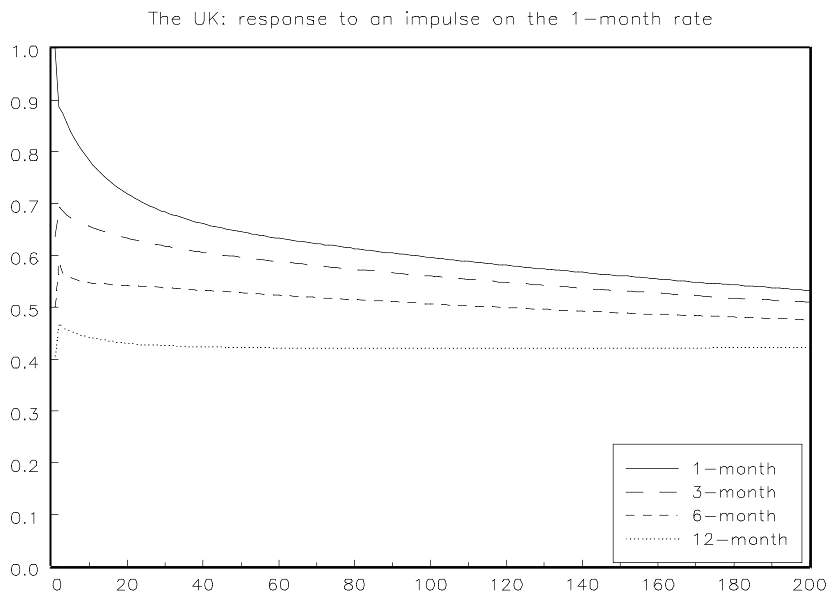
The UK: response to an impulse on the 1-month rate
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
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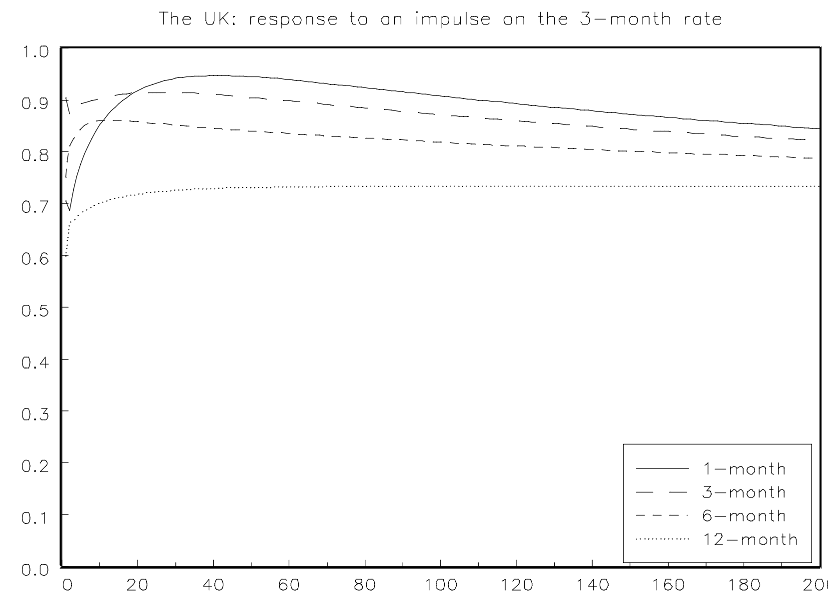
200
1-month
3-month
6-month
12-month


The UK: response to an impulse on the 3-month rate
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0.6
0.5
0.4
0.3
0.2
0.1
0.0
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80
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120
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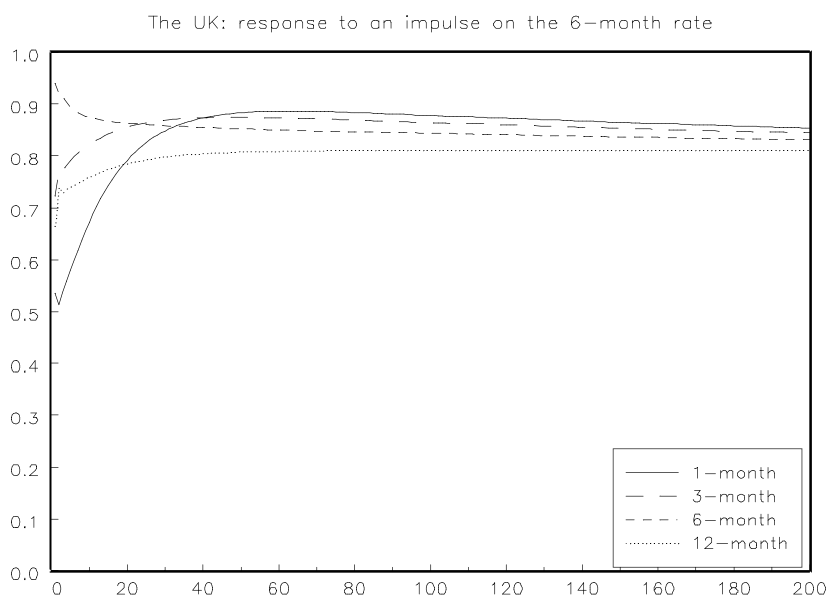
1-month
3-month
6-month
12-month


The UK: response to an impulse on the 6-month rate
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0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
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1-month
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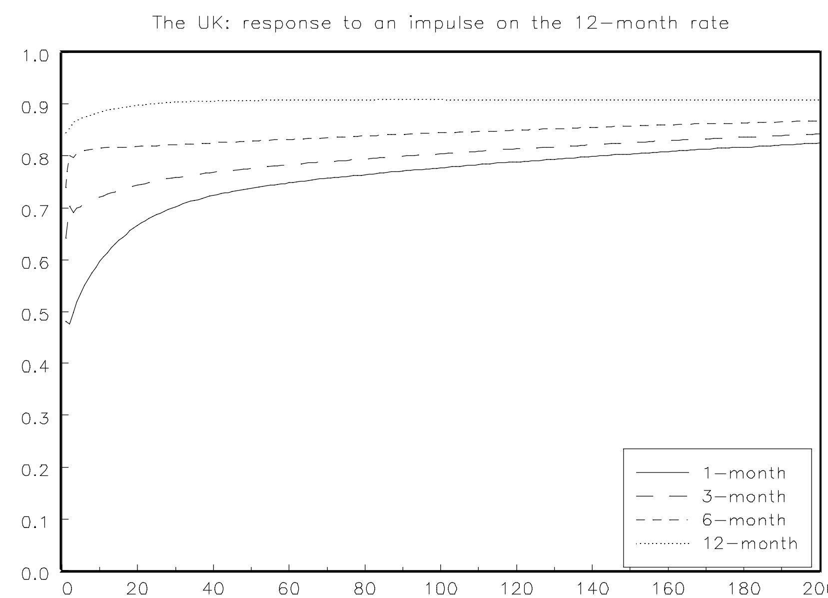
12-month


The UK: response to an impulse on the 12-month rate
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0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
20
40
60
80
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120
140
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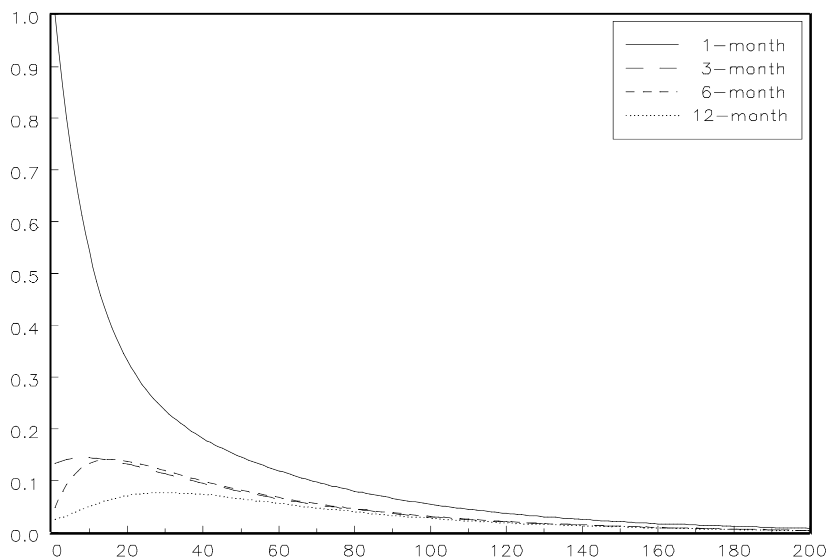
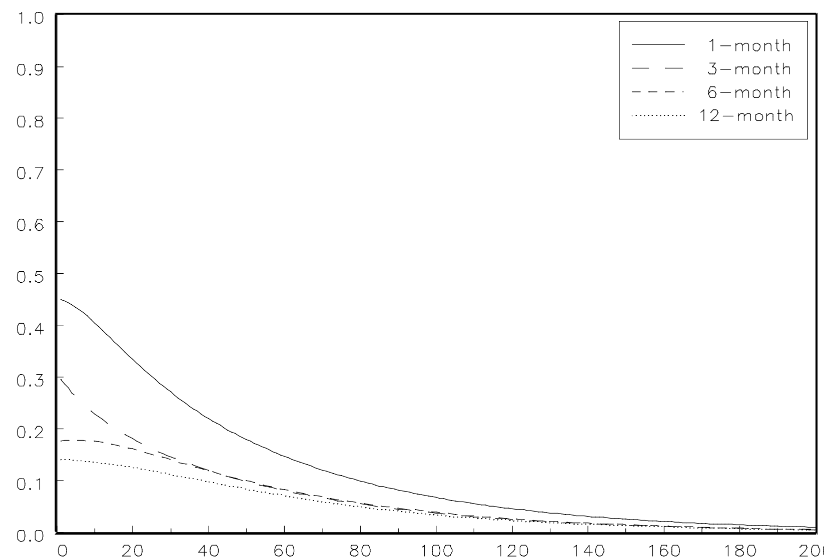
180
200
1-month
3-month
6-month
12-month

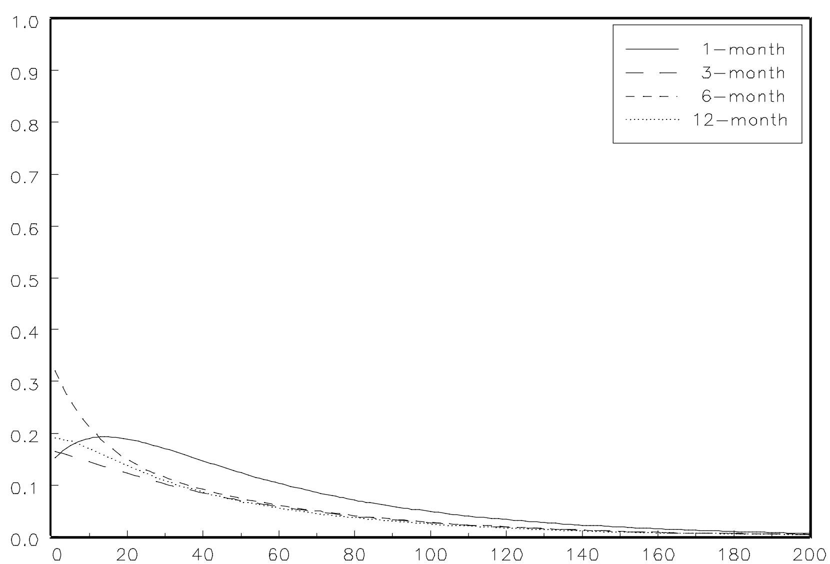
The US: response to an impulse in the 1-month rate volatility



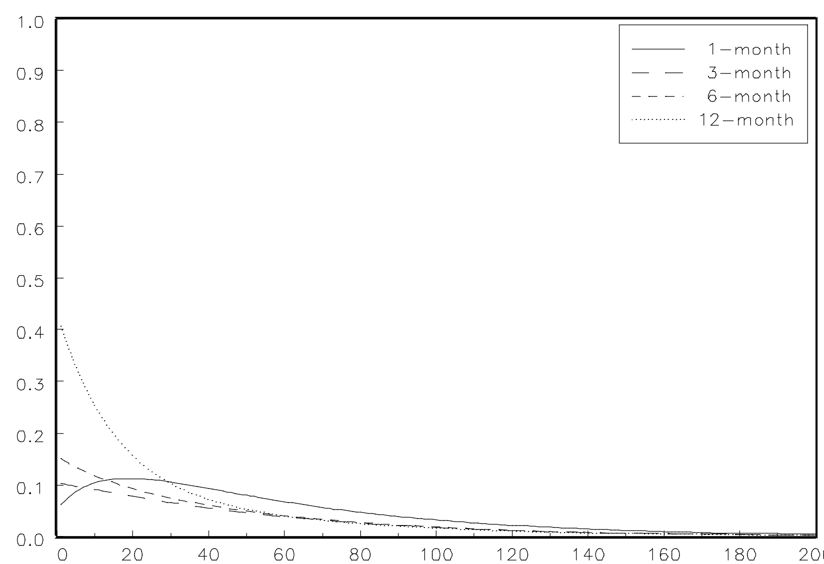
The US: response to an impulse in the 3-month rate volatility



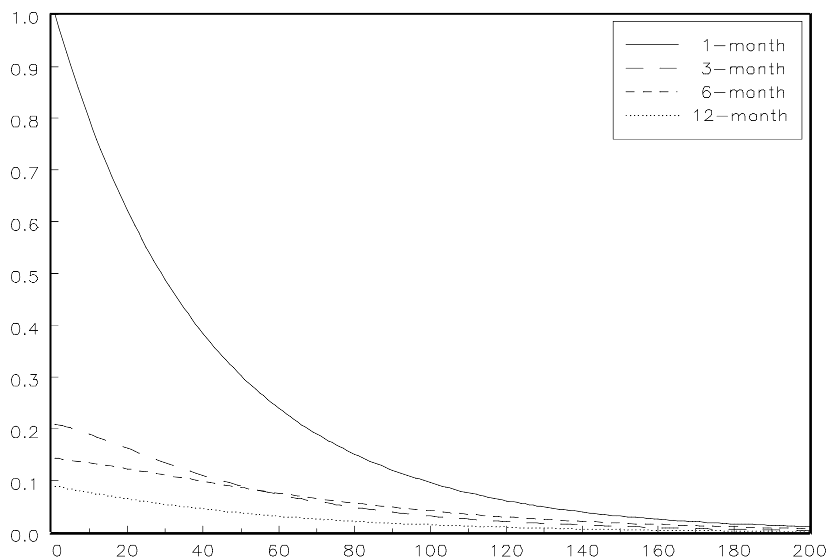
The US: response to an impulse in the 6-month rate volatility



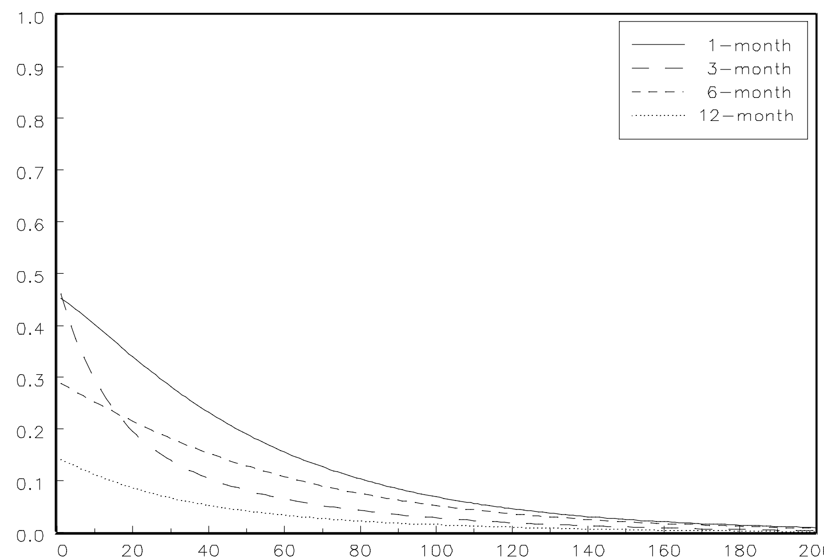
The US: response to an impulse in the 12-month rate volatility



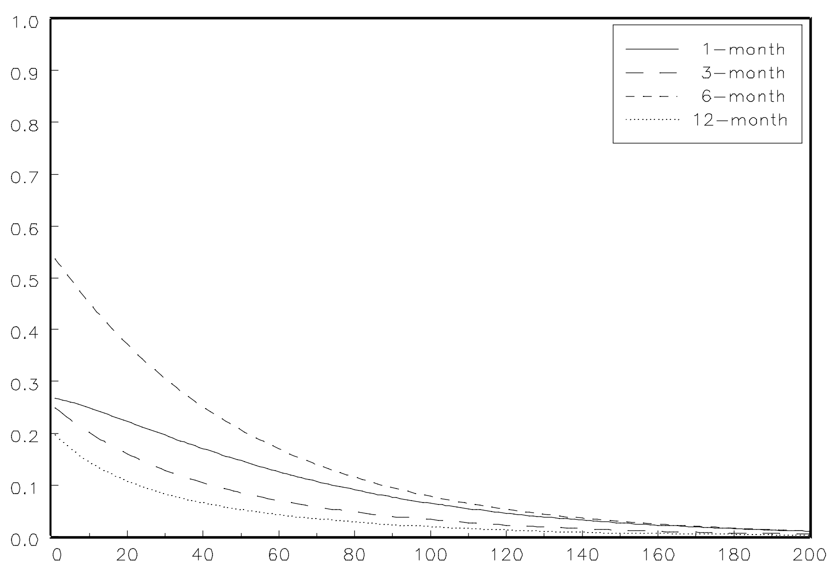
Germany: response to an impulse in the 1–month rate volatility



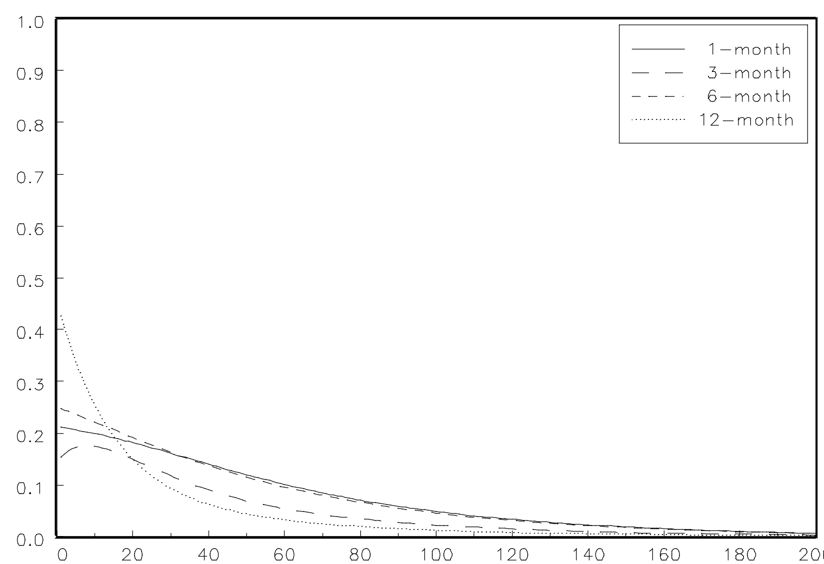
Germany: response to an impulse in the 3–month rate volatility



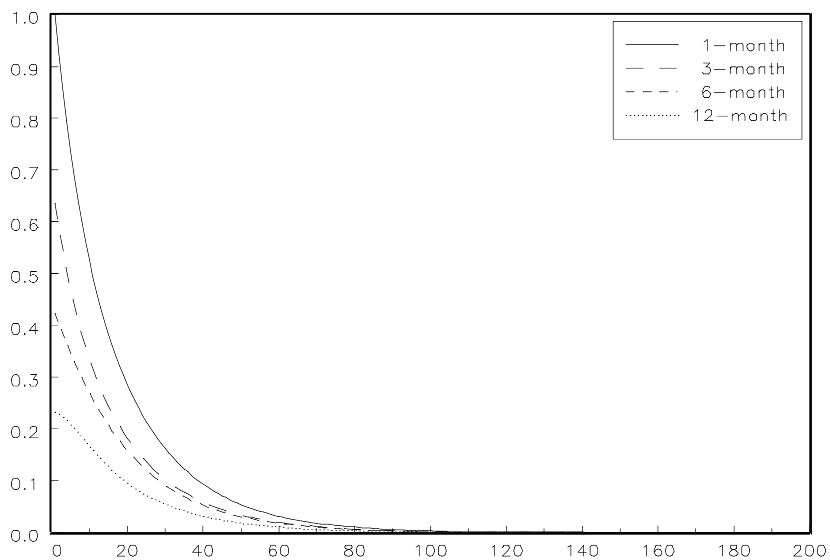
Germany: response to an impulse in the 6–month rate volatility



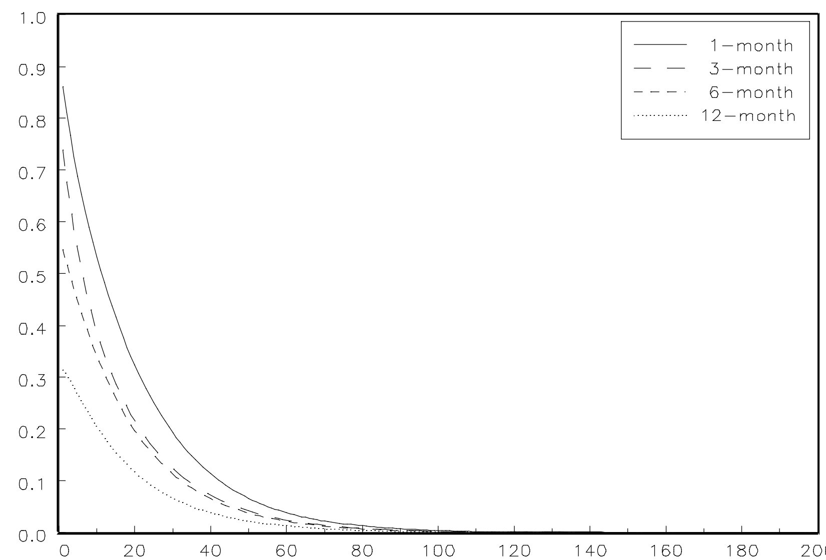
Germany: response to an impulse in the 12–month rate volatility



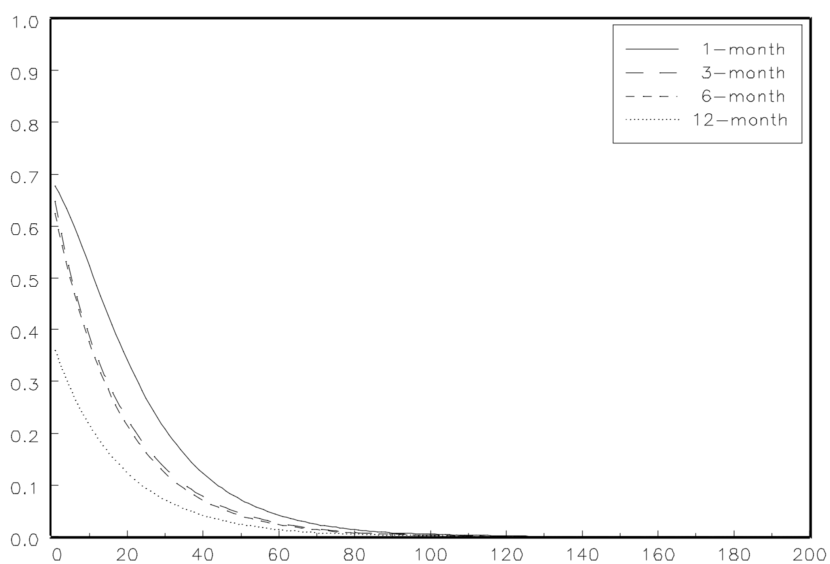
The UK: response to an impulse in the 1-month rate volatility



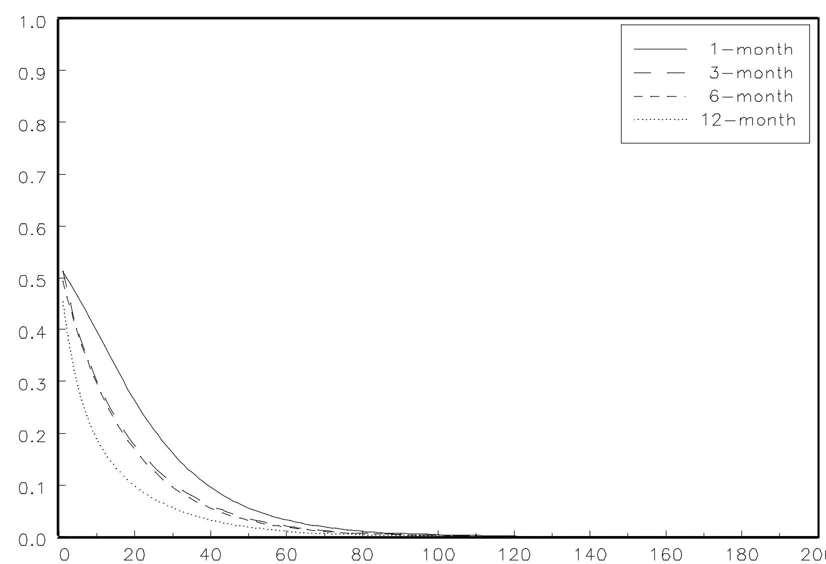
The UK: response to an impulse in the 3-month rate volatility



The UK: response to an impulse in the 6-month rate volatility



The UK: response to an impulse in the 12-month rate volatility



Notes d'Études et de Recherche

1. C. Huang and H. Pagès, "Optimal Consumption and Portfolio Policies with an Infinite Horizon: Existence and Convergence," May 1990.

2. C. Bordes, « Variabilité de la vitesse et volatilité de la croissance monétaire : le cas français », février 1989.

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