EUROPEAN CENTRAL BANK

EUROSYSTEM

WORKING PAPER SERIES

NO 1044 / APRIL 2009

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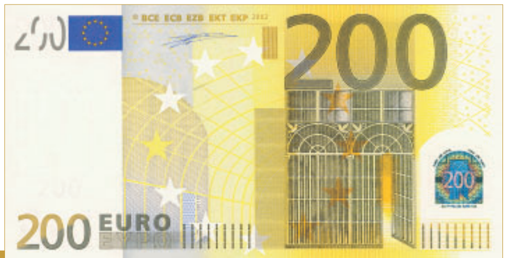

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1 The authors are indebted for useful conversations and constructive comments to Domenico Giannone, Michele Lenza, Lucrezia Reichlin, Lucio Sarno, Ilias Tsiakas and David Veredas. The authors would also like to thank for useful comments the participants of the ECB research seminar series (Oct 2007), the participants of the international macro and finance conference (ICIMF, 2008) and Money Macro and Finance conference (MMF, 2008). The authors alone are responsible for any errors that may remain and for the views expressed in the paper.
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ISSN 1725-2806 (online)

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Abstract

This paper investigates whether information from foreign yield curves helps forecast domestic yield curves out-of-sample. A nested methodology to forecast yield curves in domestic and international settings is applied on three major countries (the US, Germany and the UK). This novel methodology is based on dynamic factor models, the EM algorithm and the Kalman filter. The domestic model is compared vis-á-vis an international one, where information from foreign yield curves is allowed to enrich the information set of the domestic yield curve. The results have interesting and original implications. They reveal clear international dependency patterns, strong enough to improve forecasts of Germany and to a lesser extent UK. The US yield curve exhibits a more independent behaviour. In this way, the paper also generalizes anecdotal evidence on international interest rate linkages to the whole yield curve.

JEL classification: F31.

Keywords: Yield curve forecast, Dynamic factor model, EM algorithm, International linkages.

Non-technical summary

This paper addresses the question of whether information from foreign yield curves helps improve domestic yield curve forecasts. In order to do that, it investigates the existence of dependency patterns across yield curves of different countries and tests whether they are strong enough to improve domestic yield curve forecasts out of sample.

This paper expands our rather limited knowledge on cross-border dependencies of yield curves. Looking at the yield curve literature, the empirical evidence to-date suggests strong contemporaneous dynamic interdependencies of yield curves across countries, in line with increased globalization and financial integration. Nevertheless, the literature does not investigate non-contemporaneous correlations, although evidence of such dependency patterns is recorded in studies of specific interest rates, which investigate the role of certain countries as global players. Furthermore, dependency patterns recorded in the real business cycles between the US and the euro area can also rationalize such dependencies, to the extent that output affects nominal interest rates.

Based on this reasoning, we propose, estimate and forecast (out-of-sample) a novel dynamic factor model for the yield curve, where information from foreign yield curves can be introduced in domestic yield curve forecasts. We want to compare the forecast accuracy of our international model versus a purely domestic model. In order to do that, we first summarize the information contained in each domestic yield curve into three country-specific dynamic factors. We then exploit the dynamic structure of the factors to produce forecasts. Domestic forecasts will be produced purely from the domestic factors, whereas international forecasts will be produced by the interaction of domestic factors with foreign factors in a vector autoregression setting. As a consequence, under the international model domestic factor forecasts are enriched with information from foreign factors. Finally, we reconstruct future yields from the factor forecasts and compare the forecasts under the domestic and the international approach. In that sense, the international model nests the domestic model and allows direct forecast comparisons.

Our estimation method employs Maximum Likelihood (ML) techniques based on the EM algorithm and the Kalman filter (Doz et al., 2006; Coroneo et al., 2007), in order to effectively cope with two main estimation challenges. The first is to impose restrictions in order to identify the factors driving the yield curve as level (L), slope (S) and curvature (C) according to the methodology of Diebold and Li (2006). This technique allows the generalization of our modeling methods and our forecast results to the whole yield curve. The second is to use an extensive data set consisting of a large cross-section of yields for three countries (US, Germany and UK). Previous international yield curve techniques involved

two-step procedures, where the L, S and C factors of each country were typically extracted outside the maximization process, mainly because the econometric tools being used were prohibiting the use of estimation methods with embedded restrictions for a large cross-section of data (Diebold et al. 2006). Our estimation method sidesteps these problems and allows us to directly estimate our yield curve factors from multi-country information sets, while imposing the necessary identifying restrictions (Coroneo et al., 2007).

Our results reveal dependency patterns among the countries considered and provide ample support for the international model in forecasting the yield curves of the dependent countries. In fact, we show that international yield curve linkages can significantly improve forecasts of some countries. On the contrary, more independent countries in the international setting, i.e. not so much influenced by international information, appear not to benefit largely from the international model. More precisely, we find that German yield curve forecasts are particularly improved by including information from the US and the UK, thus suggesting a dynamic dependency of Germany on these two countries. The relationship appears unidirectional for the US, where the domestic model appears to provide superior forecasts, confirming the leading role of the US. Finally, the UK is partly influenced by international linkages, mainly at longer forecast horizons. Our results suggest clear dependency patterns among the countries considered. They are broadly in line with previous anecdotal empirical evidence on specific interest rates, but generalize these findings for the whole yield curve.

Overall, this paper makes several important contributions: First, we extend the yield curve forecast literature to the international direction. The relevant forecast literature has used, up to now and to the best of our knowledge, only domestic information. We show that using an international model can help improve forecasts for certain countries. Second, we record, for the first time, international dependency patterns for the whole yield curve. Previous yield-curve literature has focused on contemporaneous relationships and empirical evidence of dependency patterns has emerged in the literature for specific interest rates only. We now extend such evidence to the whole yield curve. Third, we do that in a robust way, by means of out-of-sample forecasts. Evidence on international dependencies among specific interest rates has relied on a variety of in-sample fit techniques. Under this light, our results support a more outward-looking perspective in modeling financial variables.

1 Introduction

This paper addresses a simple yet important question: Whether information from foreign yield curves can help improve domestic yield curve forecasts. Addressing this question generates three important and original implications. First, it provides insight on the appropriate model for forecasting the yield curve. If international information matters, then a model including such information, i.e. an international model, should be used instead of a purely domestic one. Second, it potentially reveals international dependency patterns between the yield curves of different countries, to the extent that international information helps forecast the domestic yield curve. Finally, it tests the strength of these dependency patterns in the most robust way, i.e. using an out-of-sample forecast test. We investigate these implications in an effort to extend the yield curve forecast literature towards the international direction.

Our up to date knowledge on dependency patterns among yields curves of different countries is limited. Looking at the yield curve literature, the empirical evidence to-date informs us of strong contemporaneous dynamic interdependencies of yield curves across countries, in line with increased globalization and financial integration. The aim of the relevant studies is to demonstrate the existence of common factor(s) explaining a significant part of individual country yields (see Dewachter and Maes, 2001; Diebold et al., 2006; Pérignon et al., 2007). Nevertheless, the literature does not investigate non-contemporaneous correlations. And yet, evidence of such dependency patterns[1] is recorded in studies focusing on specific interest rates, which look at the role of certain countries as global players. Evidence from these studies suggests a leading role for the US. Moreover, dependency patterns recorded in the real business cycles between the US and the euro area (Giannone and Reichlin, 2007) can also rationalize such linkages, to the extent that output affects nominal interest rates (Ang and Piazzesi, 2004). Building on this evidence, we investigate the existence of such lead-lag relationships in the yield curve and whether they are strong enough to help us forecast the whole yield curve out-of-sample.

We propose, estimate and forecast (out-of-sample) a novel dynamic factor model for the yield curve, where information from foreign yield curves can be introduced in domestic yield curve forecasts. We want to compare the forecast accuracy of our international model versus a purely domestic model. In order to do that, we first summarize the information contained in each domestic yield curve into three country-specific dynamic factors. We then exploit the dynamic structure of the factors to produce forecasts. Domestic forecasts will be produced purely from the domestic factors, whereas international forecasts will be produced by the interaction of domestic factors with foreign factors in a vector autoregression setting.

[1] In this paper, the terms dependency patterns, causality linkages and lead-lag relationships are used interchangeably.

As a consequence, under the international model domestic factor forecasts are enriched with information from foreign factors. Finally, we reconstruct future yields from the factor forecasts and compare the forecasts under the domestic and the international approach. In that sense, the international model nests the domestic model and allows direct forecast comparisons.

Our estimation method employs Maximum Likelihood (ML) techniques based on the EM algorithm and the Kalman filter (Doz et al., 2006; Coroneo et al., 2007), in order to effectively cope with two main estimation challenges. The first is to impose restrictions in order to identify the factors driving the yield curve as level (L), slope (S) and curvature (C) according to the methodology of Diebold and Li (2006)[2]. This technique allows the generalization of our modeling methods and our forecast results to the whole yield curve[3]. The second is to use an extensive data set consisting of a large cross-section of yields for three countries (US, Germany and UK). Previous international yield curve techniques involved two-step procedures, where the L, S and C factors of each country were typically extracted outside the maximization process, mainly because the econometric tools being used were prohibiting the use of estimation methods with embedded restrictions for a large cross-section of data (Diebold et al. 2006). Our estimation method sidesteps these problems and allows us to directly estimate our yield curve factors from multi-country information sets, while imposing the necessary identifying restrictions (Coroneo et al., 2007).

Our results reveal dependency patterns among the countries considered and provide ample support for the international model in forecasting the yield curves of the dependent countries. In fact, we show that international yield curve linkages can significantly improve forecasts of some countries. On the contrary, more independent countries in the international setting, i.e. not so much influenced by international information, appear not to benefit largely from the international model. More precisely, we find that German yield curve forecasts are particularly improved by including information from the US and the UK, thus suggesting a dynamic dependency of Germany on these two countries. The relationship appears unidirectional for the US, where the domestic model appears to provide superior forecasts, confirming the leading role of the US. Finally, the UK is partly influenced by international linkages, mainly at longer forecast horizons. Our results suggest clear dependency patterns among the countries considered. They are broadly in line with previous anecdotal empirical evidence on specific interest rates, but generalize

[2] The Diebold and Li (2006) model is flexible enough to capture the changing shape of the yield curve, yet it is parsimonious and easy to estimate. This is especially important within our context, where the multiplicity of countries puts further strains on the estimation procedure.

[3] This is possible, since the imposed restrictions adequately summarize all possible maturities contained in a yield curve. Should the coefficients not be identified, then we would not be able to generalize our results to all maturities, observed or unobserved, therefore we could not talk about the "yield-curve".

these findings for the whole yield curve.

Overall, this paper makes several important contributions: First, we extend the yield curve forecast literature to the international direction. The relevant forecast literature has used, up to now and to the best of our knowledge, only domestic information. We show that using an international model can help improve forecasts for certain countries. Second, we record, for the first time, international dependency patterns for the whole yield curve. Previous yield-curve literature has focused on contemporaneous relationships and empirical evidence of dependency patterns has emerged in the literature for specific interest rates only. We now extend such evidence to the whole yield curve. Third, we do that in a robust way, by means of out-of-sample forecasts. Evidence on international dependencies among specific interest rates has relied on a variety of in-sample fit techniques[4]. Under this light, our results support a more outward-looking perspective in modeling financial variables.

The paper is structured as follows. Section 2 discusses the potential sources of interest rate linkages in the literature, while also providing a more detailed view of the relevant empirical literature. Section 3 presents the factor model specifications used in this paper and elaborates on the estimation and forecast methodologies being used. Section 4 gives an overview of the data used and their sources. Section 5 analyzes the estimation results, and Section 6 summarizes.

2 International linkages in interest rates

In order to discuss the driving forces of international interest rate linkages, a distinction should be made between contemporaneous and causality international linkages. Globalization, the degree of financial integration of the domestic economy into world markets and the degree of real integration play a prominent role in synchronizing the movements of fundamental factors determining interest rates across countries (Borio and Filardo, 2007; Rogoff, 2006; Frankel et al., 2004). On the other hand, international dependency patterns rely on the distribution of shocks globally. Namely, the nature of global shocks, to the extent that these shocks are being distributed globally in an asymmetric manner, could rationalize different types of dependency patterns. Asymmetric distribution could result from heterogeneity in adjustment dynamics of interest rates across countries, e.g. due to differing degrees of financial or economic integration[5].

The up-to-date empirical literature on international yield curve linkages provides evidence of contem-

[4] The exception is Wang et al. (2007), who perform out-of-sample Granger causality tests for individual rates.

[5] For example, Frankel et al. (2004) suggest the different degrees of development of the financial system and the openness of the capital account as potential factors contributing to asymmetric adjustment processes.

poraneous linkages. It focuses on investigating the existence and the nature of global factors driving the yield curve. The evidence suggests that the number of these factors may vary, depending on the methodology and the nature of the factors. For example, using static factor analysis, Driessen et al. (2003) find evidence in favor of five common international factors. Pérignon et al. (2007), specifically allowed for local factors and report a single common (international) factor. Dewachter and Maes (2001) propose and estimate an affine term structure model of the interdependencies between two countries, the US and the UK. They allow the short term interest rate to be driven by both local and global international factors and link the pricing kernels of the two countries via exchange rate movements. More recently, Diebold et al. (2006) extend the NS yield curve framework to four major countries and use dynamic factor analysis to estimate the domestic (level and slope) yield factors of each country. They then group these factors together to extract global (level and slope) factors. It appears that, in all cases, international factors drive a large part of the domestic variations in the yield curve. Moreover, plausible interpretations appear to link international factors to global macroeconomic variables, such as output, inflation and exchange rates[6],[7]. This is in line with evidence on increased synchronized fluctuations in business cycles (Koze et al., 2004) and inflation (Mojon and Ciccareli, 2005). These two variables are found to be important in driving the domestic yield curve (And and Piazzesi, 2004).

Our motivation for exploring dependency patterns and forecastability in yield curves comes from evidence on causality linkages in a parallel literature focusing on individual maturities. The related strand of literature uses a variety of in-sample fit techniques[8] to provide evidence of strong international dependencies among specific interest rates. For example, Frankel et al., (2004) employ cointegration methods on 3-month rates to asses the dynamic dependence of domestic interest rates on international ones, under different currency regimes. They find that eventually, local interest rates adjust to foreign ones under any exchange rate arrangement, nevertheless, the degree of adjustment might differ, suggesting various dependency patterns among interest rates of various countries. Chin and Frankel (2005) examine

[6] Most of the relevant papers merely identify global factors as level, slope and curvature factors. Pérignon et al. (2007), reports a single common (international) factor, associated most notably with changes in the level of domestic term structures. Dewachter and Maes (2001) suggest that the international factors correspond to international level effects, and the local factors to national slope effects. However, Diebold et al. (2006) move a step forward and suggest that the level factor relates to global inflation and the slope factor global business cycle. Interestingly, output and inflation are highly correlated with the factors driving the (domestic) yield curve (Ang and Piazzesi, 2003).

[7] The role of exchange rates in yield curve modeling has been brought forward by Dewachter and Maes (2001). Focusing on interest rate differentials, Chinn and Frankel (2005) suggest a dichotomy of interest rate differentials into a country premium (determined by such factors as capital controls, transaction costs, imperfect information, default risk, tax differentials, and risk of future capital controls) and a foreign exchange risk premium (determined by expected depreciation plus the exchange risk premium).

[8] With the exception of Wang et al. (2007).

the role of the US or the euro area rate as the world interest rate by employing Granger causality tests in a cointegrating framework, separately for money market rates and for 10 year benchmark bond rates. Moreover, Wang et al. (2007) examine causality linkages among major Eurocurrency interest rates following a similar approach, but employ out-of-sample causality tests. They both report clear dependency patters for certain countries. Nevertheless, to the extent that growth considerations drive interest rates, evidence on international dependency patterns between the growth rates (business cycles) of the US and the euro area (Giannone and Reichlin, 2006) could also rationalize similar patterns in the interest rates, although perhaps for medium-term maturities.

The causality linkages clearly illustrated in the above studies, reveal clear directions. In general, the US is found to have a leading role. The role of other major countries, such as Germany and the UK is broadly unclear. Looking at the respective literature, Frankel et al., (2004) use a large number of developed and developing countries and find that the US, Germany and Japan seem to be the only countries in their panel that can choose their own interest rates in the long run, suggesting a leading role for these countries. Chin and Frankel (2005) focus on the US and the euro area and find that short and long term interest rates have been driven more from the US side than the European side. Nevertheless, they report bidirectional linkages since the creation of the European Monetary Union. Wang et al. (2007) analyze major economies and find that the German eurocurrency rate had a strong global player status before the introduction of the euro. Nevertheless, after the introduction of the euro, the role of the US rate in affecting euro-zone currency interest rates increased.Interestingly, Diebold et al. (2006) also provide some evidence implying the leading role of the US. They find that the global share of bond yield variation is smallest for the US across all maturities, consistent with relative independence of the US market.

How does our paper fit into this literature? Our appeal to international information in order to forecast the yield curve should be straightforward given the large amount of literature recording strong international relationships among yields across countries. The yield curve literature up to know has focused on research only on contemporaneous relationships. Nevertheless, relevant literature provides evidence of dependency patterns for specific yields across countries, thereby suggesting similar patterns for the whole yield curve. Should causality linkages be strong enough, they should be able to help us forecast the yield curve out of sample. This paper investigates the existence of lead-lag international yield-curve linkages and tests their strength using out-of -sample forecast techniques. Ultimately, it investigates whether international linkages help improve domestic forecasts. It, therefore, expands the yield curve forecasting literature towards the international dimension, and suggests the existence of dependency patterns across the yield curve of various countries.

3 Methodology

We use a dynamic factor model and maximum likelihood estimation techniques based on the EM algorithm to estimate and forecast out-of-sample the yield curve in domestic and international settings. We summarize the yield curve of each country into three dynamic factors and we forecast the yields by forecasting the factors. The domestic setting allows only own factor information (single autoregression), whereas the international setting allows information from all countries factors (vector autoregression). In this way, the international framework is a straightforward extension of the domestic and the exercise can be seen as an out-of-sample dependency test[9]. Our estimation window starts from January 1986 to December 1999 and our evaluation window extends from January 2000 to May 2006. We use as a benchmark a simple random walk model (RW) and compare the relative forecasting power of each model against the benchmark.

Overall, we compare the domestic with the international model in two formulations: The *domestic yields-only model*, where the L, S and C factors of each country are extracted purely from domestic yields and their forecasts use own information only and the *international yields-only model*, where the L, S and C factors of each country are extracted purely from domestic yields but their forecasts use information from all countries. We structure the models in such way so that the international model nests the domestic one, thereby providing direct comparison between the two formulations.

We explore the dynamic dependencies between Germany, the US and the UK. German yields are dynamically dependent on international yields, if including information from the latter improves German forecasts. The link is bidirectional if German information also helps forecast foreign yields. The same principle holds for the other countries. In that sense, our methodology acts as an out-of-sample dependency test on the whole term structure of interest rates, thus providing generalized evidence on dynamic dependencies across countries.

Finally, the use of ML techniques combined with the EM Algorithm and the Kalman Filter is the ideal methodology for our approach. It is the only one that allows us to consistently estimate large cross sections (Doz et al.,2006), while at the same time effectively deal with restrictions in the factor loadings

[9] Out-of-sample Granger causality tests are more powerful and robust tests than the respective in-sample ones, since they convey the maximum amount of information for testing the Granger causality hypothesis (Granger, 1969; Ashley et al. 1980) and is, therefore, closer to the spirit of Granger's (1969) true definition of causality.

(Coroneo et al., 2007). We can, therefore, exploit information from an extended data set, while at the same time generalize our results to the whole yield curve, in a simple one-step estimation process. We thereby sidestep estimation issues which were up-to-know barring similar routes of research in this field.

3.1 Modeling the yield curve using a dynamic factor model

Dynamic factor models capture the common features (correlations) among economic series within unobserved common factors. In contrast to static factor models (i.e. principal components), dynamic factor models allow the underlying factors to evolve dynamically, so they have the advantage of measuring contemporaneous and temporal comovements among the variables. Such models were originally proposed by Stock and Watson (2002 a, b) and advanced by Forni et al. (2000, 2002, 2005).

3.2 A domestic factor model for the yield curve

Nelson and Siegel (1987) and Diebold and Li (2006) have customized dynamic factor models on the yield curve. Diebold and Li (2006) interpret the parsimonious yield curve model of Nelson and Siegel (1987) as a three latent factor model, where factors are identified as L, S and C by imposing appropriate restrictions on the factor loadings. Namely,

$$y_t(m) = L_t + S_t\left(\frac{1-e^{-\lambda m}}{\lambda m}\right) + C_t\left(\frac{1-e^{-\lambda m}}{\lambda m} - e^{-\lambda m}\right) + \varepsilon_{t(m)}, \tag{1}$$

the yield of maturity m at time t, $y_t(m)$, depends on the factors L, S, C and on $\varepsilon_{t(m)}$, the residual or pricing error. The factors are identified by setting the predetermined loadings $[1, \frac{1-e^{-\lambda m}}{\lambda m}, \frac{1-e^{-\lambda m}}{\lambda m} - e^{-\lambda m}]$. These loadings depend on maturities (m) and the λ parameter. The latter governs the exponential decay rate of the yield curve at each maturity. Diebold and Li (2006) keep the λ parameter constant at 0.069 over time in order to reduce the volatility of the factors, thus making the model more predictable[10]. In effect they consider the following matrix form:

$$Y_t = \Gamma' F_t + \varepsilon_t \tag{2}$$

[10] In this paper we follow the approach of Diebold and Li (2006) in setting λ, without running country regressions. This procedure could be seen as imposing similar patterns on the data. For this reason we used the EM algorithm to estimate the parameter λ for each country, and results were not qualitatively much different. That would suggest that setting the value of λ as in Diebold and Li (2006) is a reasonable specification. Moreover, it would also allow for comparisons across models.

Nevertheless, setting the value of λ as in Diebold and Li (2006) would likely not dramatically change the results, given that it does not impose or lead to the imposition of lead-lag relationships, the detection of which, is the scope of our international model.

or

$$Y_t = \begin{bmatrix} \Gamma_L & \Gamma_S & \Gamma_C \end{bmatrix} * \begin{bmatrix} L_t \\ S_t \\ C_t \end{bmatrix} + \varepsilon_t \ , \tag{3}$$

where Y_t is a vector containing the cross-section of observed yields at time t, i.e. the observed yields of maturity m at time t. Γ is a vector containing the predetermined yield-curve factor loadings [Γ_L, Γ_S, Γ_C] of Diebold and Li, that is $[1, \frac{1-e^{-\lambda m}}{\lambda m}, \frac{1-e^{-\lambda m}}{\lambda m} - e^{-\lambda m}]$ respectively for every m, at time t. In their turn, the yield curve factor loadings [L_t, S_t, C_t] at time t are contained in vector F_t. The yield-factors are modeled as separate first-order autoregressive or AR(1) processes and forecasts of the factors are being used to generate forecasts of the yields. This formulation outperforms RW forecasts of the US yield curve at longer forecast horizons (12 steps ahead) for almost all maturities involved. We use this formulation in our model as our benchmark *domestic yields-only model.*

3.3 An international factor model for the yield curve

Our methodology extends the line of Diebold and Li (2006) to the international setting, resulting to the *international yields-only model.* In this case, we consider a vector Y_t containing information on the yields of more than one country (in our case three countries, Germany, US and the UK). The main idea remains that we summarize the information from each country's yield curve into three country-specific yield factors contained in vector F_t, and a country-specific yield pricing error $\varepsilon^c_{t,Y}$. The factors are identified as L^c_t, S^c_t and C^c_t (where $c = \{GE, US, UK\}$) by imposing the predetermined factor loadings on the yield curve factors of each country.

In a general form, our model looks like:

$$Y_t = \Gamma' F_t + \varepsilon_t, \tag{4}$$

or

$$\begin{bmatrix} Y_t^{GE} \\ Y_t^{US} \\ Y_t^{UK} \end{bmatrix} = \begin{bmatrix} \Gamma_L & 0 & 0 & \Gamma_S & 0 & 0 & \Gamma_C & 0 & 0 \\ 0 & \Gamma_L & 0 & 0 & \Gamma_S & 0 & 0 & \Gamma_C & 0 \\ 0 & 0 & \Gamma_L & 0 & 0 & \Gamma_S & 0 & 0 & \Gamma_C \end{bmatrix} * \begin{bmatrix} L_t^{GE} \\ L_t^{US} \\ L_t^{UK} \\ S_t^{GE} \\ S_t^{US} \\ S_t^{UK} \\ C_t^{GE} \\ C_t^{US} \\ C_t^{UK} \end{bmatrix} + \begin{bmatrix} \varepsilon_t^{GE} \\ \varepsilon_t^{US} \\ \varepsilon_t^{UK} \end{bmatrix}, \tag{5}$$

where now Y_t is a vector containing the observed cross-section of yields for each country c at time t, summarized as $[Y_t^{GE}, Y_t^{US}, Y_t^{UK}]$. Γ is a block-diagonal matrix containing the yield curve predetermined loadings ($[\Gamma_L,\ \Gamma_S,\ \Gamma_C]$) for the yield factors of each country $[L_t^c, S_t^c, C_t^c]$ respectively. The latter are contained in vector F_t. Finally, ε_t contains the country-specific, yield curve pricing errors $[\varepsilon_t^{GE}, \varepsilon_t^{US}, \varepsilon_t^{UK}]$, which are assumed to be zero mean, contemporaneously uncorrelated, normal random variables. In this setting we need to estimate only the factors contained in F. It is important to stress that the factors estimated in F, are still domestic factors and the only difference from the domestic model, up until this point is that the estimation involves more than one countries contemporaneously.

It is the transition equation that makes the distinction between the domestic and the international model clear. This is achieved by modeling in a vector autoregressive (VAR) framework the same class of factors across countries, thereby allowing interactions across factors of different countries. More specifically, for the yields-only (macro-yields) model, the factors contained in F_t are modeled separately as a first-order vector autoregressive or VAR(1) process. The order of lags has been selected based on Bayesian information criteria. The transition equation for each of the factors across countries, is

$$F_t^{\varphi} = A^{\varphi} F_{t-1}^{\varphi} + w_t^{\varphi}, \tag{6}$$

where φ corresponds to $L, S,\ C$, i.e. $\varphi = \{L, S, C\}$. A^{φ} contains the autoregressive coefficients that measure the persistence of the factors. It is a full matrix, thereby allowing international interactions among the factors of each country. Although we allow international spill-overs among countries we do not do so among the factors themselves. For example, L^{US} (S^{US}, C^{US}) can affect only the L^{GE} (S^{GE}, C^{GE}) and vice-versa. This is a plausible assumption, given that the correlation among the same class of factors of different countries is high, whereas the correlation among different classes of factors is low (Diebold et al., 2006). Finally, w_t is the innovation vector with components that are zero mean, contemporaneously uncorrelated normal random variables, orthogonal to the common factors, $E(F_t\ w_t') = 0$ and the idiosyncratic component $E(\varepsilon_t\ w_t') = 0$.

For exposition purposes we fully demonstrate the dynamics of the level factor, L_t, across countries:

$$\begin{bmatrix} L_t^{GE} \\ L_t^{US} \\ L_t^{UK} \end{bmatrix} = \left[A^L\right] * \begin{bmatrix} L_{t-1}^{GE} \\ L_{t-1}^{US} \\ L_{t-1}^{UK} \end{bmatrix} + \begin{bmatrix} w_{t,GE}^L \\ w_{t,US}^L \\ w_{t,UK}^L \end{bmatrix}. \tag{7}$$

In sum, the structure of our domestic versus the international model specification now becomes clear. The domestic model uses purely domestic information, since it contain yields only from country c in the Y_t vector. For example, for c=GE, the domestic model for Germany will only contain the cross section of

German yields in the Y_t vector. L^{GE}, S^{GE},C^{GE} will summarize information from the domestic Y_t vector and evolve without receiving feedback from each other, or from foreign sources. In the international model the Y_t vector contains yields from all c countries. In that case, the country-specific L^c, S^c, C^c factors summarize the yield curve information of their respective countries, but international feedback across the same class of factors will be allowed to form their evolution. Should international information add further value, the evolution of the factors will be different under the international model.

Two things, therefore, become apparent. First, the international model is an extension of the domestic model when it comes to the dynamic evolution of the yield curve factors. In this sense, it can be seen as an out-of-sample dependency test, since information from other countries helps forecast the domestic yield curve out-of-sample. Second, in this paper we are not interested in establishing global factors driving the domestic yield curves (as is the case of i.e. Diebold and Li, 2006). Rather, we only care to provide a framework where international information can be introduced in an efficient and flexible way into the information set of the each country and be used to forecast each country's yield curve.

3.4 Forecasting the yield curve

This section describes the procedure we use to forecast the yield curve based on the domestic and the international model. Our benchmark is a naive RW forecast, where the best forecast for a given yield today is yesterday's value. We employ a recursive forecast exercise on each model, which can be described as follows: We start with a sub-sample of our data (from January 1986 to December 1999) and apply the EM algorithm to extract the underlying factors and estimate the parameters. Based on these estimates we produce out-of-sample forecasts, one, six and twelve steps ahead ($h = 1, 6, 12$), using the iterative forecast method, with:

$$\widehat{F}_{t+h} = (A^{\varphi})^h F_t, \tag{4.3}$$

where $(A^{\varphi})^h$ is the A^{φ} matrix raised to the power h. Given the forecast of the factors it is now easy to revert the procedure in Section 2.3 and derive the forecast of the whole yield curve as

$$\widehat{Y}_{t+h} = \Gamma' \widehat{F}_{t+h}. \tag{4.3}$$

To continue, we compare the forecasted value with the actual value of the yield and calculate the squared forecast error (SFE). We then include one more observation (actual value) in our sample and start again the extraction, estimation, forecast and evaluation of the new sample period. The repetitions last until we reach the full length of our sample, by which time we have a series of SFE. We take the mean of the SFE (MSFE) series as a measure of the model's forecasting accuracy. The lower the MSFE measure, the more accurate the forecast.

This procedure is followed both for the domestic model and the international model. Our focus rests entirely on comparing these two models, however we also introduce naive RW forecasts for the interest rate series, where $\widehat{Y}_{t+h} = Y_t$ for all h, as a standard benchmark in this literature. We, therefore, display the forecasting performance of the domestic and international model relative to the RW forecast. The lower the MSFE ratio between the model-based forecast and the RW, the higher the forecasting accuracy. A ratio of unity (1) indicates equal forecasting power between the chosen model and the RW model. A ratio of less than unity suggests that the chosen model's forecast outperforms the RW forecast.

To formalize our forecasting results, we apply White's (2000) "reality check". This is a test of superior forecast accuracy, where a benchmark model can be tested among a number of potential alternative models. The null hypothesis is that none of the alternative specifications has superior forecast accuracy than the benchmark. We implement the model in the following fashion: First, we take the international model as a benchmark versus the domestic and RW models. Should we accept the null, it means that none of the alternative models has superior forecast accuracy. However, to establish that our model is superior, we cross-check by running pairwise bootstrap tests, following Hördahl et al. (2005). In these tests we alternate the benchmark between the RW and the domestic model and run the tests for each benchmark vs the international model. Should we reject the null in both cases, it means that the international is indeed the best forecast.

4 Data

We use an extensive data set, which consists of monthly zero-coupon bond yield series for three major countries, Germany, the US and the UK for a period spanning a common sample from January 1986 to May 2006. Bond yield maturities range from 1 year to 10 years (i.e. $m = 1$ to 10 years). Our source is the Bank for International Settlements (BIS), which accumulates zero-coupon data for a large panel of countries, provided by the respective central banks[11].

[11] The BIS data are provided after the respective central banks calculate zero coupon yield curves, using their in-house calculation methods. In our case, these methods include models which extend the Nelson and Siegel model.

An implication would be that our domestic model is effectively a restricted version of the model generating the data and this could lead to marginal differences in the fit of the yield curve. Nevertheless, as long as no international lead-lag relationships are accounted for when generating the data, the marginally different fit would likely not change the main thrust of our results.

5 Results

In this section we present the statistical results of our forecast exercise for the different model specifications and interpret the findings in the light of international dependencies among the countries considered. The statistical findings are summarized in Tables 1 to 6. Tables 1, 2 and 3 present our forecast results for Germany, the US and the UK respectively. Tables 4 to 6 present the bootstrap tests for superior forecasting accuracy between the international and the domestic model for each country.

5.1 Analysis

Comparing the international with the domestic model, our results suggest clear forecasting patterns for each country: The international model proves to be a very good forecasting tool for countries dependent on international information (in a statistical sense). Looking separately at each country, we observe the following:

For the case of Germany, the international model beats the domestic model. This is a general result that holds for all maturities, all forecast horizons and all model specifications. The international model (All) produces consistently lower MSFE ratios (Table 1) which tend to decline on average with longer forecast horizons. For the 6 and 12 steps ahead horizons, the lowest MSFE are recorded for maturities in the medium term, around 5 years. This finding might suggest the effect of similar dependency patterns on business cycles, which would tend to affect interest rates in the medium to long term horizons (Giannone and Reichlin, 2006 have provided evidence on German business cycles being affected by the US ones). These readings are confirmed by the bootstrap tests (Table 4). The White test shows that the null of no other superior model is generally accepted (Benchmark: All), whereas the pairwise bootstrap test confirms that the alternative international forecast is indeed superior than the domestic one (Benchmark: GE). Moreover, we find that the international model has superior forecasting accuracy compared to the RW for longer forecast horizons whereas for short forecast horizons the two models perform equally well (Benchmark RW).

We find the opposite results for the US. In fact, adding information from Germany and the UK to the domestic US model does not improve forecasting power in a statistically significant sense (yields-only model). MSFE appear to be very close to unity for almost all model specifications, horizons and maturities, suggesting that the different models have equal forecasting accuracy (Table 4). Indeed, evidence from the bootstrap tests (Table 5) confirms this result (i.e. the null is not rejected in any case), therefore suggesting equal forecasting accuracy for all three models (i.e. the MSFE are not statistically significant from unity).

The results on the UK appear someway in between German and US results. Adding international information appears to significantly improve forecasts (in mdium term maturities for 6 steps ahead forecasts and for almost all maturities for 12 steps ahead forecasts). In that case MSFE drop below unity (Table3), in what appears to be a statistically significant drop (the pairwise tests in Table 6 suggest that the alternative international model is superior, whereas the white's test does not reject the null of no other model's superiority). Therefore, the domestic model clearly outperforms the two others for long horizon forecasts. For the rest of cases the three models have equal forecasting power (i.e. MSFE are not statistically different from unity). Looking at the behaviour of the MSFE across maturities, we observe the same pattern as in the case of Germany, i.e. MSFE drop to their lowest point at medium term maturities, around 5 years (for the case of 6 and 12 steps ahead). This, as previously mentioned, might suggest some similar patterns in output driving interest rates at these maturities.

5.2 Assessment

Our fundamental question of whether the inclusion of international information helps improve the predictability of a domestic series can be viewed as an out-of-sample Granger causality test. In that light, our results reveal dependency patterns with clear directions. Germany and the US appear at the two ends of the spectrum, with the first profiting greatly from international information while the second being sufficient on domestic information. The UK appears to lie mid-way. In other words, our findings suggest a more independent role for the US in the international environment (i.e. causality linkages among other countries and the US are unidirectional). Germany appears to be particularly dependent on information coming from foreign sources (one way causality with the US and UK), while the UK appears dependent to a much smaller extent (two-way causality with Germany and one-way with the US). Such evidence generalizes previous literature results on international linkages in interest rates (Frankel et al., 2004; Chinn and Frankel, 2005; Belke and Gross, 2005), further supporting a leading role for the US and the existence of lagging dependency patterns between the US and Germany.

However, some limitations to our study exist by construction. In essence, the above dependency patterns are established in a statistical sense only. This has two implications: First, it is not clear if such linkages are economically significant, i.e. if trading gains can be established based on our forecasts. This is an analysis that would need to involve more inputs (such as establishing arbitrage opportunities and including trading costs and restrictions to replicate trading strategies). Second, the channels generating these linkages, are not exposed, albeit clearly exploited: In this study we document dependency patterns in the yield curves of different countries, strong enough to help us in forecasting. However, we do not identify the cause of such linkages, e.g. what can cause the asymmetric distribution of shocks across countries. A theoretical model detailing the channels and mechanisms linking economies remains an open challenge for future research.

In terms of policy implications, our results suggest an outward looking perspective in modeling policy related variables. Of course, more elaborate policy recommendations require further insights into the causes of such yield curve dependencies. More specifically, our results suggest that international dependency patterns can be strong enough to help some monetary authorities with their forecasts of domestic yield curves. However, having a structural model rationalizing the underlying causes of such linkages could help further deciding appropriate policy actions. For example, our evidence suggests that forecasts in medium maturities appear to be better than in short or very long maturities. This could reflect similar dependency patterns in macroeconomic variables driving interest rates in the medium run and would argue probably against the notion of monetary policy dependency patterns. However, even if we could ascertain the validity of this statement, this could happen because different countries might have different resistance levels to various global shocks, thereby reacting to them at a later stage. In that case, even independent reactions to common (global) shocks could elicit dependency patterns in the yield-curves of various countries. Overall, policy implications can be different depending on the underlying forces of the such linkages. Although a structural model outlining such linkages should be the issue of further research, our simple reduced-form version suggests a clear scope for international considerations when modeling policy relevant variables.

6 Conclusion

This paper presents a novel methodology to explore international dependency linkages among yield curves of different countries in an out-of-sample forecast exercise. The motivation stems from related literature establishing dependency in the yields of different countries. The paper extends this analysis to the whole yield curve in a robust way by means of an out-of sample forecast. It adopts the prior that augmenting a purely domestic information set with international information could improve forecasting power. This conjecture is tested in a three country setting, where each country has its own yield curve representation, summarized into (domestic) level, slope and curvature factors. However, international information comes into play in the forecasting phase. There, information from foreign yield curves is allowed to enter in the forecast of the domestic yield curve. This is the international counterpart to the domestic forecast, where only domestic information feeds into the forecast of the domestic yield curve.

The methodology employs a dynamic factor model and ML estimation techniques based on the EM algorithm and the Kalman filter to estimate and forecast the different model specifications. The combination of the EM algorithm and the Kalman filter allows efficient estimation of the model using a large number of variables and successfully restricting factor loadings to identify yield factors as L, S and C. This methodology improves the competitive edge of the paper, since it allows the generalisation of results to the whole yield curve, while extending the data set and the analysis to more than one countries in a compatible way between the two models (domestic and international).

Results suggest the existence of non-contemporaneous international linkages strong enough to improve yield curve forecasts for certain countries. More precisely, the international model works particularly well for the German case. In the UK, international information from Germany and the US helps at longer forecast horizons, whereas the US appears to be impervious to transatlantic developments. Such findings imply a clearly leading role for the whole US term structure and a lagging dependency pattern for Germany. The results of this paper are in line with previous anecdotal evidence on interest rates, thereby generalizing such evidence to the whole yield curve.

Overall, this paper presents a novel methodology to address a topical question of whether adding international information can help forecast the domestic yield curve in a simple but holistic way. In so doing, it extends the yield curve forecast literature to the international direction and records, for the first time, dependency patterns for the whole yield curve. It therefore extends previous anecdotal evidence of dependency patterns for specific interest rates to the whole yield curve in a robust way. Under this light, this paper empirically supports a more outward-looking perspective in modeling financial variables.

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Table 1. Out of sample forecasts: Germany

	$MSFE_Y/MSFE_{RW}$					
Iterative	1-steps		6-steps		12-steps	
m	GE	All	GE	All	GE	All
1	7.813	4.234	1.877	0.752	1.0092	0.671
2	3.096	1.778	1.774	0.764	1.0193	0.544
3	2.170	1.456	1.693	0.772	1.1507	0.517
4	1.713	1.257	1.577	0.738	1.3388	0.510
5	1.486	1.168	1.507	0.710	1.6026	0.521
6	1.355	1.134	1.491	0.704	1.9307	0.555
7	1.255	1.110	1.524	0.720	2.3072	0.614
8	1.163	1.068	1.604	0.751	2.7291	0.697
9	1.089	1.011	1.736	0.798	3.2053	0.808
10	1.072	0.972	1.929	0.865	3.7464	0.949

Notes: The table presents the results from the out of sample forecasts of the domestic (GE) and international (All) yields-only (Y) models compared to the RW forecast. The results displayed in the columns represent the MSFE of the yields-only model ($MSFE_Y$) divided by the MSFE of a RW ($RMSE_{RW}$) for $h = 1, 6$ and 12 steps ahead and for maturities $m = 1$ to 10.

Table 2. Out of sample forecasts: US

	$MSFE_Y/MSFE_{RW}$					
Iterative	1-steps		6-steps		12-steps	
m	US	All	US	All	US	All
1	1.076	1.493	1.091	1.662	0.981	1.247
2	1.140	1.489	1.071	1.7222	0.994	1.350
3	1.046	1.404	1.045	1.885	1.069	1.558
4	0.994	1.339	1.071	2.127	1.213	1.875
5	0.983	1.325	1.136	2.242	1.405	2.260
6	0.982	1.361	1.243	2.838	1.666	2.755
7	1.001	1.428	1.401	3.420	2.041	3.450
8	1.014	1.527	1.529	3.859	2.392	4.092
9	1.065	1.670	1.757	4.503	2.788	4.776
10	1.268	2.142	2.217	5.617	3.406	5.782

Notes: The table presents the results from the out of sample forecasts of the domestic (US) and international (All) yields-only (Y) models compared to the RW forecast. The results displayed in the columns represent the MSFE of the yields-only model ($MSFE_Y$) divided by the MSFE of a RW ($RMSE_{RW}$) for $h = 1, 6$ and 12 steps ahead and for maturities $m = 1$ to 10.

Table 3. Out of sample forecasts: UK

	MSFE$_Y$/MSFE$_{RW}$					
Iterative	1-steps		6-steps		12-steps	
m	UK	All	UK	All	UK	All
1	0.968	1.419	0.865	1.875	0.688	1.650
2	1.012	1.193	1.082	1.382	0.894	1.076
3	1.076	1.116	1.263	1.196	1.089	0.854
4	1.135	1.065	1.352	1.110	1.209	0.749
5	1.163	1.039	1.372	1.082	1.278	0.704
6	1.152	1.037	1.349	1.099	1.321	0.697
7	1.115	1.062	1.306	1.155	1.354	0.721
8	1.076	1.125	1.259	1.250	1.388	0.772
9	1.063	1.236	1.221	1.386	1.427	0.851
10	1.094	1.407	1.119	1.562	1.475	0.962

Notes: The table presents the results from the out of sample forecasts of the domestic (UK) and international (All) yields-only (Y) models compared to the RW forecast. The results displayed in the columns represent the MSFE of the yields-only model (MSFE$_Y$) divided by the MSFE of a RW (RMSE$_{RW}$) for $h = 1, 6$ and 12 steps ahead and for maturities $m = 1$ to 10.

Table 4. Forecast performance: Germany

	Benchmark: All			Benchmark:RW			Benchmark:GE		
m	vs: RW&GE			vs: All			vs:All		
	1 steps	6 steps	12 steps	1 steps	6 steps	12 steps	1 steps	6 steps	12 steps
1	1.000	0.109	0.090	1.000	0.000	0.001	0.000	0.000	0.014
2	1.000	0.092	0.037	0.995	0.002	0.000	0.000	0.000	0.002
3	1.000	0.134	0.050	0.987	0.007	0.000	0.000	0.000	0.000
4	0.993	0.142	0.074	0.943	0.004	0.000	0.000	0.000	0.000
5	0.980	0.148	0.123	0.888	0.006	0.000	0.004	0.000	0.000
6	0.972	0.182	0.188	0.871	0.014	0.003	0.017	0.000	0.000
7	0.980	0.245	0.264	0.842	0.027	0.012	0.056	0.000	0.000
8	0.945	0.348	0.377	0.767	0.058	0.044	0.115	0.000	0.000
9	0.868	0.459	0.539	0.603	0.124	0.161	0.143	0.000	0.000
10	0.722	0.608	0.739	0.422	0.255	0.426	0.090	0.000	0.000

Table 5. Forecast performance: US

	Benchmark: All			Benchmark:RW			Benchmark:US		
m	vs: RW&US			vs: All			vs:All		
	1 step	6 steps	12 steps	1 step	6 steps	12 steps	1 step	6 steps	12 steps
1	0.968	0.935	0.754	0.995	0.997	0.950	0.999	1.000	1.000
2	0.999	0.916	0.797	0.999	0.999	0.964	0.998	1.000	1.000
3	0.948	0.884	0.9005	0.996	0.999	0.994	0.999	1.000	1.000
4	0.805	0.904	0.977	0.990	1.000	0.999	0.999	1.000	1.000
5	0.762	0.952	0.998	0.989	1.000	1.000	0.998	1.000	1.000
6	0.764	0.982	1.000	0.994	1.000	1.000	0.999	1.000	1.000
7	0.825	0.996	1.000	0.997	1.000	1.000	1.000	1.000	1.000
8	0.857	0.999	1.000	0998	1.000	1.000	0.999	1.000	1.000
9	0.946	1.000	1.000	0.999	1.000	1.000	1.000	1.000	1.000
10	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Notes: The tables present bootstrapped p-values derived for $h = 1, 6$ and 12 steps ahead and maturities $m = 1$ to 10 from three different tests: The White's "reality check", where the international model ("All") is tested against the domestic and the random walk ("RW") and two pairwise bootstrap exercises where the RW and the domestic model are tested versus the international model. In Table 4 the domestic country is considered to be Germany ("GE") and in Table 5 the US ("US").The null hypothesis states that none of the alternative specifications has superior forecast accuracy than the benchmark.

Table 6. Forecast performance: UK

	Benchmark: All			Benchmark:RW			Benchmark:UK		
m	vs: RW&UK			vs: All			vs:All		
	1 step	6 steps	12 steps	1 step	6 steps	12 steps	1 step	6 steps	12 steps
1	0.906	0.965	0.613	0.991	1.000	0.999	0.982	0.995	0.994
2	0.717	0.961	0.637	0.961	0.992	0.697	0.924	0.886	0.761
3	0.764	0.987	0.265	0.910	0.951	0.079	0.783	0.506	0.051
4	0.956	0.981	0.080	0.835	0.901	0.003	0.435	0.204	0.002
5	0.952	0.976	0.046	0.777	0.897	0.000	0.205	0.106	0.000
6	0.949	0.989	0.049	0.777	0.946	0.000	0.166	0.099	0.000
7	0.980	0.997	0.072	0.872	0.991	0.000	0.264	0.151	0.000
8	0.973	0.999	0.134	0.953	0.998	0.001	0.542	0.293	0.000
9	0.926	1.000	0.268	0.984	0.999	0.014	0.840	0.536	0.000
10	0.909	1.000	0.568	0.992	0.999	0.150	0.964	0.777	0.000

Notes: The tables present bootstrapped p-values derived for $h = 1, 6$ and 12 steps ahead and maturities $m = 1$ to 10 from three different tests: The White's "reality check", where the international model ("All") is tested against the domestic ("UK") and the random walk ("RW") and two pairwise bootstrap exercises where the RW and the domestic model are tested versus the international model. The null hypothesis states that none of the alternative specifications has superior forecast accuracy than the benchmark.

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