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The Euro Introduction and Non-Euro Currencies

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The Euro Introduction and Non-Euro Currencies*

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Abstract

This paper documents the existence of large structural breaks in the unconditional correlations among the US dollar exchange rates of the British pound, Norwegian krone, Swedish krona, Swiss franc, and euro during the period 1994-2003. Using the framework of dynamic conditional correlation (DCC) models, we find that such breaks occurred both at the time the formal decision to proceed with the euro was made in December 1996 and at the time of the actual introduction of the euro in January 1999. In particular, we document that most correlations were substantially lower during the intervening period. We also find breaks in unconditional volatilities at the same points in time, but these are of a much smaller magnitude comparatively.

Keywords: Exchange rates, multivariate GARCH, dynamic conditional correlation, structural breaks
JEL Classification: C32; F31; F36; G15

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1 Introduction

The advent of the euro has generated a substantial body of research investigating the consequences and effects of the introduction of the common currency in Europe.[1] Topics of particular interest include integration and co-movement of bond and stock markets (Kool, 2000; Morana and Beltratti, 2002; Guiso *et al.*, 2004; Pagano and von Thadden, 2004; Baele, 2005; Bartram *et al.*, 2005; Kim *et al.*, 2005), interdependence between US and euro area money markets (Ehrmann and Fratzscher, 2005), convergence of real exchange rates (Lopez and Papell, in press) and of inflation rates (Honohan and Lane, 2003), trade effects (Micco *et al.*, 2003; Bun and Klaassen, 2004), product market integration (Engel and Rogers, 2004), foreign exchange rate risk exposure of individual firms (Bartram and Karolyi, in press), the behavior of nominal exchange rates of euro-zone countries in the run-up to the common currency (Frömmel and Menkhoff, 2001; Bond and Najand, 2002; Wilfling, 2002), and the role of the euro in the foreign exchange market (Detken and Hartmann, 2002; Hau *et al.*, 2002). Not surprisingly, most of this research focuses on the effects for countries that have adopted the common currency. The exceptions include Barr *et al.* (2003), Micco *et al.* (2003) and Guiso *et al.* (2004), who (also) examine the effects of the euro introduction on European countries that held on to their own currency. The analysis in these papers considers variables such as trade and foreign direct investment, which obviously are closely linked to the exchange rate. Only Fisher (2002) succintly considers the exchange rate itself, by exploring the volatility properties of the currencies of European countries outside the euro-zone before and after January 1999.

The first and main contribution of this paper is to further our understanding of the effects of the euro introduction on the properties of exchange rates for European countries outside the euro-zone. In particular, we consider the behavior of daily exchange rates of the British pound, Norwegian krone, Swedish krona, and Swiss franc against the US dollar over the period from January 1, 1994 until De-

[1]Since January 1, 1999 the euro replaced the national currencies of 11 countries: Belgium, Germany, Spain, France, Ireland, Italy, Luxembourg, the Netherlands, Austria, Portugal and Finland. On January 1, 2001 it also replaced the national currency of Greece. These 12 countries are now known collectively as the euro area.

cember 31, 2003.[2,3] We concentrate on the volatility and correlation properties of these exchange rates, paying particular attention to the co-movement with the euro and changes therein. Our second contribution is methodological, concerning the dynamic conditional correlation (DCC) model introduced by Engle (2002), which is the econometric framework used to perform the analysis. Here we demonstrate how to extend this model to accommodate structural changes in the unconditional correlations.

Our main findings are as follows. We find convincing evidence that large breaks in the unconditional correlations among all exchange rates considered occurred both at the time the formal decision to proceed with the euro was made in December 1996 and at the time of the actual introduction of the euro in January 1999. In particular, we document that unconditional correlations were substantially lower during the intervening period. We attribute this to increased heterogeneity in the foreign exchange market due to uncertainty about the eventual success of the single currency. Breaks also occurred in the unconditional exchange rate volatilities, but these were of a much smaller magnitude comparatively. We perform an extensive sensitivity analysis to examine the robustness of our results. We find that allowing for two breaks in unconditional correlations is appropriate, while we also find support for the break dates of December 1996 and January 1999. In addition, modelling the changes in unconditional correlations as instantaneous rather than gradual is supported by the data, except for the currency pairs involving the British pound.

The plan of the paper is as follows. Section 2 sketches the 'road to the euro', highlighting the most important exchange rate policy decisions made by the governments and central bank authorities of the outside countries. The daily exchange rate series are described in Section 3. In Section 4, the extended DCC model allowing for structural breaks in unconditional volatilities and correlations is developed. Section 5 discusses the empirical results. Finally, Section 6 concludes.

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[2]UK and Sweden are European Union (EU) members outside the euro area while Norway and Switzerland are European countries outside the EU.

[3]We do not include the Danish krone in the analysis. Denmark, an EU member, decided not to adopt the euro upon its introduction already in December 1992, a decision that was confirmed in the national referendum held on September 28, 2000. Nevertheless, it turns out that the correlation of the Danish krone with the euro has been very close to perfect ever since the euro came into existence on January 1, 1999, possibly because monetary decisions after 1992 were taken as if Denmark was going to enter EMU with other countries.

2 The introduction of the euro

In this section we provide an overview of the crucial decisions taken in the process towards the introduction of the euro on January 1, 1999. This includes the main actions taken by the governments and central bank authorities of not only the countries that adopted the common currency, but also European Union (EU) members that decided to stay outside 'euroland' (UK and Sweden) and countries that did not belong to the EU in the first place (Norway and Switzerland).[4]

Countries in Europe have long been passionate with the objective of reducing exchange rate variability by means of increased policy coordination. On March 13, 1979, a new process to achieve this goal was started with the creation of the European Monetary System (EMS). The key ingredient of the EMS was the exchange rate mechanism (ERM), specifying fixed central exchange rates for each currency vis-a-vis all other participating currencies, with a band around these central rates within which the exchange rates could fluctuate freely. Central bank interventions were used to keep the exchange rates within the band, while realignments of the central rates were permitted in case a particular parity could not be defended. The numeraire of the ERM was the European Currency Unit (ECU), defined as a 'basket' of fixed quantities of the currencies of the member states. The value of the ECU against the US dollar was determined as a weighted average of the US dollar exchange rates of the component currencies. The central ERM rates of the participating currencies were expressed in terms of the ECU.

The EMS was in fact much more than just an exchange rate mechanism. It also involved the adjustment of monetary and economic policies as tools for achieving exchange rate stability. Its participants were able to create a zone in which monetary stability increased and capital controls were gradually relaxed. It thus fostered a downward convergence of inflation rates and stimulated a high degree of exchange rate stability, which led to improved overall economic performance, for example through protecting intra-European trade and investment from excessive exchange

[4]This section draws upon information available at the websites of the European Council (`http://ue.eu.int/`), the European Central Bank (`http://www.ecb.int/`), the Bank of England (`http://www.bankofengland.co.uk/`), the Swedish Riksbank (`http://www.riksbanken.se/`), the Norges Bank (`http://www.norgesbank.no/`), and the Swiss National Bank (`http://www.snb.ch/`), as well as speeches by central bank governors published in the BIS Review (`http://www.bis.org/review/`).

rate uncertainty (but see Darby *et al.* (1998) for a critical perspective).

This gradual process of stabilization and economic integration received a new impulse in June 1988, when the European Council confirmed the objective of the progressive realization of Economic and Monetary Union (EMU). The Delors committee, which subsequently was mandated to study and propose concrete stages leading to this union, suggested that EMU should be achieved in three discrete but evolutionary steps. Stage One of EMU, which began on July 1, 1990, involved abolishing all restrictions on capital movements between member states, free use of the ECU, increased cooperation between central banks and further coordination of monetary policies of the member states with the aim of achieving price stability. The Treaty of Rome, establishing the European Economic Community, was revised in 1991 to enable Stages Two and Three of EMU. The resulting Treaty on European Union was signed in Maastricht in February 1992 and after a prolonged ratification process came into force in November 1993.

Stage Two of EMU was entered on January 1, 1994, with the establishment of the European Monetary Institute (EMI). The two main tasks of the EMI were to strengthen central bank cooperation and monetary policy coordination, and to make the necessary preparations for establishing the European System of Central Banks (ESCB), for the conduct of the single monetary policy and for the creation of a single currency in the third stage.[5] In December 1995, the European Council decided upon the name of 'euro' for the single European currency and confirmed that the start of Stage Three of EMU would take place on January 1, 1999.

At its meeting held in Dublin on December 13-14, 1996, the European Council made decisive progress towards the third stage of EMU. In particular, it agreed upon the structure of the new Exchange Rate Mechanism (ERM II) and upon the principles and main elements of the Stability and Growth Pact for ensuring budgetary discipline in EMU countries. Both decisions were largely based upon a report presented by the EMI at the meeting. Although the resulting resolutions on ERM II and the Stability and Growth Pact were formally adopted at the European Council meeting in Amsterdam in June 1997, the Dublin meeting in December 1996 can be regarded as the time the final decision to proceed towards Stage Three of EMU and

[5]The EMI itself had no responsibility for the conduct of monetary policy nor had it any competence for carrying out foreign exchange interventions.

the introduction of the euro on January 1, 1999 was actually made.[6]

On May 2, 1998, it was decided that 11 EU member states had fulfilled the conditions necessary for participation in the third stage of EMU and the adoption of the single currency on January 1, 1999. At the same time it was also agreed that the ERM bilateral central rates would be used for determining the conversion rates for the euro. Upon the start of the third and final stage of EMU on January 1, 1999, the exchange rates of the currencies of the participating countries were irrevocably fixed accordingly. The European Central Bank (ECB) took over responsibility for conducting the single monetary policy in the euro area. Both the intra-EU exchange rate mechanism (ERM II) and the Stability and Growth Pact entered into force, and the single common currency, the euro, was officially launched.

2.1 Non-euro countries

2.1.1 UK

The Maastricht Treaty, signed in 1992, provided a special clause for the UK on the implementation of economic and monetary union in progressive stages. The British Government accepted participation up to the preparatory Stage Two, but arranged an opt-out from Stage Three, when exchange rates would be irrevocably locked, the euro would come into existence and the national currencies would be abolished.

In October 1997, the UK government set five economic tests that must be passed before it will recommend that the UK joins the euro, see Rollo (2002) for discussion. In theory, passing these tests is distinct from any political decision to join. The tests are (i) Are business cycles and economic structures compatible with European interest rates on a permanent basis? (ii) If problems emerge, is there sufficient flexibility to deal with them? (iii) Would joining the euro create better conditions for firms making long-term decisions to invest in the UK? (iv) What impact would entry into the euro have on the UK's financial services industry? (v) Would joining the euro promote higher growth, stability and a lasting increase in jobs? The UK government assessed these tests in October 1997 and June 2003, and decided on both occasions that they had not all been passed.

[6]Coincidentally, at the Dublin meeting the EMI also presented the winning designs for the euro banknotes.

These decisions are not surprising given the positive track record of the Bank of England in its conduct of monetary policy. Although the UK adopted a formal inflation target already in 1992, only in 1997 the responsibility for setting interest rates was transferred from the Treasury to the Bank, see Bean (1998) for an interesting analysis. The operational independence, which the Bank was granted at the same time, further enhanced the credibility of inflation targeting. According to the institutional framework laid down in the 1998 Bank of England Act, the Bank is required to set interest rates so as to maintain price stability and subject to that to support the economic policy of the Government, including its objectives for growth and employment. On the other hand, the Government should specify what its economic objectives are, including what is meant by price stability. If inflation deviates from target by more than 1 percentage point, the Governor of the Bank is required to write to the Treasury explaining the circumstances and setting out what action its Monetary Policy Committee (MPC) considers necessary to return to target. Against the target of 2.5% annual inflation for the RPIX (Retail Price Index exclusive of interest payments) which ran from 1997 until December 2003, average inflation was 2.4%. For 68 out of the 79 months, inflation was within 0.5 percentage point of the target - below it for 42 months, above it for 30, and on target for the remaining seven. Clements (2004) provides an in-depth evaluation of the inflation forecasts that play an important role in the MPC's decisions on interest rates.

2.1.2 Sweden

On November 19, 1992, the Sveriges Riksbank (Swedish Central Bank) abandoned its policy of pegging the krona to a trade-weighted average of foreign currencies. At the time, Sweden was neither a member of the EU nor participating in the European system of pegged exchange rates, and therefore entering the ERM was not feasible in the near future.

On January 15, 1993 the Riksbank decided to declare that the flexible exchange rate policy would be combined with an explicit target for inflation, defined in terms of the consumer price index (CPI). Specifically, the Riksbank decided that from 1994 onwards there would be a target for CPI inflation of 2 percent per year, accompanied by a 'tolerance interval' of 1 percentage point.

In late 1998, the Riksdag (Swedish Parliament) approved changes to the Riksbank

Act making the central bank legally more independent and formalizing objectives towards an inflation-targeting regime. The Riksbank had to be made more independent in order to comply with the Maastricht Treaty, which Sweden in effect had signed when deciding to become an EU member in December 1994. Although Sweden was not a full participant in the EMU as it did not plan to adopt the euro upon its inception, there was broad political support in Sweden for the idea that technical and practical preparations should be made for a possible future full membership. The parliament's decision to make the Riksbank more independent had effectively been taken already before the government's decision to postpone membership in the EMU in December 1997. This timing was probably not co-incidental; legal independence for the Riksbank was viewed as useful to maintain credibility for the inflation target as long as Sweden is not a full member of the EMU.

Unlike the UK and Denmark, Sweden does not have a formal opt-out from the monetary union and therefore must (at least in theory) convert to the euro at some point. Notwithstanding this, on September 14, 2003 a referendum on the euro was held. The euro opponents claimed that adopting the common currency could damage the country's strong economic performance and generous welfare system, especially since Sweden's trade pattern and industrial structure deviate from the European average. On the other hand, the euro advocates argued that trade and future growth would be enhanced by becoming an EMU member. The result of the referendum was a rejection of the common currency by a 14 percentage point margin (56 to 42 percent, with 2 percent voting 'blank'). Despite the lack of an opt-out option, the Swedish government argued that complying with the referendum result is possible given that one of the requirements for adopting the euro is a prior two-year participation in the ERM II. By simply choosing to stay outside the exchange rate mechanism, the Swedish government was provided a formal loophole avoiding the theoretical requirement of adopting the euro.

2.1.3 Norway

For almost the entire post-World War II period monetary policy in Norway has been oriented towards maintaining exchange rate stability, with fiscal policy bearing the main responsibility for stabilising the economy. When the European Monetary System (EMS) was set up in 1979 Norway chose to link its krone to a trade-weighted basket of currencies. Despite the objective of a fixed exchange rate, several adjustments to the international value of the krone were made during the 1970s and 1980s to compensate for high wage and price inflation. From the mid-1980s the focus of monetary policy was increasingly shifted towards the role of a stable exchange rate as a nominal anchor, against the backdrop of high inflation and relatively high domestic interest rates following the devaluation in 1986. The EU countries' track record of low inflation was used as an argument for pegging the krone rate to the ECU in 1990. The currency turmoil in Europe in 1992-93 prompted Norway to abandon the fixed rate against the ECU in favor of a 'managed float', aiming to keep the exchange rate 'stable' against European currencies, but without explicit fluctuation margins. This objective for monetary policy was formalized in the Exchange Rate Regulation, the mandate assigned to Norges Bank (the Norwegian Central Bank) by the political authorities in May 1994.

At the end of 1996 and beginning of 1997 the Norwegian krone appreciated considerably, mainly due to higher oil prices and insufficiently tight fiscal policy. Norges bank reacted by lowering key interest rates between October 1996 and January 1997 by 1.25 percentage points while also purchasing large amounts of foreign exchange. Initially the Norwegian currency continued to appreciate, but fell back later during the spring to end 1997 at about the same level as it started the year. Importantly, on January 10, 1997 Norges Bank also declared that it would no longer intervene in the foreign exchange market to any significant extent. As a consequence, the krone became much more susceptible to turbulence in international financial markets, leading to a substantial increase in its volatility, see Bernhardsen and Røisland (2000).

Early 1999 the new governor of Norges Bank reinterpreted the monetary policy guidelines laid down in the Exchange Rate Regulation. In particular, it was recognized that targeting the exchange rate directly was no longer an appropriate operational goal of monetary policy. Instead, low and stable inflation was put forward as the essential condition for exchange rate stability. Monetary policy was therefore reoriented towards reducing inflation to the ECB target (two percent). This can be interpreted as the beginning of a period of *partial inflation targeting*, see e.g. Bauwens, Rime and Sucarrat (2006). The disappointing experiences with extensive exchange rate interventions further strengthened the position of the interest rate as the most important monetary policy instrument.

On March 29, 2001, the Government officially approved the new guidelines for monetary policy. Norges Bank sets the key interest rate with a view to maintaining low and stable inflation, with a specific annual CPI inflation target of 2.5 percentage points. Under the inflation targeting regime, Norges Bank no longer has a specific exchange rate target for the Norwegian krone.

2.1.4 Switzerland

Monetary policy in Switzerland has a long history of being autonomous, with the objective to preserve long-term price stability ever since the collapse of the Bretton Woods system. Convinced that inflation is a monetary phenomenon, the Swiss National Bank (SNB) opted for a strategy aimed at a steady growth of the money stock in line with the potential growth rate of the economy, see Rich (1997). Only in 2000 this was changed to inflation targeting.

Since 1973, the Swiss franc has been floating against all major currencies. Despite the flexible exchange rate regime, the Swiss franc has been remarkably stable against other European currencies ever since the early 1980s. Given that the SNB refrained from intervening in the foreign exchange market, this quasi-fixed exchange rate was achieved by market forces alone.

In the run-up towards the introduction of the euro, the SNB expressed concerns about the stability of the Swiss franc, about the ability of the Swiss to conduct an independent monetary policy, about the exchange rate sensitivity of the Swiss economy, and about the position of the Swiss franc as a transaction currency (even in Switzerland itself), see Fisher (2002) for discussion. The SNB implemented a pragmatic monetary policy aimed towards granting the Swiss economy the monetary flexibility necessary for handling these risks and uncertainties. After the launch of the euro, it soon appeared that the Swiss' fears did not materialize: The Swiss franc remained very stable against the euro, the SNB managed to hold on to its monetary independence, and the Swiss franc was not crowded out by the euro as a vehicle currency.

Summarizing the above, our main conclusion is that the two most important events in the run-up towards Stage Three of EMU were the agreement on the structure of the new Exchange Rate Mechanism (ERM II) and on the principles and main elements of the Stability and Growth Pact at the meeting of the European Council in Dublin on December 13-14, 1996, and the actual introduction of the euro on January 1, 1999. In the empirical analysis below, we examine how these events affected the currencies of the outside countries. Such effects may be expected given their close links with the Eurozone countries. In addition, changes in the exchange rate properties of the Norges krone may also have occurred due to the changes Norges Bank made in its exchange rate policy and monetary policy at the same time.

3 Data

We consider daily US dollar exchange rates of the Swiss franc (CHF), euro (EUR), British pound (GBP), Norwegian krone (NOK), and Swedish krona (SEK) over the period from January 1, 1994 (the start of Stage Two of EMU) until December 31, 2003 (2512 observations). Up to December 31, 1998, the euro series actually concerns the exchange rate of the German Deutschmark, while the euro is used as of January 1, 1999.[7] The data is obtained from the Federal Reserve Bank of New York and concerns noon buying rates in New York.

Table 1 displays summary statistics of the daily exchange rate returns. In addition to the full sample period, we also report these statistics for the three relevant subperiods that we distinguish. The first period runs from January 1, 1994 until December 15, 1996, when the formal decision to proceed with ERM II and the euro was made at the European Summit in Dublin. The second subperiod comprises the period between this decision and the actual introduction of the euro on January 1, 1999. The third and final subperiod covers the remainder of the sample period until December 31, 2003.

Apart from the important economic events that took place at the end of 1996 and 1998, the choice for these three subperiods is also motivated by the results from the following nonparametric analysis of volatilities and correlations. Let r_t denote the $(N \times 1)$ vector time series of daily exchange rate returns, where in our case $N = 5$.

[7] Although the German Deutschmark undoubtedly was the single most important currency in the Eurozone before 1999, it may not be completely representative of exchange rate developments in the euro countries. An alternative would be to use the ECU instead of the Deutschmark for the pre-euro period. We do not consider this possibility, however, for the fact that the British pound and Swedish krona were part of the ECU. This obviously may influence results, in particular those pertaining to the correlations of these currencies with the "euro".

A nonparametric estimate of the correlation matrix R_t at $t = \tau$ can be obtained as

$$\widehat{R}(\tau) = \widehat{Q}^*(\tau)^{-1}\widehat{Q}(\tau)\widehat{Q}^*(\tau)^{-1} \quad (1)$$

where $\widehat{Q}(\tau)$ is the Nadaraya-Watson kernel estimator

$$\widehat{Q}(\tau) = \frac{\sum_{t=1}^{T}(r_t - \overline{r})(r_t - \overline{r})' K_h(t-\tau)}{\sum_{t=1}^{T} K_h(t-\tau)} \quad (2)$$

where $\overline{r} = \frac{1}{T}\sum_{t=1}^{T} r_t$, $K_h(\cdot) = (1/h)K(\cdot/h)$, K is a kernel function and h a bandwidth parameter, and where $\widehat{Q}^*(\tau)$ is diagonal matrix with the square roots of the diagonal elements of $\widehat{Q}(\tau)$ on its diagonal. These also provide nonparametric estimates of the volatilities of the exchange rate returns at $t = \tau$.[8] We employ a quartic kernel function with bandwidth $h = 1$. The resulting volatility and correlation estimates, shown in Figure 1, are used in the discussion below.

Concerning the univariate statistics (mean, standard deviation, skewness and kurtosis), we first of all note that the mean exchange rate returns varied considerably. Specifically, during the middle period from December 16, 1996 until December 31, 1998 the US dollar depreciated against all currencies (except the British pound), while the first and third subperiods are characterized by an appreciation of the US dollar. The standard deviation of exchange rate returns remained relatively stable across subperiods, although the Norwegian krone experienced higher volatility in 1997-98 and towards the end of the sample period, see also panel (a) in Figure 1. More variation is observed in skewness and kurtosis. Skewness is negative for all exchange rates and subperiods, except for the British pound and the Swedish krona before December 1996 and for the Swedish krona after January 1999. For the CHF and GBP, the (absolute) magnitude of the skewness declined substantially after January 1999 and December 1996, respectively. For the EUR, NOK and SEK, skewness was considerably larger (in absolute value) during the second subperiod. Similar patterns are found for the kurtosis.

Turning to the correlations, when computed over the full sample period these are quite high, ranging from 0.483 for the British pound and the Swedish krona to 0.926 for the Swiss franc and the euro. Comparing the correlations during the three

[8] A detailed discussion of this nonparametric volatility and correlation estimator can be found in Hafner *et al.* (2006).

subperiods and inspecting panels (b)-(f) of Figure 1, we observe that all correlations among CHF, EUR, GBP and NOK decreased around the end of 1996, when the formal decision concerning the euro was taken and Norway changed its exchange rate intervention policy. These correlations increased again around the time of the actual introduction of the euro and the change in Norway's monetary policy to (partial) inflation targeting in January 1999. For the CHF, EUR and GBP, correlations in fact appear to have returned to their pre-1997 levels, while correlations of these currencies with the NOK remained somewhat below this initial level. Correlations of the Swedish krona with the other currencies show a different pattern, in the sense that they steadily and monotonically became higher in consecutive subperiods (except for the GBP-SEK correlation, which was lower between December 1996 and January 1999).

In the next section, we describe the framework of dynamic conditional correlation models. In particular, we extend the model to allow for the possibility of structural breaks in the unconditional correlations, in order to accommodate the substantial differences in co-movement of the exchange rates documented above.

4 Dynamic conditional correlation models

Let r_t denote the $(N \times 1)$ vector time series of daily exchange rate returns. Assuming that r_t is conditionally normal with mean $\mu_t = (\mu_{1t}, \ldots, \mu_{Nt})'$ and covariance matrix H_t, we have the generic model

$$r_t | \mathcal{F}_{t-1} \sim N(\mu_t, H_t), \tag{3}$$

where $\mathcal{F}_t$ is the information set that includes all information up to and including time t. The conditional covariance matrix H_t can be decomposed as

$$H_t = S_t R_t S_t, \tag{4}$$

where $S_t = \mathsf{diag}(\sigma_{1t}, \ldots, \sigma_{Nt})$ is a diagonal matrix with the conditional standard deviations σ_{it}, $i = 1, \ldots, N$, on the diagonal. The matrix R_t, with the (i, j)-th element denoted as ρ_{ijt}, is the possibly time-varying conditional correlation matrix.

We assume that σ_{it}^2 can be adequately described by a univariate GARCH(1,1) model (see Bollerslev, 1986), such that

$$\sigma_{it}^2 = \omega_i + \alpha_i \varepsilon_{i,t-1}^2 + \beta_i \sigma_{i,t-1}^2, \tag{5}$$

where $\varepsilon_{it} \equiv r_{it} - \mu_{it}$, $\omega_i > 0$, $\alpha_i > 0$, $\beta_i \geq 0$ and $\alpha_i + \beta_i < 1$, for $i = 1, \ldots, N$. The unconditional volatility of the unexpected returns ε_{it} implied by the GARCH(1,1) model is equal to $\omega_i/(1 - \alpha_i - \beta_i) \equiv \overline{\sigma}_i^2$. Hence, (5) can be rewritten as

$$\sigma_{it}^2 = (1 - \alpha_i - \beta_i)\overline{\sigma}_i^2 + \alpha_i \varepsilon_{i,t-1}^2 + \beta_i \sigma_{i,t-1}^2. \qquad (6)$$

For the matrix R_t we employ the dynamic conditional correlation (DCC) model introduced by Engle (2002). A similar model has been proposed by Tse and Tsui (2002). Defining $z_t = S_t^{-1}\varepsilon_t$, R_t is assumed to vary according to a GARCH-type process,[9]

$$Q_t = (1 - \gamma - \delta)\overline{Q} + \gamma z_{t-1} z_{t-1}' + \delta Q_{t-1}, \qquad (7)$$

$$R_t = {Q_t^*}^{-1} Q_t {Q_t^*}^{-1}, \qquad (8)$$

where Q_t^* is a diagonal matrix composed of the square roots of the diagonal elements of Q_t, γ and δ are scalars, and $\overline{Q} = \mathsf{E}[z_t z_t']$ is the unconditional covariance matrix of standardized shocks z_t.

In order to allow for structural changes in the unconditional volatilities and unconditional correlations, it is tempting (and in fact common practice) to replace $\overline{\sigma}_i^2$ in (6) and $\overline{Q}$ in (7) by $\overline{\sigma}_{it}^2$ and $\overline{Q}_t$, respectively, and specify these in a certain (parametric) way to allow for the types of changes desired. For example, the most general model that we consider in the next section allows for two instantaneous breaks in both the unconditional volatilities and unconditional correlations. This might be obtained by defining $\overline{\sigma}_{it}^2$ and $\overline{Q}_t$ as

$$\overline{\sigma}_{it}^2 = \overline{\sigma}_{i1}^2 \mathtt{I}[t \leq \tau_1] + \overline{\sigma}_{i2}^2 \mathtt{I}[\tau_1 < t \leq \tau_2] + \overline{\sigma}_{i3}^2 \mathtt{I}[\tau_2 < t], \qquad (9)$$

$$\overline{Q}_t = \overline{Q}_1 \mathtt{I}[t \leq \tau_1] + \overline{Q}_2 \mathtt{I}[\tau_1 < t \leq \tau_2] + \overline{Q}_3 \mathtt{I}[\tau_2 < t], \qquad (10)$$

where $\mathtt{I}[A]$ is the indicator function for the event A, and τ_1 and τ_2 denote the break-points with $\tau_1 < \tau_2$. These change-points can be either fixed *a priori* or left unspecified and estimated along with the other parameters in the model.

[9] Alternative models that allow for time-varying correlations are developed in Pelletier (2006) and Silvennoinen and Teräsvirta (2005), assuming that the correlations switch back and forth between a limited number of values, according to an unobserved Markov-Switching process or according to the value of observed exogenous variables, respectively. Hafner *et al.* (2006) generalize the latter approach by combining (1)-(2) with univariate GARCH models for the conditional volatility. We refer to Bauwens, Laurent and Rombouts (in press) for a comprehensive survey of multivariate GARCH models. An interesting alternative approach to modelling dependence and changes therein is by means of copulas, see Patton (in press) for an application to exchange rate returns.

However, it turns out that in this case $\overline{\sigma}_{it}^2$ and $\overline{Q}_t$ do not represent the unconditional volatility and unconditional correlations at time t. For example, for the unconditional volatility, this can be seen from recursive substitution for $\sigma_{i,t-1}^2$ in (6) with $\overline{\sigma}_i^2$ replaced by $\overline{\sigma}_{it}^2$, which renders

$$\sigma_{it}^2 = (1 - \alpha_i - \beta_i) \sum_{j=0}^{\infty} \left(\prod_{k=1}^{j} (\alpha_i z_{i,t-k}^2 + \beta_i) \right) \overline{\sigma}_{i,t-j}^2,$$

such that the unconditional volatility at time t is equal to

$$\mathsf{E}[\sigma_{it}^2] = (1 - \alpha_i - \beta_i) \sum_{j=0}^{\infty} (\alpha_i + \beta_i)^j \overline{\sigma}_{i,t-j}^2 \neq \overline{\sigma}_{it}^2.$$

In case $\overline{\sigma}_{it}^2$ is specified as in (9), for example, the unconditional volatility changes gradually from $\overline{\sigma}_{i1}^2$ via $\overline{\sigma}_{i2}^2$ to $\overline{\sigma}_{i3}^2$ instead of instantaneously. This can be remedied by first rewriting (6) as

$$\sigma_{it}^2 = \overline{\sigma}_i^2 + \alpha_i(\varepsilon_{i,t-1}^2 - \overline{\sigma}_i^2) + \beta_i(\sigma_{i,t-1}^2 - \overline{\sigma}_i^2),$$

and then generalizing this as

$$\sigma_{it}^2 = \overline{\sigma}_{it}^2 + \alpha_i(\varepsilon_{i,t-1}^2 - \overline{\sigma}_{i,t-1}^2) + \beta_i(\sigma_{i,t-1}^2 - \overline{\sigma}_{i,t-1}^2). \tag{11}$$

It is straightforward to see that $\overline{\sigma}_{it}^2$ in this specification indeed can be interpreted as the unconditional volatility at time t. Thus, in case $\overline{\sigma}_{it}^2$ is specified as in (9), for example, the unconditional volatility does exhibit instantaneous jumps at $t = \tau_1$ and τ_2. We remark that (11) effectively is an alternative representation of the Spline GARCH model developed by Engle and Gonzalo Rangel (2004).

A similar line of reasoning applies to the DCC model. Here we first rewrite (7) as

$$Q_t = \overline{Q} + \gamma(z_{t-1}z_{t-1}' - \overline{Q}) + \delta(Q_{t-1} - \overline{Q}),$$

and then allow for changes in the unconditional correlations by generalizing this as

$$Q_t = \overline{Q}_t + \gamma(z_{t-1}z_{t-1}' - \overline{Q}_{t-1}) + \delta(Q_{t-1} - \overline{Q}_{t-1}), \tag{12}$$

such that $\overline{Q}_t$ represents the unconditional correlation matrix at time t (up to scaling as in (8)).

The attractive feature of the DCC model is that parameter estimation can be done sequentially in three steps. First, estimate the (univariate) models for the conditional means μ_{it} for the individual series r_{it}, $i = 1, \ldots, N$. Second, use the first-step residuals $\hat{\varepsilon}_{it} \equiv r_{it} - \hat{\mu}_{it}$ to estimate the parameters in the univariate GARCH(1,1) models and to obtain estimates of the conditional variances σ^2_{it}. Third, use the standardized residuals $\hat{z}_t \equiv \hat{S}_t^{-1}\hat{\varepsilon}_t$, with $\hat{S}_t = \mathsf{diag}(\hat{\sigma}_{1t}, \ldots, \hat{\sigma}_{Nt})$, to estimate the parameters in the model for R_t.

The complete DCC model (6)-(8) contains $3N + N(N+1)/2 + 2$ unknown parameters. This number can be reduced to $2N + 2$, however, by employing volatility targeting and correlation targeting. Volatility targeting, introduced by Engle and Mezrich (1996), essentially means that $\overline{\sigma}^2_i$ in (6) is not treated as an unknown parameter, but is replaced by its sample analogue $\widehat{\overline{\sigma}}^2_i = \frac{1}{T}\sum_{t=1}^{T} \hat{\varepsilon}^2_{it}$, with T denoting the sample size, in the estimation of the remaining GARCH parameters α_i and β_i in the second step. This ensures that the unconditional volatility as implied by the GARCH model equals the sample variance of the first-step residuals. Similarly, correlation targeting involves replacing $\overline{Q}$ in (7) with the sample covariance matrix $\frac{1}{T}\sum_{t=1}^{T} \hat{z}_t\hat{z}_t'$. This imposes the restriction that the unconditional correlations as implied by the DCC model equal the unconditional sample correlations of the standardized residuals, and reduces the number of parameters to be estimated in the third step to two, namely γ and δ. Whether or not volatility and correlation targeting can still be employed in the DCC model with breaks, as given in (11) and (12), depends on the specification of $\overline{\sigma}^2_{it}$ and $\overline{Q}_t$. In case instantaneous breaks are allowed for, as in (9) and (10), targeting is possible by replacing $\overline{\sigma}^2_{ij}$ and $\overline{Q}_j$, $j = 1, 2, 3$, with their sample analogues.

Engle and Sheppard (2001) analyse the properties of the three-step estimation procedure for the standard DCC model without breaks in the unconditional correlations. Due to the sequential estimation of the model parameters, inference becomes a nontrivial issue, as the standard errors of the correlation parameters depend on the estimates of the conditional means and variances. Engle (2002) provides general expressions for the necessary adjustments to the third step covariance matrix to take into account the uncertainty of the first and second steps. However, this does not allow for computation of quasi-maximum likelihood (QML) standard errors that are robust to the violation of the assumption of normality in (3), as developed in Bollerslev and Wooldridge (1992). Given that this may be relevant for our exchange rate series, we decide to estimate all parameters in the model jointly, such that QML standard errors can be obtained. This is not problematic given that the dimension of our exchange rate series is reasonably small ($N = 5$), that we can use simple models for the conditional mean μ_t, and that we employ both volatility targeting and correlation targeting whenever possible.[10,11]

5 Empirical results

We estimate the DCC model discussed in the previous section for the five-dimensional vector of daily exchange rate returns, $r_t = (\text{CHF}_t, \text{EUR}_t, \text{GBP}_t, \text{NOK}_t, \text{SEK}_t)'$.[12] To determine an appropriate specification for the conditional mean μ_t, we start out with testing for cointegration among the exchange rates, but find no evidence thereof. In addition, none of the exchange rate returns series exhibits significant autocorrelation, such that we set μ_t equal to a constant, that is $\mu_t = \mu$ for $t = 1, \ldots, T$.[13]

We estimate ten different models with structural changes in volatilities and correlations, by varying the number, the type and the location of the breaks. First, we estimate the standard DCC model without breaks as given in (6)-(8). Second, we estimate six models with a single break in the unconditional volatilities only, in the unconditional correlations only, or in both, with the change occurring either at December 15, 1996 or at January 1, 1999. That is, we consider the model (8) with (11) and (12), where $\overline{\sigma}_{it}^2$ and $\overline{Q}_t$ are either constant or specified as $\overline{\sigma}_{it}^2 = \overline{\sigma}_{i1}^2 \mathtt{I}[t \leq \tau] + \overline{\sigma}_{i2}^2 \mathtt{I}[\tau > t]$ and $\overline{Q}_t = \overline{Q}_1 \mathtt{I}[t \leq \tau] + \overline{Q}_2 \mathtt{I}[\tau > t]$. Third and finally, we estimate three models with two instantaneous breaks occurring at both these dates, and affecting only the unconditional volatilities as in (9), or only the unconditional correlations as in (10), or both. For all ten specifications, we also esti-

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[10] Note that in this case $\hat{\varepsilon}_{it}$ and $\hat{z}_t$ change at each iteration of the nonlinear optimization procedure such that the unconditional sample volatilities and correlations need to be updated during the estimation process.

[11] The derivation of standard errors of the unconditional covariance matrix that is used for correlation targeting has not been worked out yet, at least not in analytic form. In the univariate context of volatility targeting in a GARCH(1,1) model, Kristensen and Linton (2004) propose to use a Newey-West type estimator, which we conjecture could also be used in the multivariate context, although its convergence rate is quite slow. We leave improvement of this approach open for future research.

[12] The analysis was also performed using bivariate models for all possible exchange rate pairs. This led to qualitatively and quantitatively similar results, which are available in full detail upon request.

[13] We should note that in all estimated models we do allow for as many structural changes in μ as there are breaks in the unconditional volatilities and correlations, as discussed below.

mate the corresponding constant conditional correlation (CCC) model of Bollerslev (1990), which sets $Q_t = \overline{Q}_t$ for all t in (12) or, equivalently, $R_t = \overline{R}_t$ for all t in (4).

Table 2 summarizes the estimation results, by showing the log-likelihood values for the CCC and DCC models, together with the estimates of the parameters γ and δ governing the correlation dynamics in the DCC model (12). These lead to several interesting conclusions. First, conditional correlations are time-varying, given the very large differences between the log-likelihood values of the DCC models and their CCC counterparts, irrespective of the specification of the unconditional volatilities and correlations. For example, in the most general specification with two breaks in both $\overline{\sigma}_{it}^2$ and $\overline{Q}_t$, the log-likelihood increases by 170 points from –4962 to –4792.

Second, allowing for structural breaks in unconditional volatilities and correlations considerably improves the fit of the model. Comparing the log-likelihood values for models with a single break, it appears that for both unconditional volatilities and correlations the most important change occurred in December 1996. The log-likelihood values of the models with two breaks in turn are considerably higher than those of the one-break models, suggesting that allowing for two structural changes is warranted.

Third, based on the log-likelihood values, structural changes in unconditional correlations appear to be more important than breaks in unconditional volatilities. The log-likelihood of the DCC model with two breaks in $\overline{Q}_t$ is equal to –4816, compared to –4899 for the DCC model with two breaks in $\overline{\sigma}_{it}^2$. The same is suggested by the estimates of the GARCH parameters α and β given in Table 3, and the estimate of $\overline{\sigma}_{it}$ in the DCC model with two breaks in unconditional volatilities and correlations shown in Figure 2, together with the estimated conditional standard deviations (in annualized percentage points). The GARCH parameter estimates hardly change when incorporating volatility breaks in the model, while the changes in the unconditional volatility are relatively small. An exception is the unconditional volatility of the Norges krone, which increased by about 50% at the end of 1996 due to the change in the intervention policy of Norges Bank. Nevertheless, both types of structural change appear to be relevant, as the model with break(s) in both unconditional volatilities and unconditional correlations substantially improves the fit compared to the models with break(s) in just one of the two. We remark that all improvements in fit due to allowing for breaks in unconditional volatilities and correlations mentioned above are statistically significant when tested formally using likelihood ratio statistics.

Fourth, allowing for structural breaks in correlations decreases the persistence of conditional correlations, as measured by $\gamma + \delta$. The estimate of δ declines if breaks are included, while the estimate of γ is virtually unchanged. The reduction in the estimate of δ from 0.968 in the standard DCC model to 0.947 in the model with two breaks in volatilities and in correlations may not appear to be all that large, but it does imply a substantial decline in persistence of shocks ε_t to the conditional correlations. Specifically, the half-life of shocks to the conditional correlations, computed as $\ln(0.5)/\ln(\hat{\gamma} + \hat{\delta})$, is reduced from 95 to 23 days.

Fifth, and perhaps most interesting, the DCC model with two breaks in unconditional volatilities and correlations confirms that the unconditional correlations were substantially lower between December 1996 and January 1999. This can be seen from Figures 3-5, displaying the estimated conditional correlations from this DCC model together with the corresponding elements of $\overline{Q}_t$.

We have not yet addressed the question of how the lower exchange rate correlations between the formal decision to proceed with the euro and its actual introduction might be explained. We attribute this to increased heterogeneity in the foreign exchange market during this intervening period. The Dublin meeting in December 1996 provided crucial information as to which countries committed themselves to take further steps towards economic and monetary unification. On the one hand, this event might have been perceived as a positive signal that the euro project was really moving towards success. According to the euro-advocates, the birth of the single currency was a matter of 'when', and not 'if'. On the other hand, the exclusion of the UK, Sweden and Denmark with their relatively recent impressive economic and monetary records, might have raised some doubts about the euro project. This negative view was particularly shared by those already skeptical of the idea of a single currency, believing that joining euro would further constrain growth of the participating countries, and therefore the euro should and would never come into existence. These two camps, the euro-advocates and the euro-sceptics, which had polarized already before the decision on ERM II, were then even more divided. This situation might have resulted in more disparate views held by both market participants and policy makers. In turn, these dissenting opinions might have led to more heterogeneity in the monetary and financial decisions taken by both investors and governments/central banks, particularly related to the exchange rates. Consequently, we could expect that the correlations among currencies of European countries, regardless of whether they are in or out of ERM II, would be weakened by the decisions made at the EC meeting in Dublin.

The formal euro introduction on January 1, 1999, confirmed that the EMU was indeed a viable project. After the launch of the euro, opinions among market participants and policy makers on the euro became less diverse as the uncertainty of whether the euro would come into existence or not had been eliminated, despite the continuing opposition from the euro-sceptics. As a result, the monetary and financial decisions related to the euro and non-euro currencies taken by investors, governments and central banks are expected to be more concerted compared to those taken during the intervening period. Hence we could expect that after the actual euro introduction, the correlations among euro and non-euro currencies would be strengthened again.

The results suggesting that all correlations substantially increased upon the introduction of the euro may also be attributed to the expected benefits from increasing monetary and financial integration in the euro. These benefits are (at least) threefold. First, the single currency helps euro area countries deal with asymmetric shocks. The elimination of exchange rate risk and the corresponding exchange rate premium provides more incentives to households and firms to diversify their investment portfolios by holding securities from other euro area countries. Thus, negative effects caused by a recession in a particular euro-area country would be mitigated more effectively as more residents of this country receive income earned from their investments in other euro-area countries. In this sense, financial integration works as an effective shock absorber that provides some assurance for the citizens of a euro-area country experiencing an asymmetric shock, especially in the absence of large EU fiscal stimuli.

Second, the elimination of exchange rate risk is also expected to provide more certainty to manufacturing and exporting firms on imported material costs and on export revenues, respectively. This might be expected to increase aggregate production and trade within euro area countries.

Third, the single currency ensures the existence of a stable monetary aggregate, which is vital for the ECB's success in monetary policy implementation. ECB's task is to optimally manage interest rates to influence real economic variables. Without a stable monetary aggregate, the ECB's monetary policy transmission mechanism will be ineffective. The euro introduction has created an integrated money market in the euro area and as a result, the existence of only one risk-free market rate stabilizes the monetary aggregate.

Having recognized the potential benefits described above, non-euro countries may wish to gain maximum positive spill-over effects by keeping their currencies more in line with the euro, explaining the increased correlations after January 1999.

Another explanation of the uniform increase of correlations among the different exchange rates relates to cross-border contagion in the banking sector, that is the transmission of idiosyncratic shocks affecting one bank or a group of banks in a given country to other (groups of) banks in other countries. Gropp and Vesala (2004) provide empirical evidence that the euro introduction has increased the relevance of such contagion effects, both among euro-area countries as well as between euro-area and non-euro countries. The integrated money market denominated in the common currency stimulates international transactions, especially among major banks that have good information and low transaction costs. Cross-border links among banks in different (euro-area and outside) countries are therefore strengthened and hence contagion becomes more prevalent and significant. Such stronger contagion may well have resulted in the increased correlations among the euro and non-euro currencies.

In addition to the sizeable breaks in the unconditional correlations, several large swings in the conditional correlations stand out in Figures 3-5. For example, the CHF-EUR conditional correlation declined substantially during the third quarter of 1997. This might be related to the Asian financial crises, particularly the resulting massive capital flight from individuals in affected countries to Swiss bank accounts. Swiss banks of course have a strong reputation worldwide as a safe haven for capital, due to their strict customer secrecy policy, among others. The fact that these unique characteristics of Swiss banks are not shared by banks in euro countries might explain why countries in the euro area did not share the Swiss experience in attracting capital from Asia during the crisis, leading to the all-time low CHF-EUR conditional correlation. A similar downward jump in the CHF-EUR conditional correlation occurred in the third quarter of 2001, presumably linked to the WTC attack on

September 11 and the subsequent war on terror.

The effective exchange rate of the British pound against the US dollar fell by around 12.5% in May 2000, completely eliminating the gains made by the pound over the previous six months. Apart from the period when the British pound left the ERM in 1992, this was the largest one-month change in its exchange rate against the US dollar since 1986. As this depreciation was not shared by other currencies, the correlations between the British pound and all other currencies dropped off substantially around that time.

Notable declines are also observed in the correlations involving the Norwegian krone in 1998. These declines are obviously related to the financial crises in Asia, Russia and Brazil, which severely affected Norway due to its heavy reliance on oil and gas exports. Weaker global demand contributed to a sharp fall in commodity prices including oil, which in turn worsened Norway's terms of trade and led to a substantial depreciation of the krone exchange rate; see also Akram (2004) for recent evidence on the sensitivity of the krone to the oil price. The Norwegian krone was down sharply from around 101 against the ECU at the beginning of 1998 to 115 in October, the weakest rate since the objective of exchange rate stability against the ECU was adopted. Norges Bank responded by raising its key interest rates in several steps in 1998. These rates were first raised in March after the krone weakened against the ECU during the first three months of the year. The krone then appreciated slightly and stabilized for a period, but pressure on the krone increased again during the summer. Norges Bank responded by raising interest rates on six further occasions. Following the last increase on August 25, the deposit rate and the overnight lending rate were 8% and 10%, respectively, or 4.5 percentage points higher than at the beginning of 1998. Norges Bank intervened to support the krone for the equivalent of NOK 29 billion in the period mid-October to mid-December. It was thought necessary to defend the krone through interventions in order to prevent a self-reinforcing and unnecessary weakening of the currency. Subsequently it was realized that the fluctuations in the exchange rate actually were amplified as a result of speculation, hedging and portfolio shifts in financial markets. These unfortunate events, together with Norway's unique economic characteristics compared to other European countries, made that all NOK correlations weakened to an unusual extent.

Finally, the Russian crisis and the ensuing unrest in international financial markets in the autumn of 1998 increased the risk aversion of investors and prompted a flight to safer assets and more secure currencies. This hit the Swedish krona (even though the economic fundamentals in Sweden were not bad in general), which explains the sharp declines in the correlations with the euro and Swiss franc observed in panels (b) of Figures 4 and 5.

5.1 Sensitivity analysis

We perform four robustness checks to validate and substantiate our empirical results as described above. First, we examine whether *a priori* imposing the breaks in unconditional volatilities and correlations to occur at December 15, 1996 and January 1, 1999 was appropriate. On the one hand, they are obvious break date 'candidates' given the important economic events that took place at these dates. On the other hand, it may be that the volatility and correlation changes actually occurred at different points in time. In particular, the introduction of the euro was decided and announced well before January 1999 and financial market participants may have changed their behavior already before this date. An obvious alternative candidate break date is May 2, 1998, when the precise membership of the first wave of EMU was decided upon and made public. To address this issue, we treat τ_1 and τ_2 in (9) and (10) as unknown parameters or, put differently, we determine the break dates endogenously. Joint estimation of the two change-points can in principle be done by means of a two-dimensional grid search over τ_1 and τ_2, using a pre-determined set $\mathcal{T}$ of 'allowable' break dates. However, in our case this is computationally prohibitive given the complexity of the model and the length of the time series. We therefore estimate the two break-points sequentially as follows.[14] We first estimate DCC models with a single break in the unconditional volatilities and correlations for all possible break-points in the inner 80% of the sample, that is between January 1, 1995 and December 31, 2002, approximately. Panel (a) of Figure 6 shows the resulting log likelihood values, from which we observe that the maximum (which delivers the estimate of the break date) occurs just before December 15, 1996. Formal test statistics for a break in volatilities and correlations occurring at an unknown point in time can be constructed from this series of log likelihood values, see Andrews (1993),

[14]Bai and Perron (1998) established the asymptotic properties of this sequential approach, demonstrating consistency and efficiency.

Andrews and Ploberger (1994), and Chu (1995). These convincingly reject the null hypothesis of no break. Next, we estimate DCC models with two breaks, fixing one of the breaks to occur at December 15, 1996 while the other break occurs at an unknown point in time, and requiring that at least 10% of the available subsamples are before and after each break. The resulting sequence of log-likelihood values in panel (b) of Figure 6 shows a clear maximum very close to January 1, 1999. Again, formal test statistics indicate that this second break is statistically significant. Based on the above analysis we conclude that imposing the breaks in unconditional volatilities and correlations to occur at the time of the formal decision to proceed with the euro in December 1996 and at the time of the actual introduction in January 1999 was appropriate.

Second, one may question whether the appropriate number of breaks indeed is two, or whether more breaks should be allowed for. We address this issue by estimating DCC models with three breaks in unconditional volatilities and correlations. We fix two of the breaks to occur at December 15, 1996 and January 1, 1999, while the third break occurs at an unknown point in time, as described above. This results in the sequence of log-likelihood values shown in panel (c) of Figure 6. We observe several local maxima (and hence candidate break dates) around July 1998, March 2000, and February 2002. The log-likelihood values at these points indicate a considerable improvement in fit relative to the model with two breaks. However, inspecting the resulting (un)conditional correlations, it appears that these potential third breaks are mostly currency-specific. As can also be seen from Figures 3-5, the break in July 1998 is relevant mostly for the Norwegian krone and to a lesser extent for the Swedish krona, as the correlations involving one of these two currencies experienced sharp declines. The probable cause for these large abrupt changes has been discussed before. The apparent break in March 2000 is caused by the substantial depreciation of the British pound leading to sharp but temporary declines in correlations with the other currencies, in particular with the euro and Swiss Franc. Similarly, increases in correlations of the British pound are responsible for the break in February 2002, although in addition we observe a considerable reduction in the correlation between the Norwegian krone and the Swedish krona around the same time. In sum, it seems that allowing for more breaks may be worthwhile, but that any such additional breaks are not common across all exchange rate pairs but rather currency-specific.[15]

Third, it might be argued that a gradual change in unconditional volatilities and correlations may be more realistic than the instantaneous jumps that we have used so far. To explore this possibility, we estimate a DCC model with such gradual changes by specifying $\overline{\sigma}_{it}^2$ in (11) and $\overline{Q}_t$ in (12) as

$$\overline{\sigma}_{it}^2 = \overline{\sigma}_{i1}^2(1 - G(t; \zeta_1, \tau_1)) + \overline{\sigma}_{i2}^2 G(t; \zeta_1, \tau_1)(1 - G(t; \zeta_2, \tau_2)) + \overline{\sigma}_{i3}^2 G(t; \zeta_1, \tau_1)G(t; \zeta_2, \tau_2), \tag{13}$$

$$\overline{Q}_t = \overline{Q}_1(1 - G(t; \zeta_1, \tau_1)) + \overline{Q}_2 G(t; \zeta_1, \tau_1)(1 - G(t; \zeta_2, \tau_2)) + \overline{Q}_3 G(t; \zeta_1, \tau_1)G(t; \zeta_2, \tau_2), \tag{14}$$

where

$$G(t; \zeta_j, \tau_j) = (1 + \exp(-\zeta_j(t - \tau_j)))^{-1}, \qquad \zeta_j > 0, \tag{15}$$

$j = 1, 2$, are logistic functions that change from 0 to 1 as t increases. The parameter ζ_j determines the smoothness of the change, with larger values of ζ_j implying faster transitions. Note that if $\zeta_j \to \infty$, the logistic function $G(t; \zeta_j, \tau_j)$ becomes indistinguishable from the indicator function $\mathtt{I}[t > \tau_j]$. Hence, the smooth transition DCC model nests the DCC model with discrete changes as a special case. For identification purposes, we impose the restriction $\tau_1 < \tau_2$, such that the unconditional correlations change from $\overline{Q}_1$ via $\overline{Q}_2$ to $\overline{Q}_3$ as time goes by.[16] An unfortunate feature of allowing for gradual changes is that volatility targeting and correlation targeting cannot be used to reduce the number of unknown parameters. Hence, we estimate the unconditional volatilities $\overline{\sigma}_{ij}^2$ for $i = 1, \ldots, N$ and $j = 1, 2, 3$ and the unconditional correlation matrices $\overline{Q}_j$, $j = 1, 2, 3$, along with the other parameters in the model (giving a total of 57 parameters to be estimated).[17] Imposing the changes in volatilities and correlations to be centered around December 15, 1996 and January 1, 1999 as before, the resulting estimates of the smoothness parameters in the

[15] A detailed analysis of the issue of the appropriate number of breaks in unconditional volatilities and unconditional correlations based on bivariate models is available upon request.

[16] Multivariate GARCH models with smoothly changing unconditional correlations are also considered by Longin and Solnik (1995), Berben and Jansen (2005) and Silvennoinen and Teräsvirta (2005). However, in both studies, this model is developed as an extension of the CCC-model, that is DCC-type dynamics in the conditional correlations are not allowed for.

[17] In the estimation procedure, we enforce that $\overline{Q}_t$ is a genuine correlation matrix by taking the Choleski decompositions of $\overline{Q}_j = P_j P_j'$, $j = 1, 2, 3$, where P_j is a lower triangular matrix and imposing constraints on the non-zero elements of P_j that lead to ones on the diagonal of $\overline{Q}_j$ and automatically give off-diagonal elements between −1 and 1; see Pelletier (2006) for details.

logistic transition functions (15) are quite large: $\hat{\zeta}_1 = 304$ and $\hat{\zeta}_2 = 165$.[18] These imply that from start to finish the first and second changes take about three and six months, respectively. As a further check, we also estimate bivariate DCC models with smooth structural changes. For most currency pairs the changes occur quite rapidly, as can be seen from Figures 3-5 where the resulting unconditional correlations are shown. Exceptions include the correlations among the Swiss Franc, the euro and the British pound, for which the second change in unconditional correlation materializes rather gradually. Generalizing the smooth transition DCC model to allow for correlation-specific speeds of change is problematic however, as it becomes difficult to guarantee that the resulting unconditional correlation matrix $\overline{Q}_t$ in (14) is positive semi-definite for all t; see Silvennoinen and Teräsvirta (2005) for further discussion.

Fourth, the DCC model may be deemed restrictive in the sense that all conditional correlations among the exchange rates are assumed to follow the same dynamics as determined by the parameters γ and δ in (7). To examine whether this is relevant for our daily exchange rate returns, we estimate a variant of the semi-generalized DCC (SGDCC) model developed by Hafner and Franses (2003), which allows for asset-specific news impact parameters by replacing (12) with

$$Q_t = \overline{Q}_t + \gamma\gamma' \odot (z_{t-1}z'_{t-1} - \overline{Q}_{t-1}) + \delta(Q_{t-1} - \overline{Q}_{t-1}), \tag{16}$$

where $\odot$ denotes the Hadamard product and $\gamma = (\gamma_1, \gamma_2, \ldots, \gamma_N)'$ now is an $(N \times 1)$ vector. Hence, in this model the effect of the cross-product $z_{i,t-1}z_{j,t-1}$ on q_{ijt} (and this on the conditional correlation ρ_{ijt}) is given by $\gamma_i\gamma_j$.[19] Estimating the ten possible models with the different number, types and location of break(s), we generally find a modest improvement in the log-likelihood values and moderate differences in the coefficients γ_i across currencies. For example, allowing for two breaks in both unconditional volatilities and correlations, the log-likelihood value for the SGDCC model is equal to -4781.60, compared to -4792.73 for the corresponding 'standard' DCC model. Hence, a formal likelihood ratio statistic for testing the restrictions $\gamma_1 = \gamma_2 = \ldots = \gamma_5$ would allow rejection of the DCC model at conventional signifi-

[18] The accompanying log-likelihood value is equal to -4767.56, compared to -4792.73 for the corresponding 'standard' DCC model with instantaneous changes in the unconditional volatilities and correlations.

[19] See Cappiello *et al.* (2003) for other generalizations of the DCC model.

cance levels against the SGDCC alternative. The estimates of γ_i (with QML standard errors in parentheses) are equal to 0.175 (0.019), 0.181 (0.018), 0.113 (0.018), 0.171 (0.025) and 0.142 (0.019) for CHF, EUR, GBP, NOK and SEK, respectively.[20] Hence, we conclude that there is some scope for generalizing the DCC model to allow for different dynamics in the conditional correlations, but that the standard model is sufficiently flexible to address the issue of breaks in unconditional correlations.

6 Concluding remarks

This paper has provided convincing evidence for structural breaks in unconditional correlations between the US dollar exchange rates of the British pound, Norwegian krone, Swedish krona, Swiss franc and the euro during the period 1994-2003. Using an extension of the dynamic conditional correlation (DCC) model, we find that such breaks occurred both at the time the formal decision to proceed with the euro was made in December 1996 and at the time of the actual introduction in January 1999. In particular, we document that most correlations were substantially lower during the intervening period. We attribute this decline in correlations to increased heterogeneity in the foreign exchange market due to dissenting opinions about the desirability and viability of the single currency. In addition, the strong and uniform increase of the correlations following the actual euro introduction may be caused by the fact that non-euro countries recognized the potential benefits of the elimination of exchange rate risk for firms, policy makers and investors, and now try to gain maximum positive spill-over effects by keeping their currencies more in line with the euro.

Our results have clear implications for financial decision making. For example, adequate currency risk management requires accurate modelling of volatility and correlation patterns of exchange rates. Our analysis demonstrates that allowing for time-varying conditional volatilities and correlations by means of a standard DCC model may not be sufficient in this respect. Incorporating occasional structural breaks in unconditional volatilities and correlations may be necessary.

[20] These may be compared with the square root of the estimate of γ in the DCC model with two volatility and correlation breaks, which is equal to 0.152.

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Table 1: Exchange rate returns - summary statistics

Currency	Mean	StD	Skew	Kurt	Correlations				
					CHF	EUR	GBP	NOK	SEK
January 1, 1994-December 31, 2003									
CHF	−1.845	10.70	−0.225	4.817	1.000	0.926	0.581	0.752	0.646
EUR	−1.073	9.73	−0.104	4.264		1.000	0.607	0.812	0.713
GBP	−1.892	7.56	0.080	4.510			1.000	0.534	0.483
NOK	−1.225	9.73	−0.104	5.900				1.000	0.731
SEK	−1.481	9.88	−0.019	4.282					1.000
January 1, 1994-December 15, 1996									
CHF	−4.148	11.18	−0.369	6.718	1.000	0.942	0.621	0.887	0.531
EUR	−4.004	9.48	−0.060	5.686		1.000	0.658	0.945	0.559
GBP	−3.956	7.09	0.396	6.380			1.000	0.674	0.470
NOK	−5.165	8.30	−0.036	5.462				1.000	0.626
SEK	−6.969	8.92	0.186	4.334					1.000
December 16, 1996-December 31, 1998									
CHF	2.071	10.49	−0.380	4.003	1.000	0.886	0.416	0.565	0.585
EUR	3.701	9.16	−0.237	3.559		1.000	0.447	0.680	0.662
GBP	−0.074	8.00	−0.040	4.454			1.000	0.348	0.377
NOK	7.778	11.47	−0.333	7.993				1.000	0.706
SEK	8.660	10.02	−0.568	5.590					1.000
January 1, 1999-December 31, 2003									
CHF	−2.086	10.50	−0.056	3.666	1.000	0.935	0.631	0.784	0.737
EUR	−1.292	10.10	−0.081	3.767		1.000	0.646	0.821	0.806
GBP	−1.415	7.64	−0.019	3.668			1.000	0.565	0.533
NOK	−2.580	9.72	−0.012	3.806				1.000	0.793
SEK	−2.386	10.34	0.098	3.758					1.000

Note: The table reports summary statistics of daily exchange rate returns. StD denotes standard deviation, Skew is skewness and Kurt is kurtosis. Mean returns and standard deviations are given in annualized percentage points.

Table 2: Estimated DCC models for daily exchange rate returns

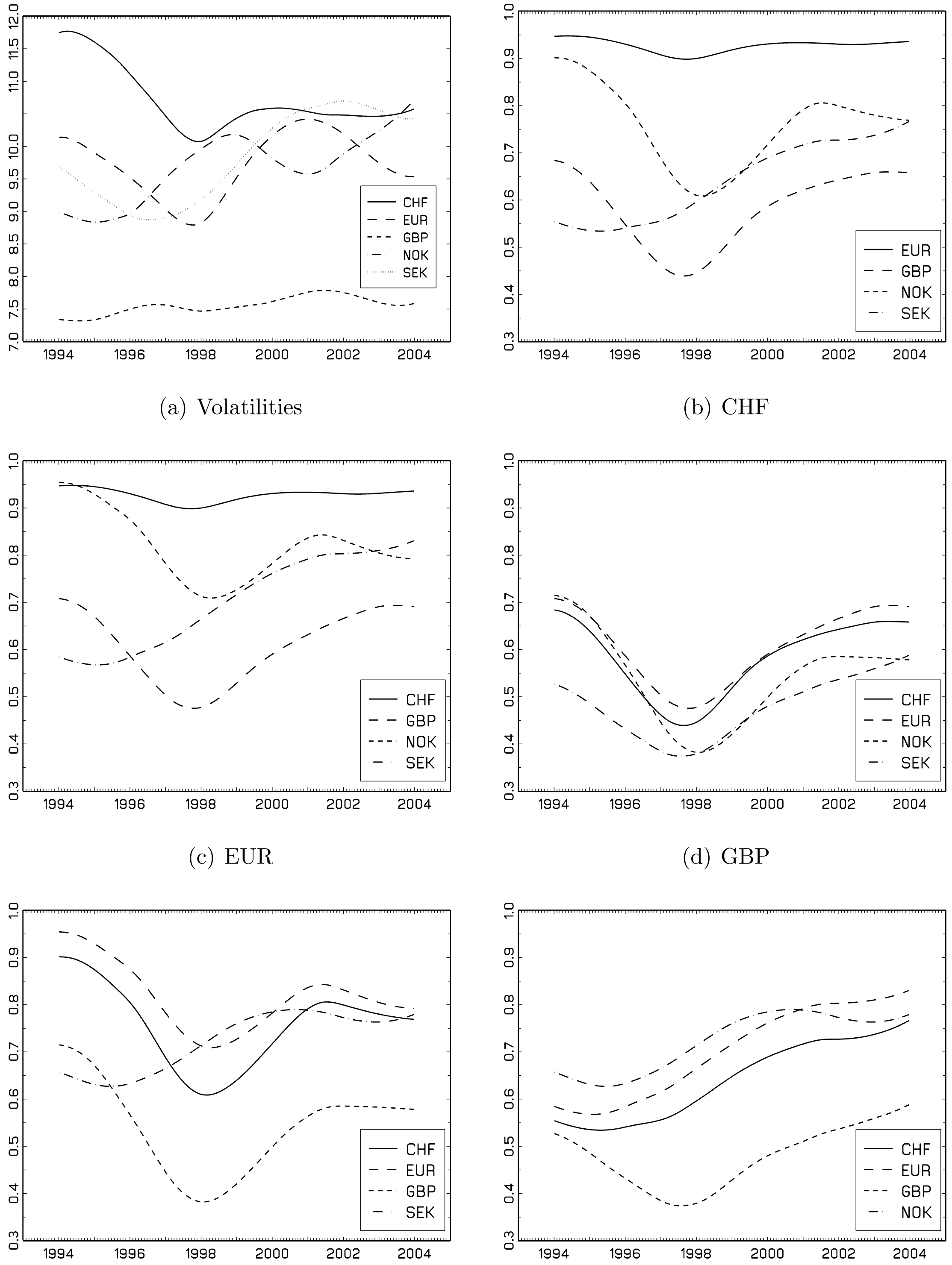
Model	$\mathcal{L}$(CCC)	$\mathcal{L}$(DCC)	γ	δ
NB	-5448.70	-4931.56	0.025	0.968
			(0.003)	(0.005)
SBV(12-15-1996)	-5426.94	-4907.17	0.025	0.967
			(0.003)	(0.005)
SBV(12-31-1998)	-5446.54	-4921.80	0.025	0.968
			(0.003)	(0.005)
SBC(12-15-1996)	-5112.37	-4850.85	0.024	0.956
			(0.004)	(0.009)
SBC(12-31-1998)	-5332.24	-4925.56	0.024	0.967
			(0.003)	(0.006)
SBVC(12-15-1996)	-5091.68	-4834.65	0.024	0.956
			(0.004)	(0.008)
SBVC(12-31-1998)	-5322.70	-4919.07	0.024	0.966
			(0.003)	(0.006)
TBV	-5422.66	-4899.00	0.025	0.967
			(0.003)	(0.005)
TBC	-4991.13	-4816.42	0.023	0.948
			(0.004)	(0.012)
TBVC	-4961.64	-4792.73	0.023	0.947
			(0.004)	(0.012)

Note: The table reports estimation results of of CCC and DCC models for daily exchange rate returns over the period January 1, 1994-December 31, 2003. NB denotes the model with no structural breaks; XBV (XBC) denotes models with structural breaks in the unconditional volatilities (correlations) and no breaks in the unconditional correlations (volatilities); XBVC denotes models with structural breaks in both the unconditional volatilities and in the unconditional correlations; X=S or T depending on whether a single (S) or two (T) structural breaks are allowed for. $\mathcal{L}$(CCC) and $\mathcal{L}$(DCC) denote the log-likelihood values of the CCC and DCC models, respectively. Point estimates of the parameters γ and δ in the DCC model (12) are given, with Bollerslev-Wooldridge type QML standard errors given in parentheses.

Table 3: Estimated GARCH(1,1) models for daily exchange rate returns

Currency	NB		SBVC(12-15-1996)		TBVC	
	α_i	β_i	α_i	β_i	α_i	β_i
CHF	0.047	0.928	0.046	0.922	0.044	0.922
	(0.009)	(0.016)	(0.010)	(0.020)	(0.009)	(0.022)
EUR	0.047	0.935	0.046	0.931	0.044	0.930
	(0.008)	(0.014)	(0.010)	(0.019)	(0.009)	(0.019)
GBP	0.046	0.919	0.048	0.910	0.049	0.904
	(0.011)	(0.024)	(0.012)	(0.026)	(0.011)	(0.027)
NOK	0.058	0.927	0.050	0.927	0.046	0.930
	(0.016)	(0.023)	(0.015)	(0.026)	(0.012)	(0.024)
SEK	0.038	0.949	0.034	0.952	0.033	0.955
	(0.007)	(0.012)	(0.014)	(0.014)	(0.007)	(0.013)

Note: The table reports estimates of the GARCH parameters α_i and β_i in the DCC model with no structural breaks (NB), and in the DCC models with a single and two structural breaks in the unconditional volatilities and unconditional correlations (SBVC and TBVC). Bollerslev-Wooldridge type QML standard errors are given in parentheses.



(a) Volatilities

(b) CHF

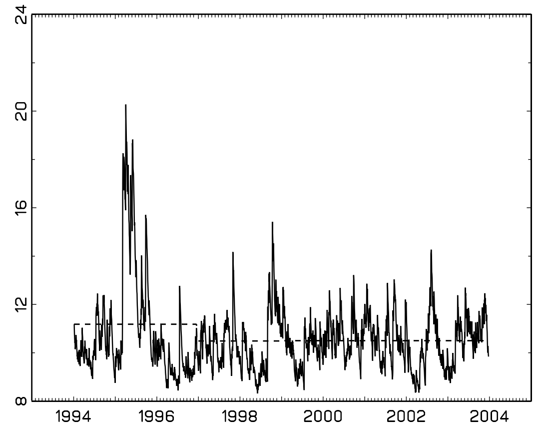
(c) EUR

(d) GBP

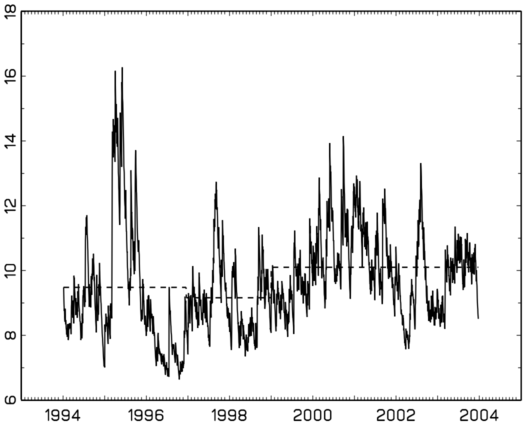
(e) NOK

(f) SEK

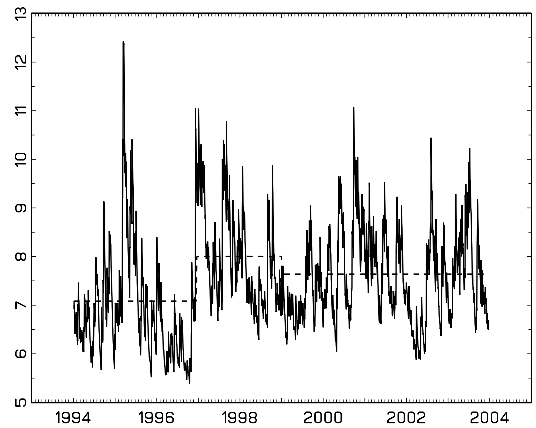
Figure 1: Nonparametric volatility estimates (panel (a)) and correlation estimates (panels (b)-(f)) for daily exchange rate returns over the period January 1, 1994-December 31, 2003, obtained from (1) using a quartic kernel function with bandwidth $h = 1$.



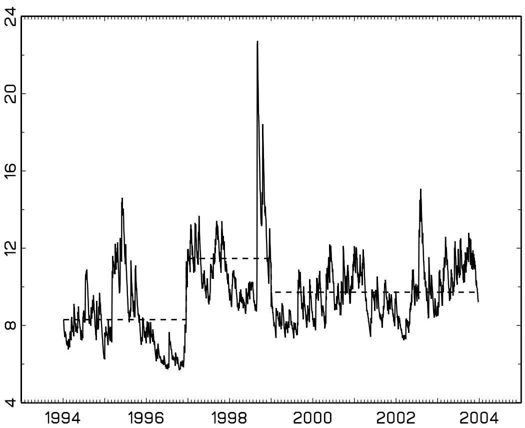
(a) CHF



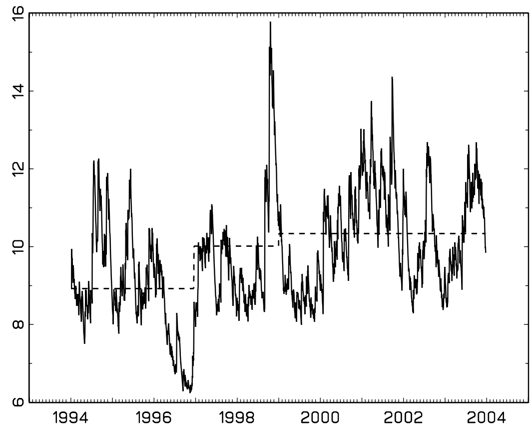
(b) EUR



(c) GBP

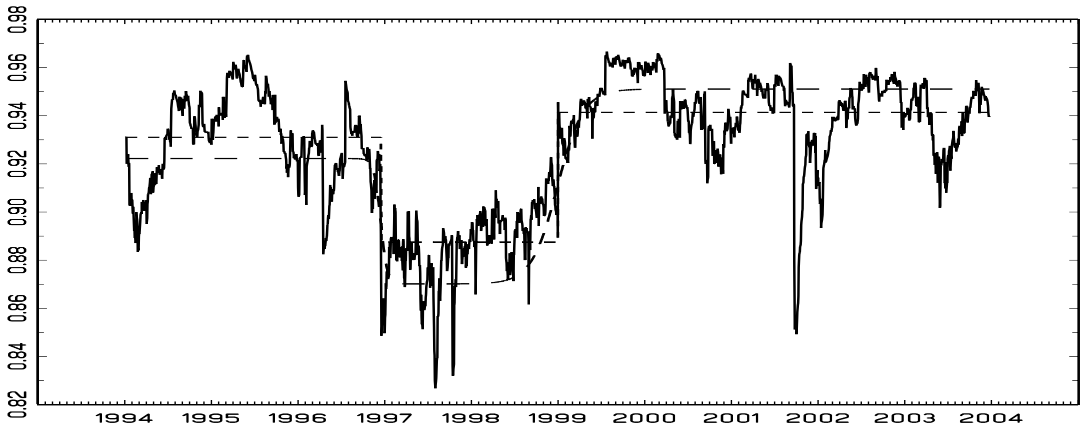


(d) NOK

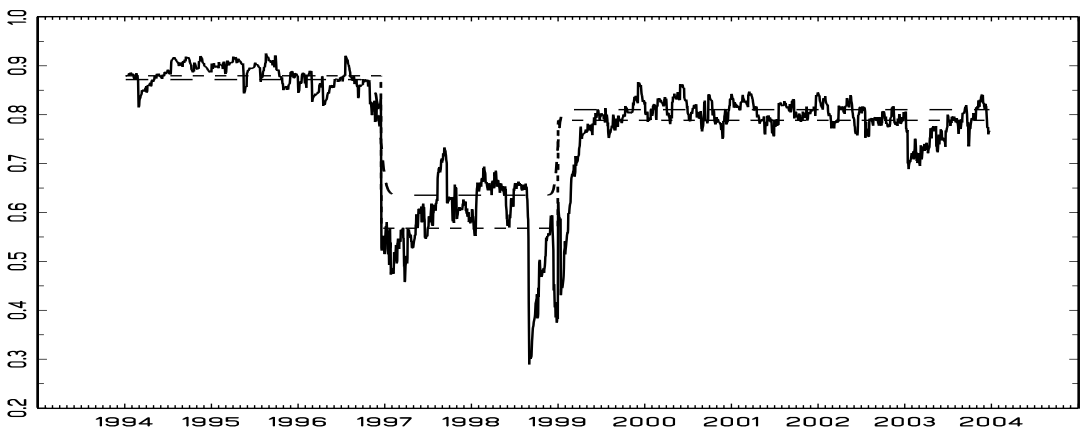


(e) SEK

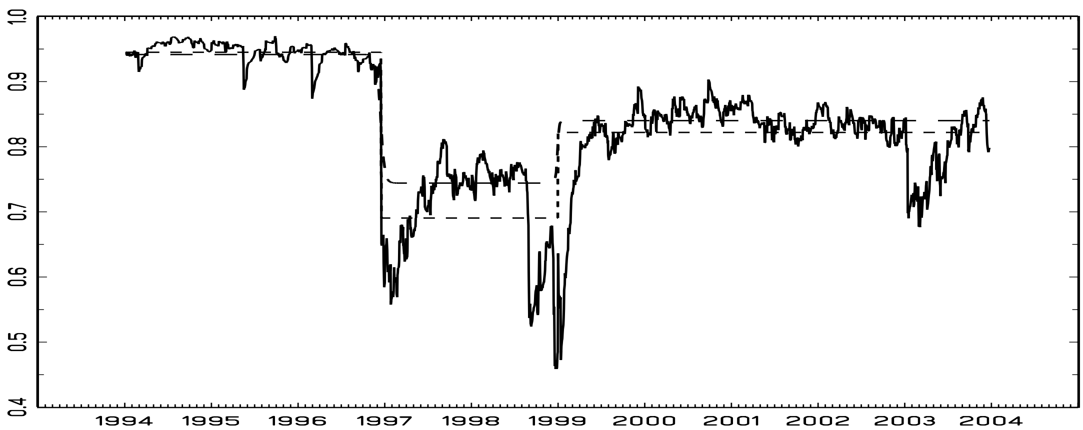
Figure 2: Conditional volatilities of daily exchange rate returns in GARCH(1,1) model with breaks in unconditional volatilities occurring at December 15, 1996 and January 1, 1999 (solid line). Dashed lines are unconditional variances.



(a) CHF-EUR

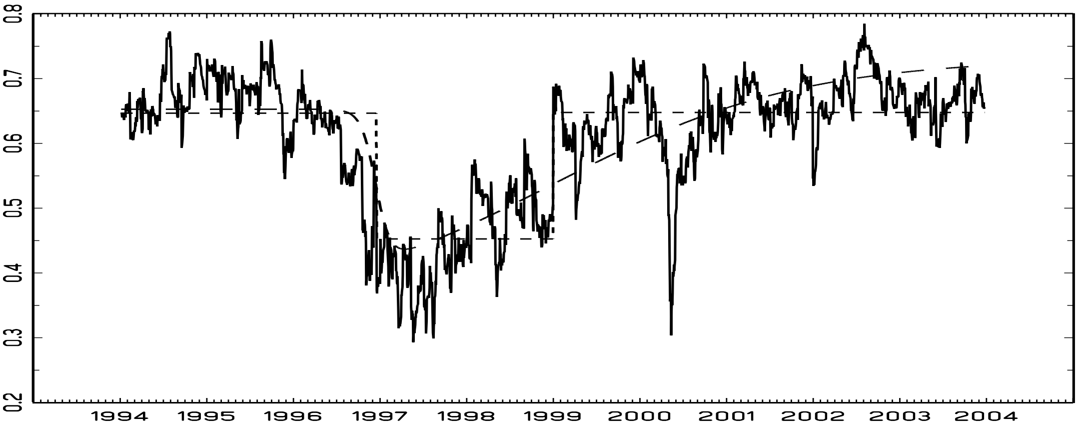


(b) CHF-NOK

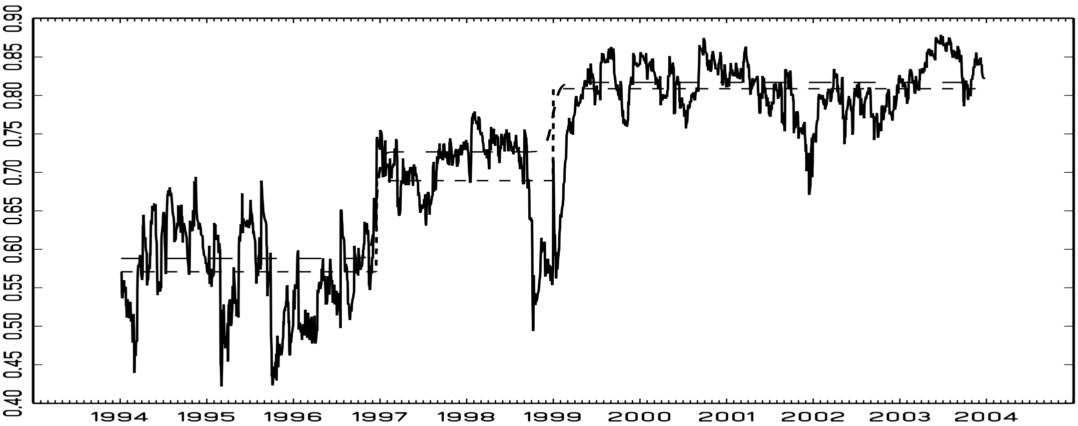


(c) EUR-NOK

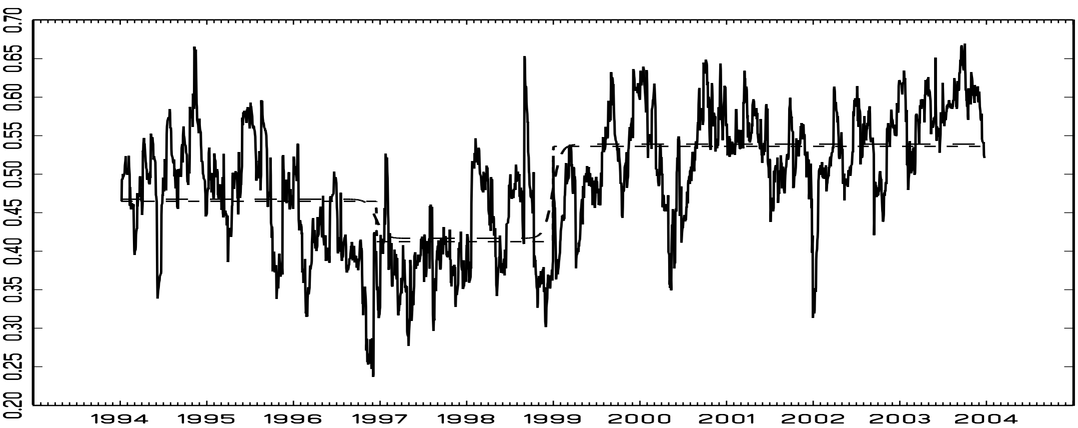
Figure 3: Dynamic conditional correlation between daily exchange rate returns in DCC model with breaks in unconditional volatilities and unconditional correlations occurring at December 15, 1996 and January 1, 1999 (solid line). Short-dashed lines are unconditional correlations. Long-dashed lines are unconditional correlations in bivariate smooth transition DCC models.



(a) EUR-GBP

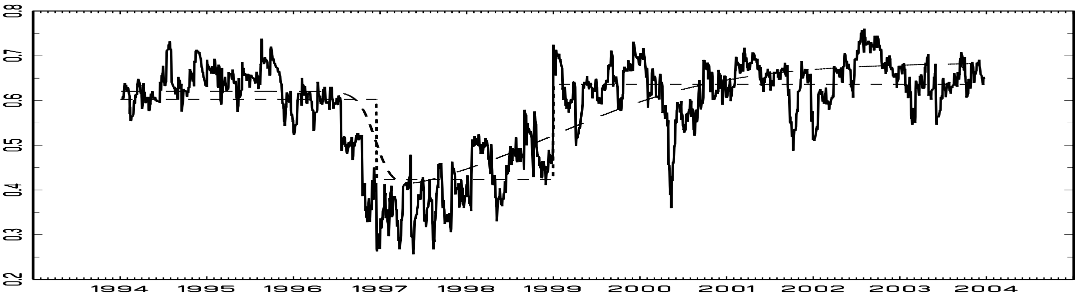


(b) EUR-SEK

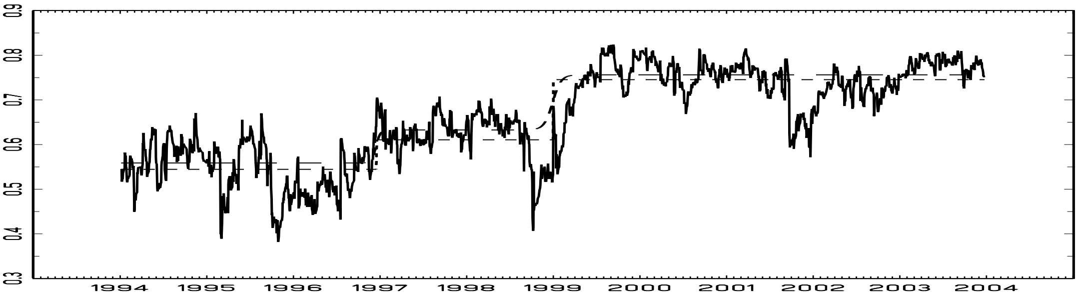


(c) GBP-SEK

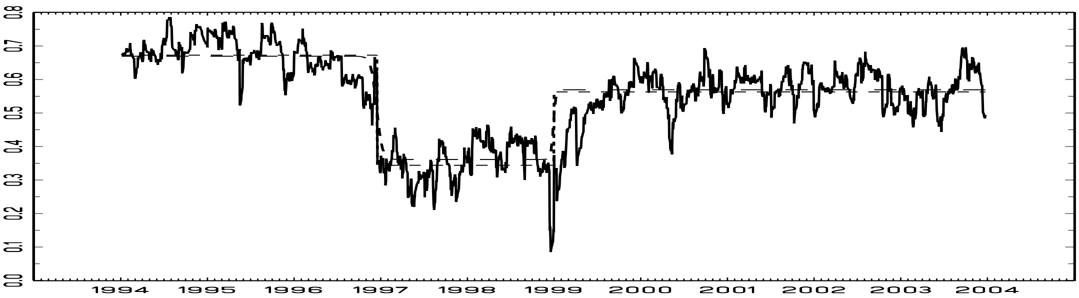
Figure 4: Dynamic conditional correlation between daily exchange rate returns in DCC model with breaks in unconditional volatilities and unconditional correlations occurring at December 15, 1996 and January 1, 1999 (solid line). Short-dashed lines are unconditional correlations. Long-dashed lines are unconditional correlations in bivariate smooth transition DCC models.



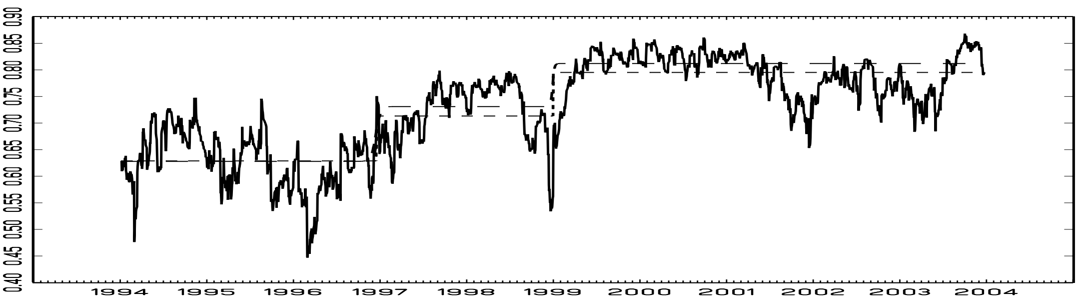
(a) CHF-GBP



(b) CHF-SEK

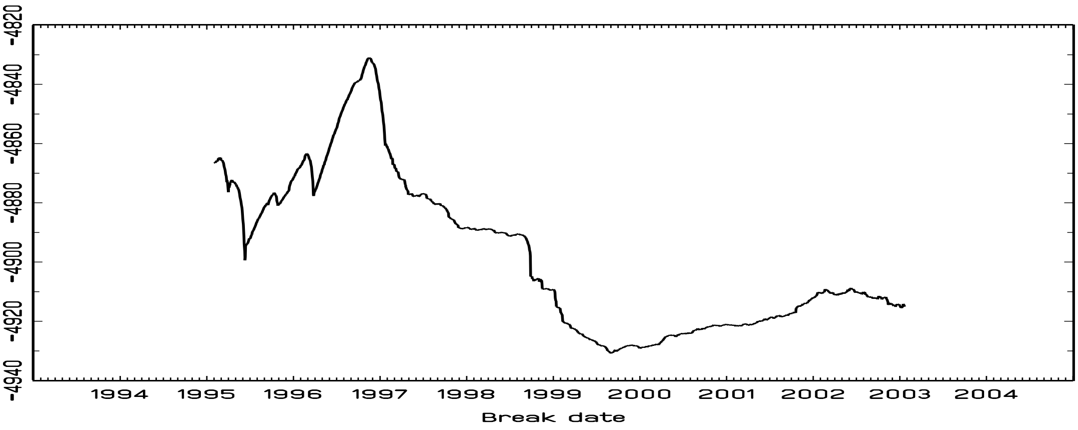


(c) GBP-NOK

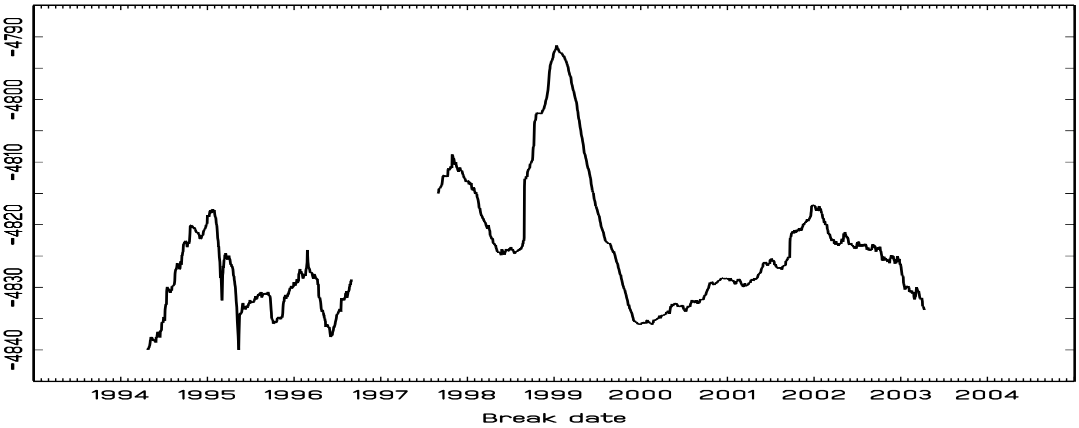


(d) NOK-SEK

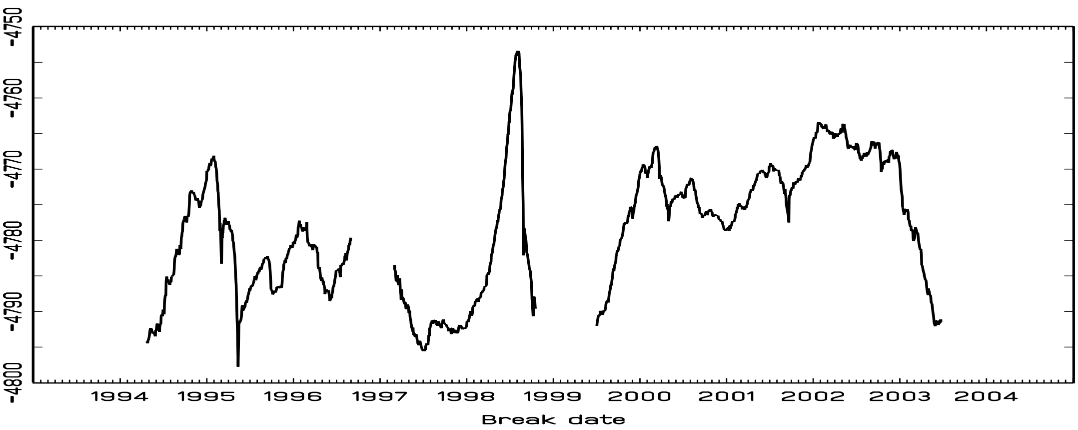
Figure 5: Dynamic conditional correlation between daily exchange rate returns in DCC model with breaks in unconditional volatilities and unconditional correlations occurring at December 15, 1996 and January 1, 1999 (solid line). Short-dashed lines are unconditional correlations. Long-dashed lines are unconditional correlations in bivariate smooth transition DCC models.



(a) Single break



(b) Two breaks



(c) Three breaks

Figure 6: Log-likelihood value for different break dates in DCC model with a single break (panel (a)), with two breaks where one of the breaks occurs at December 15, 1996 (panel (b)), and with three breaks where two of the breaks occur at December 15, 1996 and January 1, 1999 (panel (c)).