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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 British pound, Norwegian krone, Swedish krona, Swiss franc, and euro exchange rates (against the US dollar) 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 intermittent 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; Billio and Pellizon, 2003; Bartram *et al.*, 2004; Guiso *et al.*, 2004), 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, 2003), the behavior of nominal exchange rates of euro-zone countries in the run-up to the common currency (Frömmel and Menckhoff, 2001; Bond and Najand, 2002; Frömmel, 2004), 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. However, to the best of our knowledge, the impact of the euro introduction on the properties of exchange rates themselves has not been investigated before for European countries outside the euro-zone. In this paper, we aim to fill this gap. In particular, we consider the behavior of daily exchange rates of the Swiss franc, British pound, Norwegian krone, and Swedish krona against the US dollar over the period from January 1, 1994 until December 31, 2003.[2] We concentrate on the volatility and correlation properties of these exchange rates, paying particular attention to the co-movement with the euro (and its predecessor the ECU) and changes therein.

The analysis is performed in the framework of the dynamic conditional correlation

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[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.

[2] We do not include the Danish krone in the analysis. Denmark 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. Also, Greece is not considered, although it adopted the euro only two years after its initial introduction.

(DCC) model introduced by Engle (2002), which we extend to allow for structural changes in the unconditional correlations. 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 intermittent period. Breaks also occurred in the unconditional exchange rate volatilities, but these were of a much smaller magnitude comparatively.

The plan of the paper is as follows. In Section 2, we sketch 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. We describe the daily exchange rate series in Section 3. In Section 4, we develop the extended DCC models allowing for structural breaks in unconditional volatilities and correlations. In Section 5, we discuss the empirical results. Finally, Section 6 concludes.

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 decided to adopt 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).[3]

Countries in Europe have long been passionate with the objective of reducing intra-currency 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 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 ECU was intended to function as the numeraire of the exchange rate mechanism (ERM), implying that the central rates of the participating currencies were expressed in terms of the ECU. The ECU central rates were

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[3] This section draws upon information available at the websites of the European Council (`http://ue.eu.int/`), the ECB (`http://www.ecb.int/`), the Norges Bank (`http://www.norgesbank.no/`), the Swiss National Bank (`http://www.nationalbank.ch/`), the Bank of England (`http://www.bankofengland.uk/`), and the Swedish Riksbank (`http://www.riksbanken.se/`).

then used to determine the bilateral ERM central rates around which intervention rates were fixed.

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 an improvement in overall economic performance, for example through protecting intra-European trade from excessive exchange rate uncertainty.

In June 1988 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.[4] The EMI itself had no responsibility for the conduct of monetary policy nor had

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[4] In more detail, the EMI undertook (i) to prepare a range of instruments and procedures for the conduct of monetary policy and to analyse potential monetary policy strategies, (ii) to promote the harmonisation of the collection, compilation and distribution of euro-area statistics concerning money and banking, balance of payments and other financial data, (iii) to develop the framework for conducting foreign exchange operations as well as for holding and managing the official foreign exchange reserves of Member states, (iv) to promote the efficiency of cross-border payment and securities settlement transactions, and (v) to prepare the euro banknotes. Furthermore, for the establishment of the ESCB, the EMI specifically took on the task of (i) elaborating harmonised accounting rules and standards to make it possible to construct a consolidated balance sheet of the ESCB for internal and external reporting purposes, (ii) putting in place the necessary information and communications systems support for the operational and policy functions to be undertaken within the ESCB, and (iii) identifying the possible ways in which the ESCB would

it any competence for carrying out foreign exchange intervention. In December 1995, the European Council agreed upon the name of 'euro' for the single European currency to be introduced at the start of Stage Three of EMU, and confirmed that this 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 the introduction of the euro on January 1, 1999 was actually made.[5]

Upon the start of the third and final stage of EMU on January 1, 1999, the exchange rates of the currencies of the 11 participating Member States were irrevocably fixed.[6] The European Central Bank took over responsibility for conducting the single monetary policy in the euro area. Also, the ESCB, consisting of the European Central Bank (ECB) and the national central banks of the EU member states, started to operate. Both the intra-EU exchange rate mechanism (ERM II) and the Stability and Growth Pact entered into force. And of course, last but not least, the single common currency was introduced.

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 in progressive stages of economic and monetary union. 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

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contribute to the policies conducted by the competent supervisory authorities to foster the stability of credit institutions and the financial system.

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

[6] In May 1998, it was decided that 11 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 irrevocable conversion rates for the euro.

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. In theory, these tests will be 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.

These decisions are not surprising given the positive track record of the Bank of England in its conduct of monetary policy. One of the core purposes of the Bank of England is maintaining the integrity and value of monetary policy which is pursued primarily through guarding price stability. In 1992, the Bank adopted a formal inflation target. 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 is required to specify what its economic objectives are, including what is meant by price stability. If inflation deviates from target by more than 1%, the Governor is required to write to the Chancellor explaining the circumstances and setting out what action the Monetary Policy Committee considers necessary to return to target. In 1997, the Bank of England was granted operational independence, which further enhanced the credibility of inflation targeting. Against the target of 2.5% for RPIX (the short term interest rate) which ran from 1997 until December 2003, average inflation was 2.4%. For 68 out of the 79 months, inflation was within 0.5 percent of the target - below it for 42 months, above it for 30, and on target for the remaining seven.

Although joining euro seems distant, since 1996, the Bank of England has been publishing technical information on the euro concerning two important aspects. First, the evolution of the euro financial markets in practice and second, the technical financial sector preparations for potential UK entry to EMU.

2.1.2 Sweden

On November 19, 1992, the Sveriges Riksbank (Swedish Central Bank) abandoned its policy of pegging the value of 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 II was not feasible in the near future. Neither were the experiences of money stock targeting in other countries encouraging. Furthermore, the financial system was in the midst of a deep crisis, which made the stability of money demand questionable and successful targeting of the money stock unrealistic.

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

In late 1998, the Riksdag (Swedish Parliament) approved changes to the Riksbank Act making the central bank more legally independent and formalizing objectives towards an inflation-targeting regime. Sweden had to make the Riksbank 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 has not adopted the euro and is therefore not a full participant in the EMU, there has been 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 was taken 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 (in theory at least) convert to the euro at some point. Notwithstanding this, on September 14, 2003 a referendum on the euro was held, the result of which was a rejection of the common currency by a 14 percentage point margin (56 to 42 percent, with 2 percent voting ‘blank’). 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 ERM II member.

Despite the lack of an opt-out option, the Swedish government has argued that complying with the referendum result is possible given that one of the requirements for adopting the euro is a prior two-year membership of ERM II. By simply choosing to stay outside the exchange rate mechanism, the Swedish government is provided a formal loophole avoiding the theoretical requirement of adopting the euro.

2.1.3 Norway

Monetary policy in Norway has been oriented towards maintaining exchange rate stability for almost the entire post-World War II period. When the Bretton Woods system collapsed in the early 1970s, Norway joined the currency 'snake'.[7] However, when the European Monetary System (EMS) was set up in 1979 Norway chose to link its krone to a trade-weighted basket of currencies.

In spite of 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 the loss of cost competitiveness due to 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 very 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', now aiming at keeping the exchange rate 'stable' against European currencies, but with no fluctuation margins. A drastic change in Norwegian exchange rate policy was made on January 10, 1997 as monetary authorities decided to discontinue the interventions that had been necessary to stabilize the Norwegian krone exchange rate.

Petroleum activity constitutes an important part of the Norwegian economy. Oil and

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[7] Prior to the collapse, the fluctuation band in the Bretton Woods system was widened to ±2.25%. Following this, the European Community (EC) currencies could fluctuate against each other by as much as 9%. In order to stabilize the exchange rates within the EC, a European currency system was therefore established in 1972. It reduced the overall fluctuation band between the EC currencies to 4.5%. This system was known as the 'snake' as the exchange rates could 'slither' between the margins fixed by the Bretton Woods system.

gas account for the largest share of Norwegian exports. In 1998, the world economy was hit by the financial crisis in Asia, Russia and Brazil, falling commodity prices and widespread unrest in international financial markets. The Asian crisis proved to be more serious and prolonged than envisaged, and the contagion effects were more severe than most observers had anticipated. Weaker global demand contributed to a sharp fall in commodity prices, which in turn had a severe impact on commodity-based economies such as Norway. The terms of trade worsened and the krone exchange rate depreciated substantially; see also Farooq 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 (the Norwegian Central 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% 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.

On March 29, 2001, the Government approved a new operational target for monetary policy. Norges Bank sets the key interest rate with a view to maintaining low and stable inflation. The inflation target is set at 2.5%. 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 overriding 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. 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. Effectively, the stability was due to convergence in economic fundamentals and similarities in monetary policy.

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). The SNB implemented a pragmatic monetary policy aimed towards granting the Swiss economy the monetary flexibility necessary for handling these risks and uncertainties. On December 11, 1998, the SNB Governing Board, in agreement with the Federal Government, decided to continue this policy in 1999 during Stage Three of EMU. 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.

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.

The Dublin meeting 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 and the birth of euro as common currency was a matter of 'when', not a matter of 'if'. On the other hand, the exclusion of the UK, Sweden and Denmark with their successful economic and monetary records relative to other European countries, might have raised further doubts about the euro project. This view was particularly shared by those already skeptical of the euro as a single currency, believing that joining euro would further constrain growth and welfare 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 ERM II, were then even more divised. 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 and central banks, particularly related to the exchange rates. Consequently, we could expect that the correlations among currencies of the countries, regardless whether they are in or out of ERM II, would be weakened by the decisions made at the EC meeting in Dublin in December 1996.

The second event, 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 group. As a result, the monetary and financial decisions related to the euro and non-euro currencies, performed by investors and governments/central banks are expected to be more concerted compared to those taken during the intermittent period. Consequently, we could expect that after the actual euro introduction, the correlations among euro and non-euro currencies would be strengthened again.

3 Data

We consider daily exchange rates of the Swiss franc (CHF), euro (EUR), British pound (GBP), Norwegian krone (NOK), and Swedish krona (SEK) against the US dollar over the period from January 1, 1994 (the start of Stage Two of EMU) until December 31, 2003 (2544 observations). Up to December 31, 1998, the euro series actually concerns the ECU exchange rate, while the euro exchange rate is used as of January 1, 1999.[8] The data is obtained from the ECB website and concerns the reference rates that are based on the regular daily concertation procedure between central banks within and outside the ESCB, which normally takes place at 2.15 p.m. ECB time (CET).

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

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[8] We acknowledge that the British pound and Swedish krona were part of the ECU, which potentially affects our results. We address this concern by repeating the entire empirical analysis using the German Deutschmark instead of the ECU for the pre-euro period, which leads to qualitatively and quantitatively similar findings.

that we distinguish. The first period runs from January 1, 1994 until December 14, 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 $N = 5$. A nonparametric estimate of the correlation matrix R_t at $t = \tau$ can be obtained as

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

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

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

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 $t = \tau$.[9] 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 return 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 appreciation of the US dollar. The standard deviation of exchange rate returns remained relatively stable across subperiods, although it can be observed that all currencies except the SEK experienced somewhat lower volatility between 1996 and 1999, 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 Norwegian krone between December 1996 and January 1999. For the Swiss

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[9] A detailed discussion of this type of nonparametric volatility and correlation estimates can be found in Hafner, van Dijk and Franses (2005).

franc, the euro and the Norwegian krone, the absolute magnitude of the skewness declined over time. For the British pound, skewness was smaller during the second subperiod, while for the Swedish krona the reverse pattern is found. Similar patterns are found for the kurtosis.

Turning to the correlations, when computed over the full sample period these are quite high, ranging between 0.530 for the British pound and Swedish krona to 0.925 for the Swiss franc and the euro. Comparing the correlations during the three 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 policy. Around the time of the actual introduction of the euro in January 1999, these correlations increased again. For the CHF, EUR and GBP, correlations in fact appear to have returned to their pre-1997 levels, while correlations of these exchange rates with the NOK remained somewhat below this initial level. Correlations of the Swedish krona with the other exchange rates 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 daily exchange rate returns 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

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

where $\varepsilon_{it} = r_{it} - \mu_{it}$, $\omega_i > 0$, $\alpha_i > 0$, $\beta_i \geq 0$ and $\alpha_i + \beta_i < 1$, for $i = 1, \ldots, N$.[10]. 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

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

Engle and Mezrich (1996) developed the idea of volatility targeting, which essentially means that $\overline{\sigma}_i^2$ is not treated as an unknown parameter, but is replaced by its sample analogue $\widehat{\overline{\sigma}}_i^2 = \frac{1}{T}\sum_{t=1}^T \varepsilon_{it}^2$, with T denoting the sample size, in the estimation of the remaining parameters α_i and β_i. This ensures that the unconditional volatility as implied by the model equals the sample variance of ε_{it}.

For the conditional correlation matrix R_t we employ the dynamic conditional correlation (DCC) model introduced by Engle (2002). A very 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,[11]

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

$$R_t = Q_t^{*\,-1} Q_t Q_t^{*\,-1}, \tag{8}$$

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.

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[10] Given that our empirical application involves exchange rate returns, there is no obvious reason or motivation to consider nonlinear GARCH models such as the GJR-GARCH model of Glosten, Jagannathan and Runkle (1993) to allow for different effects of positive and negative unexpected returns $\varepsilon_{i,t}$ on conditional volatility.

[11] Alternative models that allow for time-varying correlations are developed in Pelletier (in press) 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.* (2005) generalize the latter approach by combining (2)-(1) with univariate GARCH models for the conditional volatility. We refer to Bauwens *et al.* (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.

We are particularly interested in examining the possibility of structural changes in the unconditional volatilities and unconditional correlations due to (decisions concerning) the introduction of the euro. For that purpose, we extend the DCC model to allow for breaks in $\overline{\sigma}_i^2$ in (6) and $\overline{Q}$ in (7). The most general model that we consider in the next section allows for two breaks in both the unconditional volatilities and unconditional correlations. This model is obtained by replacing $\overline{\sigma}_i^2$ and $\overline{Q}$ with $\overline{\sigma}_{it}^2$ and $\overline{Q}_t$, respectively, which are defined as

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

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

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.

The attractive feature of the DCC model is that estimation of the parameters in the model can be performed 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, estimate the univariate GARCH(1,1) models to obtain estimates of the conditional variances σ_{it}^2. Here, $\overline{\sigma}_i^2$ in the specification given in (6) can be replaced by the sample variance of the residuals $\hat{\varepsilon}_{it} = r_{it} - \hat{\mu}_{it}$. Similarly, in the specification with breaks in unconditional volatilities, volatility targeting can still be employed by replacing $\overline{\sigma}_{ij}^2$, $j = 1, 2, 3$, in (9) with their sample analogues. Third, estimate the parameters in the model for R_t. "Correlation targeting" can be used here, by replacing $\overline{Q}$ in (7) with the sample covariance matrix $\frac{1}{T}\sum_{t=1}^{T} \hat{z}_t \hat{z}_t'$ of the standardized residuals $\hat{z}_t \equiv \hat{S}_t^{-1} \hat{\varepsilon}_t$. Again, if breaks in the unconditional correlations are incorporated as in (10), sample analogues of $\overline{Q}_j$, $j = 1, 2, 3$, can be used. This imposes the restriction that the unconditional correlations as implied by the model equal the unconditional sample correlations, and reduces the number of parameters to be estimated in the second step to two, namely γ and δ. See Engle and Sheppard (2001) for analysis of the properties of the three-step estimation procedure in this context. Due to the sequential estimation of the model parameters, inference becomes a nontrivial issue, because the standard errors of the correlation parameters depend on the estimates of the conditional mean 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.[12]

5 Empirical results

We estimate the DCC model discussed in the previous section for the five-dimensional vector of daily exchange rate returns, $r_t = (\mathrm{CHF}_t, \mathrm{EUR}_t, \mathrm{GBP}_t, \mathrm{NOK}_t, \mathrm{SEK}_t)'$.[13] 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.

We estimate ten different DCC 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 $\overline{\sigma}_i^2$ only, in the unconditional correlations $\overline{Q}$ only, or in both, with the change occurring either at December 15, 1996 or at January 1, 1999. Finally, we estimate three models with two breaks occurring at both these dates, and affecting only the unconditional volatilities, or only the unconditional correlations, or both. For all ten specifications, we also estimate the corresponding constant conditional correlation (CCC) model of Bollerslev (1990), which sets $Q_t = \overline{Q}_t$ for all t in (7) 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 (7). These lead to several interesting conclusions.

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[12] 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.

[13] 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.

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 structural breaks in unconditional volatilities and correlations.

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 the most important change in correlations occurred in December 1996, while for volatilities the break in January 1999 was more important. The log-likelihood values of the models with two breaks again are considerably higher than those of the one-break models, suggesting that allowing for two structural changes is warranted.

Third, structural breaks in unconditional volatilities and unconditional correlations both appear to be important, as the model with break(s) in both substantially improves the fit compared to the models with break(s) in either volatilities or correlations alone. 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, and finally, allowing for structural breaks in correlations decreases the persistence of conditional correlations, as the estimate of δ declines if one or two breaks are included. The reduction from 0.968, the largest estimate of δ, to 0.938, the estimate 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. For example, the half-life of shocks is reduced from 22 to 11 days.

Figure 2 plots the estimated conditional variances from the univariate GARCH(1,1) models with two breaks in unconditional volatility, together with the level of $\overline{\sigma}_{it}^2$. Similarly, Figures 3-5 display the estimated conditional correlations from the DCC model with two breaks in unconditional volatilities and unconditional correlations, together with the corresponding elements from $\overline{Q}_t$. By construction, the unconditional volatilities and unconditional correlations in these graphs are (almost) identical to the numbers presented in Table 1.

In addition to the sizeable breaks in the unconditional correlations, several large swings in the conditional correlations are worth noting. 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. The 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 euro countries' banks might explain why countries in the euro area did not share the Swiss experience in attracting capital from Asia during the crisis. This situation might explain the all-time low CHF-EUR conditional correlation. A similar downward jump in CHF-EUR conditional correlation occurred in the third quarter of 2001, possibly linked to the WTC attack on September 11 and the subsequent war on terror.

The correlations between the British pound and all other currencies dropped substantially around mid-2000. This apparently followed the fall of the pound's effective exchange rate by around 12.5% against the US dollar 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, all correlations with the pound considerably dropped off.

Notable swings are also observed in all correlations with the Norwegian krone in 1998. These declines are obviously related to the sharp depreciation of the krone following the financial crises in Asia, Russia and Brazil. Given the heavy reliance of Norway on oil and gas exports, the weaker global demand due to the crises instigated the fall in commodity prices (including oil), which subsequently worsened the terms of trade and depreciated the exchange rate. As discussed in Section 2.1.3 Norges Bank responded by raising interest rate several times and undertaking extensive and persistent foreign exchange interventions. The resulting fluctuations of the krone were furthermore exacerbated by speculation, hedging and portfolio shifts in financial markets. These unfortunate events, together with Norway's unique economic characteristics compared to other European countries, make that all correlations with NOK weakened to an unusual extent.

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. For example, 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. To address this issue, we treat the break dates τ_1 and τ_2 as unknown or, put differently, we consider them as unknown parameters. 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), 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 sequence of log-likelihood values shown 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

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

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 likelihood values at these points are approximately equal and indicate a substantial 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 mainly by the sharp depreciation of the British pound leading to sharp but temporary declines in correlation of with the other currencies, in particular with the euro and Swiss Franc. Similarly, increases in correlation 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 time. In sum, it seems that allowing for more breaks may be worthwhile, but that any such additional breaks are not common across all currencies but rather currency-specific.

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 replacing $\overline{\sigma}_{it}^2$ in (9) and $\overline{Q}_t$ in (10) with

$$\overline{\sigma}_{it}^2 = \overline{\sigma}_{i1}^2(1 - G(t;\zeta_1,\tau_1)) + \overline{\sigma}_{i2}^2 G(t;\zeta_1,\tau_1)(1 - G(t;\zeta_2,\tau_2)) + \overline{\sigma}_{i3}^2 G(t;\zeta_1,\tau_1)G(t;\zeta_2,\tau_2), \tag{11}$$

$$\overline{Q}_t = \overline{Q}_1(1 - G(t;\zeta_1,\tau_1)) + \overline{Q}_2 G(t;\zeta_1,\tau_1)(1 - G(t;\zeta_2,\tau_2)) + \overline{Q}_3 G(t;\zeta_1,\tau_1)G(t;\zeta_2,\tau_2), \tag{12}$$

where

$$G(t;\zeta_j,\tau_j) = (1 + \exp(-\zeta_j(t - \tau_j)))^{-1}, \qquad \zeta_j > 0, \tag{13}$$

$j = 1, 2$, 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 $\mathtt{I}[t \leq \tau_j]$. 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.[15] 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 $\overline{\sigma}_{i,j}$ 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).[16] 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 logistic transition functions (13) are quite large: $\hat{\zeta}_1 = 190$ and $\hat{\zeta}_2 = 506$. These imply that the first change takes about six months from start to finish, while the second change occurred almost instantaneously. 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 pairs involving the British pound for which the second change in unconditional correlation materializes rather gradually, especially with the Swiss franc and the euro. The same holds for the NOK-SEK pair. 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 (12) 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 the semi-generalized DCC-GARCH model developed by Hafner and Franses (2003), which allows for asset-specific news impact parameters by replacing (7) with

$$Q_t = (1 - \overline{\gamma}^2 - \delta)\overline{Q} + \gamma\gamma' \odot z_{t-1}z_{t-1}' + \delta Q_{t-1}, \tag{14}$$

where $\odot$ denotes the Hadamard product and $\gamma = (\gamma_1, \gamma_2, \ldots, \gamma_N)'$ now is an $(N \times 1)$

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

[16] In the estimation procedure, we enforce that $\overline{Q}_t$ is a genuine correlation matrix by taking the Choleski decompositions of $\overline{Q}_j = P_jP_j'$, $j = 1, 2, 3$, 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 (in press) for details.

vector. Note that in this model the effect of the product $z_{i,t-1}z_{j,t-1}$ on q_{ijt} (and hence on the conditional correlation ρ_{ijt} is given by $\gamma_i\gamma_j$.[17] Estimating the 10 possible models with the different number, types and location of break(s) that we consider, 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 -3912.48, compared to -3919.11 for the corresponding 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 significance levels. The estimates of γ_i (with QML standard errors in parentheses) are equal to 0.195 (0.017), 0.201 (0.014), 0.146 (0.015), 0.201 (0.014) and 0.180 (0.016) for CHF, EUR, GBP, NOK and SEK, respectively.[18] 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 British pound, Norwegian krone, Swedish krona, Swiss franc and the euro exchange rates (against the US dollar) 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 experienced substantial declines during the intermittent period.

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.

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

[18] 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 0.181.

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Table 1: Exchange rate returns - summary statistics

					Correlations				
Currency	Mean	StD	Skew	Kurt	CHF	EUR	GBP	NOK	SEK
January 1, 1994-December 31, 2003									
CHF	−1.696	11.43	−0.459	5.769	1.000	0.925	0.622	0.789	0.668
EUR	−1.123	9.91	−0.410	5.454		1.000	0.679	0.849	0.760
GBP	−1.822	7.59	−0.190	4.767			1.000	0.586	0.530
NOK	−1.083	9.81	−0.133	6.004				1.000	0.750
SEK	−1.359	10.16	−0.206	4.383					1.000
January 1, 1994-December 15, 1996									
CHF	−4.223	12.16	−0.696	8.707	1.000	0.947	0.673	0.934	0.567
EUR	−4.044	8.87	−0.563	9.639		1.000	0.766	0.986	0.635
GBP	−3.898	6.92	−0.162	6.431			1.000	0.760	0.519
NOK	−5.102	8.94	−0.609	9.746				1.000	0.648
SEK	−6.857	9.33	−0.150	4.470					1.000
December 16, 1996-December 31, 1998									
CHF	2.626	11.40	−0.448	4.473	1.000	0.896	0.472	0.566	0.597
EUR	3.699	8.60	−0.431	3.669		1.000	0.562	0.683	0.704
GBP	0.168	7.91	0.034	3.432			1.000	0.309	0.387
NOK	7.977	10.64	0.062	6.484				1.000	0.725
SEK	8.789	10.06	−0.362	3.960					1.000
January 1, 1999-December 31, 2003									
CHF	−1.956	11.00	−0.270	3.678	1.000	0.941	0.663	0.812	0.761
EUR	−1.353	10.92	−0.344	4.315		1.000	0.686	0.858	0.832
GBP	−1.406	7.84	−0.299	4.629			1.000	0.625	0.590
NOK	−2.381	9.94	−0.045	4.120				1.000	0.809
SEK	−2.227	10.65	−0.179	4.426					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

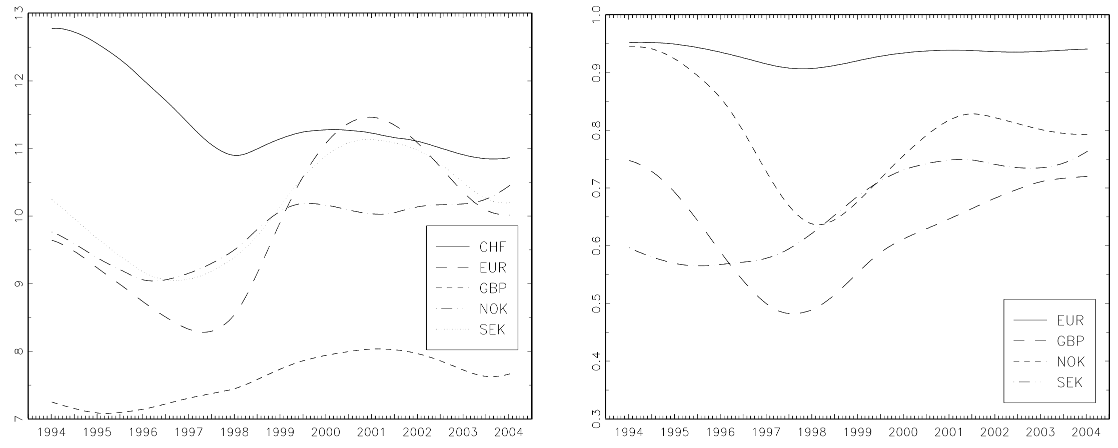
Model	$\mathcal{L}$(CCC)	$\mathcal{L}$(DCC)	γ	δ
NB	-5110.73	-4155.50	0.030	0.953
			(0.003)	(0.006)
SBV(12-15-1996)	-5045.71	-4118.91	0.029	0.968
			(0.003)	(0.003)
SBV(12-31-1998)	-5078.98	-4125.98	0.029	0.968
			(0.002)	(0.003)
SBC(12-15-1996)	-4405.37	-3997.88	0.032	0.950
			(0.004)	(0.007)
SBC(12-31-1998)	-5010.67	-4156.61	0.029	0.968
			(0.002)	(0.003)
SBVC(12-15-1996)	-4352.76	-3966.83	0.033	0.947
			(0.004)	(0.008)
SBVC(12-31-1998)	-4954.04	-4126.07	0.029	0.968
			(0.002)	(0.003)
TBV	-5053.79	-4106.60	0.029	0.968
			(0.003)	(0.003)
TBC	-4300.82	-3972.40	0.031	0.944
			(0.003)	(0.008)
TBVC	-4217.67	-3919.11	0.033	0.938
			(0.004)	(0.009)

Note: The table reports summary statistics of DCC models estimated for daily exchange rate returns over the period January 1, 1994-December 31, 2003. Bollerslev-Wooldridge type QML standard errors of γ and δ are given in parentheses. 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.

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

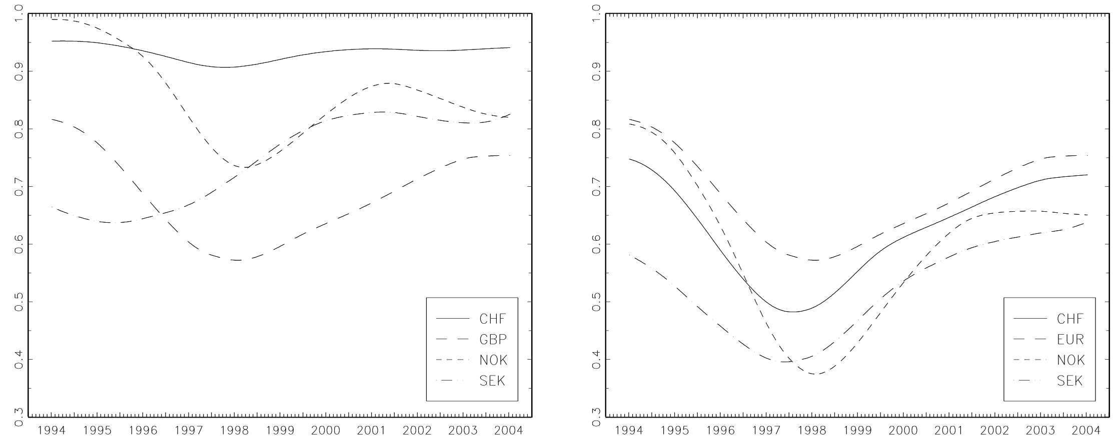
Currency	NB		SBVC(12-15-1996)		TBVC	
	α_i	β_i	α_i	β_i	α_i	β_i
CHF	0.047	0.938	0.054	0.909	0.053	0.899
	(0.006)	(0.010)	(0.009)	(0.019)	(0.009)	(0.020)
EUR	0.060	0.928	0.069	0.896	0.072	0.883
	(0.009)	(0.012)	(0.012)	(0.022)	(0.011)	(0.024)
GBP	0.048	0.926	0.062	0.881	0.066	0.865
	(0.015)	(0.030)	(0.018)	(0.047)	(0.018)	(0.050)
NOK	0.058	0.929	0.066	0.900	0.068	0.889
	(0.009)	(0.012)	(0.013)	(0.024)	(0.013)	(0.027)
SEK	0.059	0.923	0.066	0.901	0.066	0.897
	(0.009)	(0.014)	(0.011)	(0.021)	(0.012)	(0.022)

Note: The table reports summary statistics of DCC models estimated for daily exchange rate returns over the period January 1, 1994-December 31, 2003. Bollerslev-Wooldridge type QML standard errors of α_i and β_i are given in parentheses. 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.



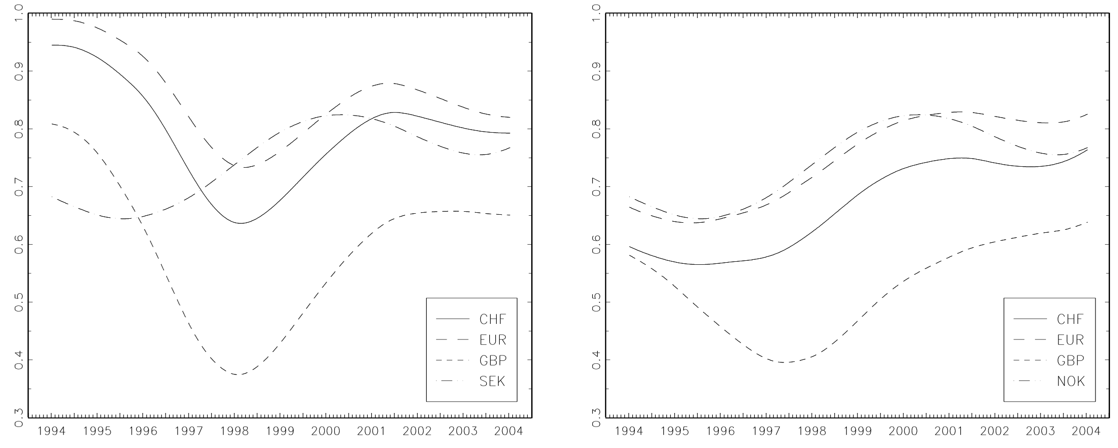
(a) Volatilities

(b) CHF



(c) EUR

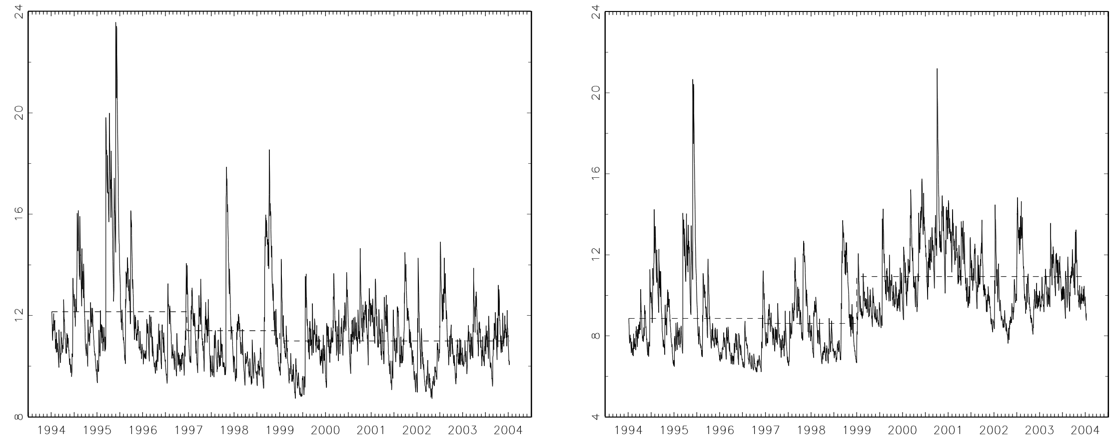
(d) GBP



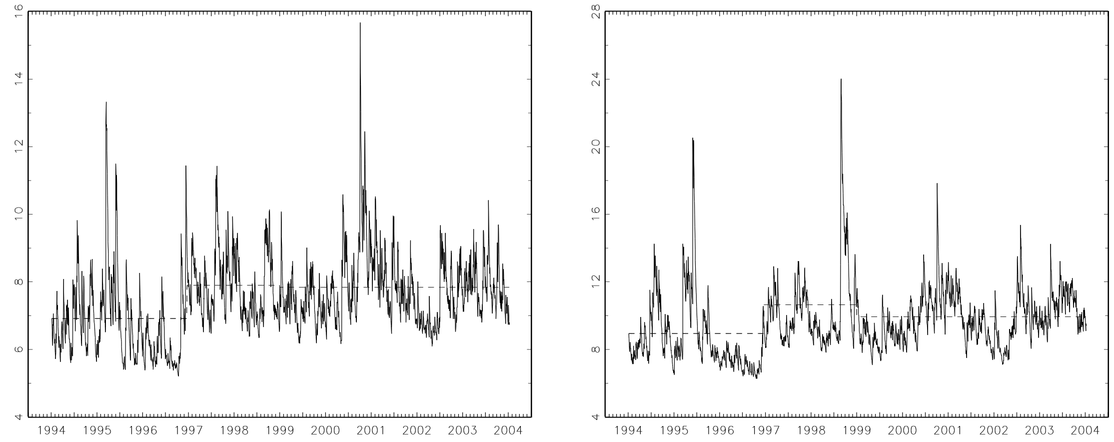
(e) NOK

(f) SEK

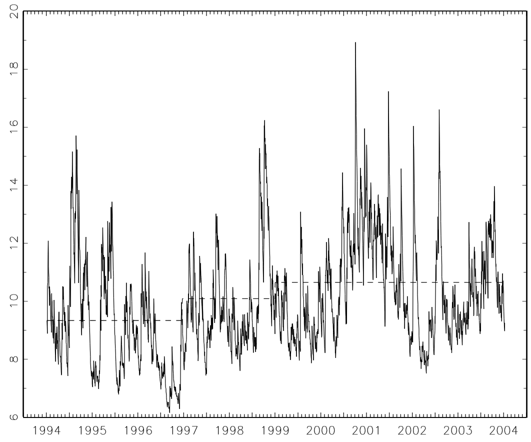
Figure 1: Nonparametric volatility estimates (panel (a)) and correlation estimates (panels (b)-(f)) for daily exchange rate returns over the period January 1, 1994-December 31, 2003, obtained from (1) using a quartic kernel function with bandwidth $h = 1$.



(a) CHF (b) EUR

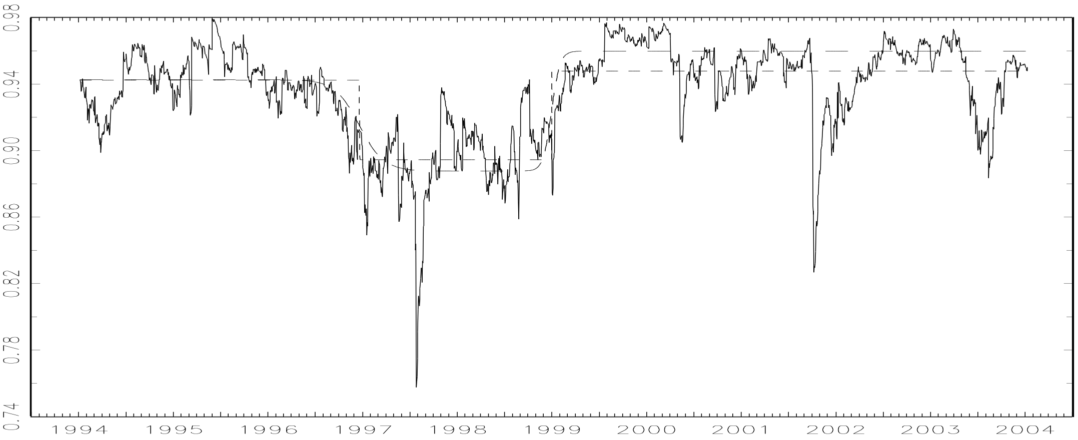


(c) GBP (d) NOK

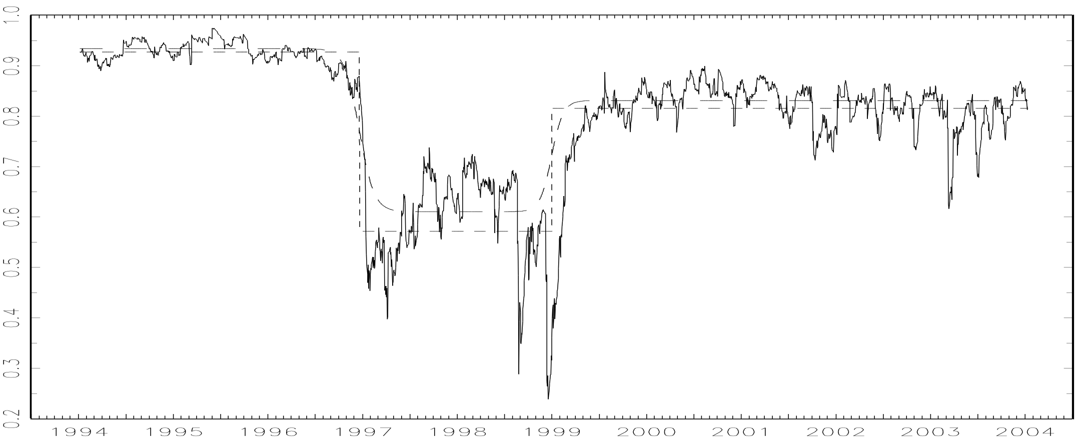


(e) SEK

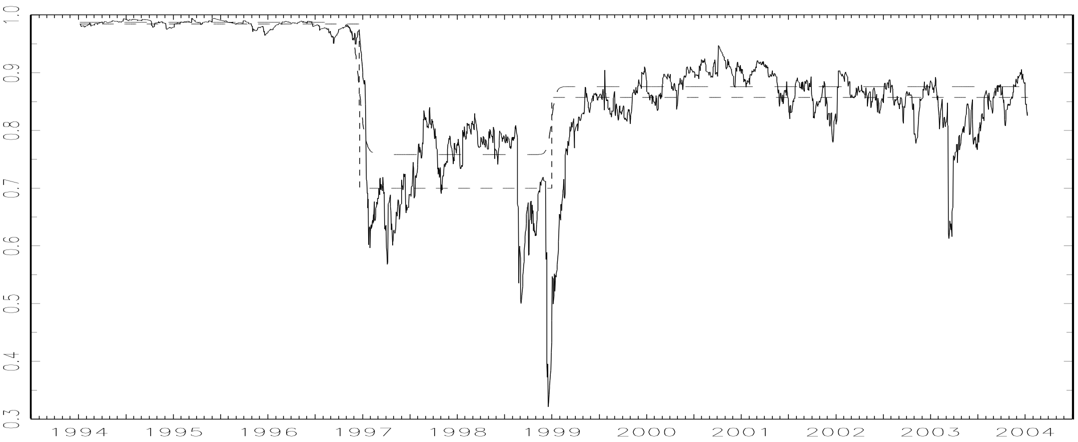
Figure 2: Conditional volatilities of daily exchange rate returns in GARCH(1,1) model with breaks in unconditional volatilities occurring at December 15, 1996 and January 1, 1999 (solid line). Dashed lines are unconditional variances.



(a) CHF-EUR

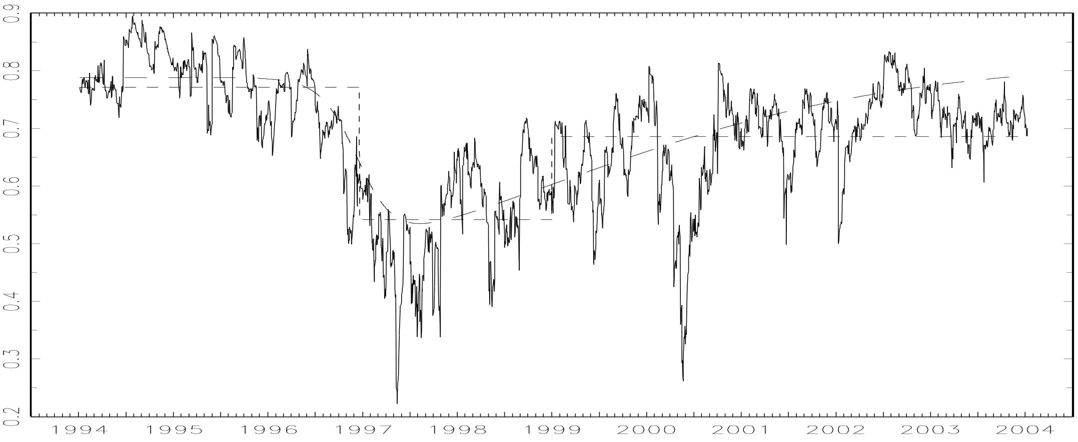


(b) CHF-NOK

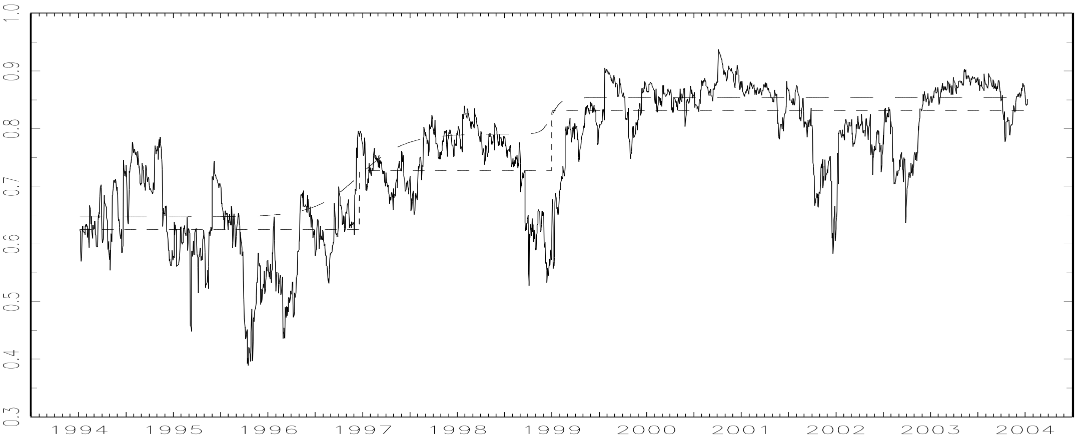


(c) EUR-NOK

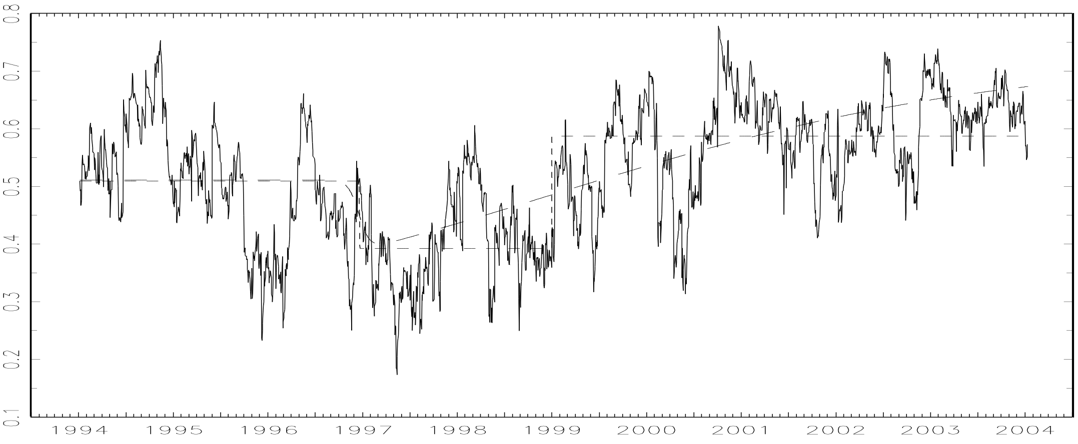
Figure 3: Dynamic conditional correlation between daily exchange rate returns in DCC model with breaks in unconditional volatilities and unconditional correlations occurring at December 15, 1996 and January 1, 1999 (solid line). Short-dashed lines are unconditional correlations. Long-dashed lines are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



(a) EUR-GBP

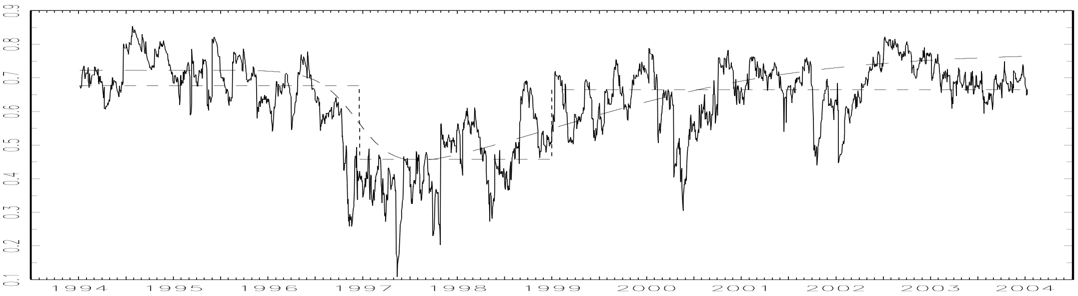


(b) EUR-SEK

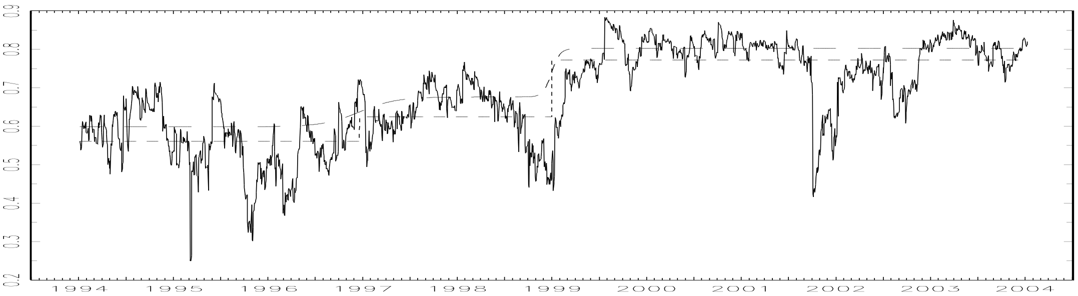


(c) GBP-SEK

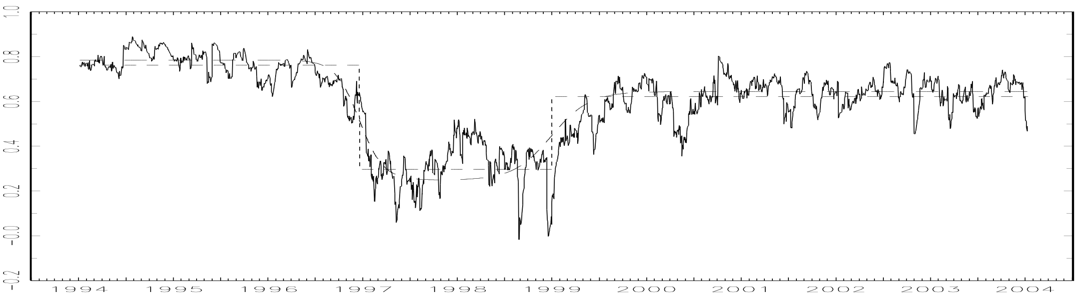
Figure 4: Dynamic conditional correlation between daily exchange rate returns in DCC model with breaks in unconditional volatilities and unconditional correlations occurring at December 15, 1996 and January 1, 1999 (solid line). Short-dashed lines are unconditional correlations. Long-dashed lines are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



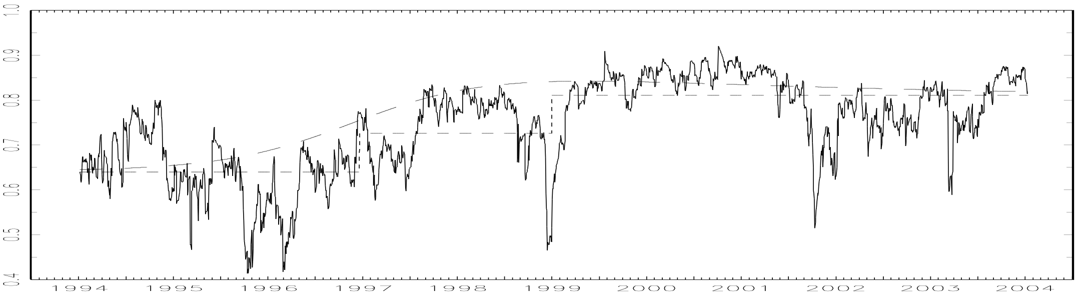
(a) CHF-GBP



(b) CHF-SEK

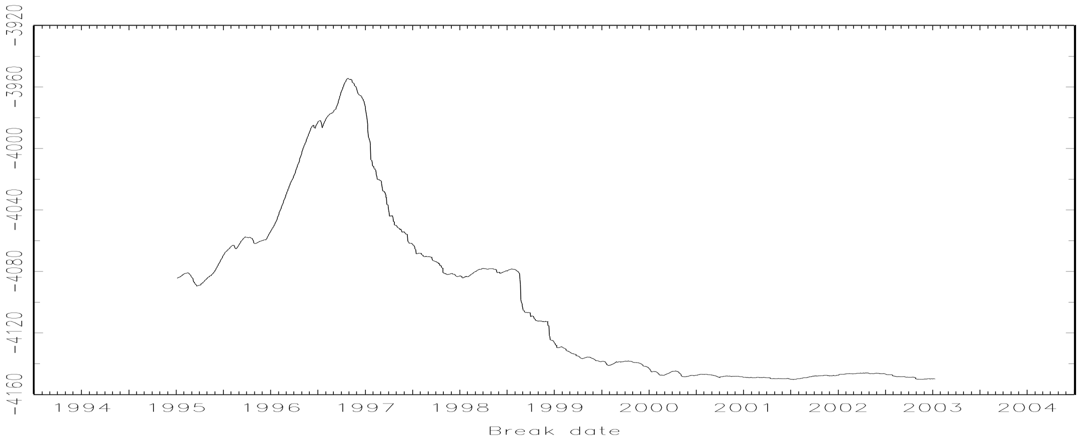


(c) GBP-NOK

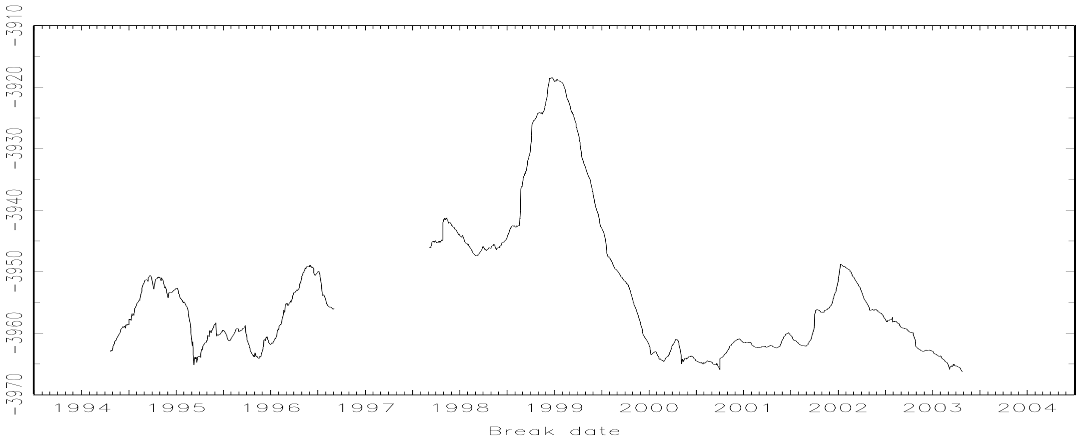


(d) NOK-SEK

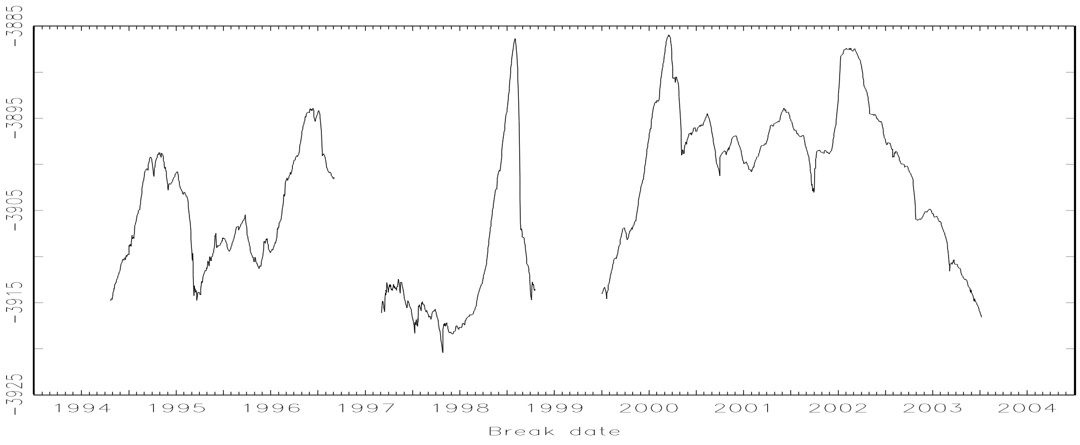
Figure 5: Dynamic conditional correlation between daily exchange rate returns in DCC model with breaks in unconditional volatilities and unconditional correlations occurring at December 15, 1996 and January 1, 1999 (solid line). Short-dashed lines are unconditional correlations. Long-dashed lines are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