Change Points in Affine Term-Structure Models: Pricing, Estimation and Forecasting*

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Abstract

In this paper we theoretically and empirically examine structural changes in a dynamic term-structure model of zero-coupon bond yields. To do this, we develop a new arbitrage-free one latent and two macro-economics factor affine model to price default-free bonds when the parameters in the dynamics of the factor evolution, in the model of the market price of factor risks, and in the process of the stochastic discount factor, are all subject to change at unknown time points. The bonds in our set-up can be priced straightforwardly once the change-point model is re-formulated in the manner of Chib (1998) as a specific unidirectional Markov process with restricted transition probabilities. We consider five versions of our general model - with 0, 1, 2, 3 and 4 maximum number of possible change-points - to a collection of 16 yields measured quarterly over the period 1972:I to 2007:IV. Our empirical approach to inference is fully Bayesian with priors set up to reflect the assumption of a positive term-premium. The use of Bayesian techniques is particularly relevant because the models are high-dimensional and non-linear, and because it is more straightforward to compare our different change-point models from the Bayesian perspective. Our estimation results indicate that the model with 3 change-points is most supported by the data and that the breaks occurred in 1980:II, 1985:IV and 1995:II. These dates correspond (in turn) to the time of a change in monetary policy, the onset of what is termed the great moderation, and the start of technology driven period of economic growth. We also utilize the Bayesian framework to derive the out-of-sample predictive densities of the term-structure. We find that the forecasting performance of our proposed model is substantially better than that of the other models we examine. (JEL G12, C11, E43)

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1 Introduction

Affine term structure models provide a flexible approach for modeling the dynamics of bond prices and yields. This is especially true of multi-factor affine models (for example, Duffie and Kan (1996) where the factors under the physical measure follow a stationary Gaussian VAR process and Dai and Singleton (2000) where the factors follow a CIR type process) and of multi-factor models that include macro-economic factors (for example, Ang and Piazzesi (2003), Ang, Dong, and Piazzesi (2007) and Chib and Ergashev (2009)) and/or permit the possibility of regime-changes (for example, Dai, Singleton, and Yang (2007), Bansal and Zhou (2002), Ang, Bekaert, and Wei (2008)). The literature on these topics is quite impressive and the recent strengthening of links between macro-economics and finance in this area is a rather promising development.

One of our main objectives in this paper is to develop a new multi-factor affine model with macro factors within the context of a change-point model of regime-changes, rather than the Markov-switching model of regime-changes that has been used in the existing literature. In our change-point model, a regime once occupied and vacated is never visited again. In contrast, in a Markov switching model, the regimes recur, which implies that a regime occupied in the past (distant or near) can occur in the future. The latter assumption may not be appropriate if one believes that the confluence of conditions that determine a regime is unique and not repeated. For generality, we assume that all the parameters of the model, including those in the dynamics of the factor evolution, in the model of the market price of factor risks, and in the process of the stochastic discount factor (SDF), are subject to change at unknown time points. We model parameter-changes (equivalently, regime-changes) in this way because this assumption appears particularly appropriate in affine models with macro factors. In such models, when the macro factors are the inflation rate and the growth rate of GDP, the short rate is essentially the Taylor rule of macroeconomics. The Taylor rule reflects the behavior of monetary policy. If one believes that monetary policy is constant over epochs but different across epochs, then it is reasonable to assume that the processes of the factors and the SDF should also be different across epochs. Another reason for adopting the change-point model is empirical. The filtered regime probabilities in the empirical analysis of Dai et al. (2007) and Ang and Bekaert (2002)
strongly indicate that the same regime has prevailed after 1986. This pattern seems to be more suggestive of a change-point rather than a Markov switching process.

Our modeling of the factor process, the market price of factor risk and the SDF is of course similar but not identical to that of the existing literature. In fact, these primary building blocks of affine models can be, and have been, specified in different ways. Like Dai et al. (2007), our model of regime-change is in the context of models with Gaussian factors although we go beyond their exclusive reliance on latent factors to include two macro factors. In addition, we follow Bansal and Zhou (2002) to assume that the factor loadings are regime-specific. In this we depart from Dai et al. (2007) and Ang et al. (2008) where the factor loading matrix is assumed to be constant across regimes. Under our time-varying factor loading assumption bond prices can only be derived by an approximate solution to the risk-neutral pricing formula, as in Bansal and Zhou (2002) and Bansal, Tauchen, and Zhou (2004). This seems to be a minor inconvenience since allowing for regime dependence of the factor loadings is essential to capture the changes in the Taylor rule and our analysis on the data supports this assumption. In our work, the dynamics of the factors at time $t$ depend on both the regime $s_t$ at time $t$ and the regime $s_{t-1}$ at time $t-1$. On the other hand, in Dai et al. (2007), the factor dynamics at time $t$ depend on the regime $s_{t-1}$ in period $(t-1)$, rather than on $s_t$. In Bansal and Zhou (2002) and Ang et al. (2008), the factor dynamics depend on the current regime $s_t$. Finally, in contrast to Dai et al. (2007), our model does not price regime-shift risk. It is not possible to identify this risk when each regime-shift occurs once. It should be noted that this risk cannot be directly isolated either in the models of Ang et al. (2008) and Bansal and Zhou (2002) because their modeling of the SDF is such that this risk is confounded with the market price of factor risk. We are, however, able to identify the market price of factor risk since we assume that the SDF is independent of $s_{t+1}$ conditioned on $s_t$, as in the model of Dai et al. (2007).

We apply our model to the largest collection of yields that has been considered in this literature. In particular, we fit up to 4 change point model (which has 4 maximum number of possible change points) on 16 quarterly yields containing 209 parameters. Our method of inference is Bayesian with a prior distribution on the parameters that reflects the assumption of a positive term-premium, as in Chib and Ergashev (2009). We adopt the Bayesian perspective because it is virtually impossible to fit the models by maximum likelihood because of the
number of parameters, the severe non-linearities, and potential multi-modalities in the likelihood surface. As we show, our Bayesian approach is both feasible and reliable. It also offers a formal way to compare different versions of our model and provides the basis for calculating the out of sample predictive densities, all desirable inferential goals.

We compare five versions of the general model - with 0, 1, 2, 3 and 4 change points (that we refer to as the \( C_0 \), \( C_1 \), \( C_2 \), \( C_3 \) and \( C_4 \) models, respectively) in terms of marginal likelihoods and Bayes factors. The main findings from our empirical analysis (from quarterly yields of sixteen US T-bills between 1972:I and 2007:IV) are as follows. The 3 change point model, \( C_3 \), is the one that is most supported by the data (in comparison with models with 0, 1, 2 and 4 change-points) and that the breaks occurred in 1980:II, 1985:IV and 1995:II. These change-points can be attributed, in turn, to changes in monetary policy, the onset of what is termed the great moderation, and the start of the technology driven period of economic growth. One striking feature emerging from this finding is that the most recent break occurs in 1995, not 1985, as is commonly believed. The differences in the distribution of the term-structure can be seen in Figure 1 where we display the 5%, 50% and 95% quantiles of the yield curve in each of the four regimes. In addition, there are substantial differences in the parameters across regimes. In particular we find support for our assumption that the mean-reversion parameters in the factor dynamics and the factor loadings are regime-specific. Finally, we show that the predictive performance of our best model is substantially better than that of the other models we consider.

The rest of the paper is organized as follows. In Section 2 we present our change point term-structure model and derive the resulting bond prices. We outline the prior-posterior analysis of our model in Section 3 deferring details of the MCMC simulation procedure to the appendix of the paper. Section 4 deals with the empirical analysis of the real data and Section 5 has our conclusions.

2 Model Specification

We describe our model in two steps. First, we characterize the change-point process and then second, as dictated by the framework of Duffie and Kan (1996), we define the exogenous factors \( f_t \) (containing both latent and observed macro-economic variables), the stochastic evolution
equation of the factors, the model of the market price of factor risks $\gamma_{t,s_t}$, and the model of the stochastic discount factor $\kappa_{t,t+1}$. Given these ingredients, we then derive the prices of our default-free zero coupon bonds.

2.1 Change-point Process

Let $\{s_t\}$ be a discrete stochastic process that takes one of the values $\{1, 2, \ldots, q+1\}$ such that $s_t = j$ indicates that the $t$th observation has been drawn from the $j$th regime. We then suppose that the parameters in the evolution equation of the factors, the market-price of factor risks, and the SDF, are subject to change at the unknown times $\{t^*_1, t^*_2, \ldots, t^*_q\}$ such that $s_{t^*_j-1} = j$ and $s_{t^*_j} = j + 1$ ($j = 1, 2, \ldots, q$). Notice that these $q$ change-points give rise to $(q + 1)$ distinct regimes. Unlike a Markov switching process, the regimes induced by the change-points are not revisited once vacated.

We now present a reformulation of the change-point model due to Chib (1998) that facilitates risk-neutral pricing and the subsequent Bayesian estimation of the model. It is assumed that $s_t$ is Markov and its distribution is governed by the homogenous transition probability

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Figure 1: Term structure of interest rates. Data summary of the term-structure - data obtained from http://www.federalreserve.gov/econresdata/researchdata.htm. The graphs display the 5%, 50% and 95% quantiles of the yield curve for bonds of maturity 1, 2, 3, 4, 5, 6, 7, 8, 10, 12, 16, 20, 24, 28, 36 and 40 quarters.
matrix
\[
P = \begin{bmatrix}
p_{11} & 1 - p_{11} & 0 & \cdots & 0 \\
0 & p_{22} & 1 - p_{22} & \cdots & 0 \\
0 & 0 & p_{33} & \cdots & 0 \\
\vdots & \vdots & \ddots & \ddots & \ddots \\
0 & 0 & 0 & \cdots & p_{q+1|q+1}
\end{bmatrix}
\]

(2.1)

where \( p_{jk} = \Pr[s_{t+1} = k|s_t = j] \). As shown in Chib (1998), this Markov process can be mapped into a change-point process by letting \( p_{jk} = 1 - p_{jj}, k = j + 1 \) and \( p_{q+1|q+1} = 1 \) \((j = 1, 2, \ldots, q)\). Thus, under this specification, \( s_t = j \) either stays at the current value \( j \) or jumps to the next higher value \( (j + 1) \). As required, return visits to a previously occupied state are not possible and the last state is absorbing.

This reformulation of the change-point model in terms of a restricted unidirectional Markov process facilitates pricing (as we show below). It also makes obvious how the change-point assumption differs from the Markov-switching regime process in Dai et al. (2007), Bansal and Zhou (2002) and Ang et al. (2008) where the transition probability matrix is unrestricted. As we have argued in the introduction, there are strong reasons for looking at the term structure from the change-point perspective.

It should be noted that in pricing bonds economic agents are presumed to know \( q \), the maximum number of possible change points whereas the future regimes are unknown.

2.2 Factor Specification

Following the new affine term-structure literature, we explain the dynamics of bond-prices in terms of the dynamics of both latent and observed macro-economics variables. For concreteness, we assume (as in our empirical work) that the factors \( f_t \) consist of one latent variable \( u_t \) and two observed macroeconomic factors \( m_t \). We next suppose that the evolution of these exogenous factors is governed by the Gaussian regime-specific mean-reverting first-order autoregression

\[
f_{t+1} = \left( \begin{array}{c} u_{t+1} \\ m_{t+1} 
\end{array} \right) | f_t, s_{t+1}, s_t \sim N_3(\mu_{s_{t+1}} + G_{s_{t+1}} (f_t - \mu_{s_t}), \Omega_{s_{t+1}}),
\]

(2.2)

where \( N_3(.,.,.) \) denotes the 3-dimensional normal distribution, and for \( j = 1, 2, \ldots, q + 1 \), \( \mu_j \) is a \( 3 \times 1 \) vector, \( G_j \) and \( \Omega_j \) are \( 3 \times 3 \) matrices. It is important to note that under this specification

\[
E[f_{t+1}|f_t, s_{t+1} = k, s_t = j] = \mu_k + G_k (f_t - \mu_j)
\]
and
\[ Var[f_{t+1}|f_t, s_{t+1} = k, s_t = j] = \Omega_k. \]
The conditional expectation, therefore, depends on both \( \mu_k \) and \( \mu_j \). The appearance of \( \mu_j \) in this expression is natural because one would like the autoregression at time \((t + 1)\) to depend on the deviation of \( f_t \) from the regime in the previous period. Of course, the parameter \( \mu_j \) can be interpreted as the expectation of \( f_{t+1} \) in regime \( j \). The matrices \( \{G_j\} \) can also be interpreted in the same way: as the mean-reversion parameters in regime \( j \).

### 2.3 Market Price of Factor Risk

We now move to our model of \( \gamma_{t,s_t} \), the vector of market prices of factor risks in regime \( s_t \). Following Dai et al. (2007), we assume that
\[
\gamma_{t,s_t} = \tilde{\gamma}_{s_t} + \Phi_{s_t}(f_t - \mu_{s_t})
\]
where \( \tilde{\gamma}_{s_t} : 3 \times 1 \) is the regime dependent expectation of \( \gamma_{t,s_t} \) and \( \Phi_{s_t} : 3 \times 3 \) is a matrix of regime-specific parameters. We refer to the collection \( \{\tilde{\gamma}_{s_t}, \Phi_{s_t}\} \) as the factor-risk parameters. Note that in this specification \( \gamma_{t,s_t} \) is the same across maturities but different across regimes. Negative market prices of risk have the effect of generating a positive term premium. We exploit this feature to develop a proper prior distribution on the risk parameters.

### 2.4 Short-rate and the SDF

The instantaneous short rate \( r_{t,s_t} \) in regime \( s_t \) is also assumed to be an affine function of the factors
\[
r_{t,s_t} = \delta_{1,s_t} + \delta'_{2,s_t}(f_t - \mu_{s_t})
\]
It is essential that \( \delta_{1,s_t} \) be regime-specific if the aim is to allow for shifts in the level of the term structure. We also allow \( \delta_{2,s_t} : 3 \times 1 \) to be regime-dependent in order to capture shifts in the effects of the macroeconomic factors on the term structure. This is a departure from both Ang et al. (2008) and Dai et al. (2007) where the coefficient on the factors is constrained to be constant across regimes to get tractable expressions for the bond-prices. We now assume that the SDF \( \kappa_{t,t+1} \) in time \( t \) is given by
\[
\kappa_{t,t+1} = \exp \left( -r_{t,s_t} - \frac{1}{2} \gamma'_{t,s_t} \gamma_{t,s_t} - \gamma'_{t,s_t} \omega_{t+1} \right)
\]
where $\omega_{t+1}$ is a vector of regime independent normalized $N_3(0, I_3)$ factor shocks. Because $\kappa_{t,t+1}$ is independent of $s_{t+1}$ conditional on $s_t$, it is easily checked that $E[\kappa_{t,t+1}|f_t, s_t = j]$ equals the price of a zero coupon bond with ($\tau = 1$):

$$E[\kappa_{t,t+1}|f_t, s_t = j] = \sum_{s_{t+1} = j}^{j+1} p_{js_{t+1}} E[\kappa_{t,t+1}|f_t, s_t = j, s_{t+1}] = \exp(-r_{t,j}), \ j \in \{1, 2, .., q\}$$

(2.6)

Thus, the SDF satisfies the intertemporal no-arbitrage condition (Dai et al. (2007)).

2.5 Bond Prices

We now derive the price of our default-free zero-coupon bonds. Let $P_t(s_t, \tau)$ denote the price of the bond at time $t$ in regime $s_t$ that matures in period $(t + \tau)$. From the risk-neutral pricing formula we have that

$$P_t(s_t, \tau) = E_t[\kappa_{t,t+1}P_{t+1}(s_{t+1}, \tau - 1)]$$

(2.7)

where $E_t$ is the expectation under the physical measure conditioned on $(f_t, s_t)$. The expectation is over the factor shocks in $(t + 1)$ and the two possible values that $s_{t+1}$ can take given $s_t$.

Following Duffie and Kan (1996), we assume now that $P_t(s_t, \tau)$ is a regime-dependent exponential affine function of the factors taking the form

$$P_t(s_t, \tau) = \exp(-\tau R_{\tau t})$$

(2.8)

where $R_{\tau t}$ is the bond’s continuously compounded yield given by

$$R_{\tau t} = \frac{1}{\tau}a_{s_t}(\tau) + \frac{1}{\tau}b_{s_t}(\tau)'(f_t - \mu_{s_t})$$

(2.9)

and $a_{s_t}(\tau)$ is a scalar function and $b_{s_t}(\tau)$ is a $3 \times 1$ vector of functions, both depending on $s_t$ and $\tau$.

By the usual techniques, we find the expressions for the latter functions by the method of undetermined coefficients. By the law of the iterated expectation, the risk-neutral pricing formula in (2.7) can be expressed as

$$1 = E_t \left\{ E \left[ \kappa_{t,t+1} \frac{P_{t+1}(s_{t+1}, \tau - 1)}{P_t(s_t, \tau)} | f_t, s_t, s_{t+1} \right] \right\}$$

(2.10)
where the inside expectation is conditioned on $s_{t+1}$ as well as $s_t$. One now substitutes $P_t(s_t, \tau)$ and $P_{t+1}(s_{t+1}, \tau - 1)$ from (2.8) and (2.9) into this expression. We integrate out $s_{t+1}$ after a log-linearization that is discussed in Appendix A. We match common coefficients and solve for the unknown functions. When $j \in \{1, \ldots, q\}$ and $k = j + 1$, this procedure produces the following recursive system for the unknown functions

$$
\begin{align*}
    a_j(\tau) &= \begin{pmatrix} p_{jj} & p_{jk} \end{pmatrix} \begin{pmatrix} \delta_{1,j} - \hat{\gamma}_j L_j' b_j(\tau - 1) - b_j(\tau - 1)' L_j L_j' b_j(\tau - 1)/2 + a_j(\tau - 1) \\ \delta_{1,j} - \hat{\gamma}_j L_k' b_k(\tau - 1) - b_k(\tau - 1)' L_k L_k' b_k(\tau - 1)/2 + a_k(\tau - 1) & \end{pmatrix} \\
    b_j(\tau) &= \begin{pmatrix} p_{jj} & p_{jk} \end{pmatrix} \begin{pmatrix} \delta_{2,j} + (G_j - L_j \Phi_j)' b_j(\tau - 1) \\ \delta_{2,j} + (G_k - L_k \Phi_j)' b_k(\tau - 1) \end{pmatrix}
\end{align*}
$$

and when $j = q + 1$ we have that

$$
\begin{align*}
    a_j(\tau) &= \delta_{1,j} - \hat{\gamma}_j L_j' b_j(\tau - 1) - b_j(\tau - 1)' L_j L_j' b_j(\tau - 1)/2 + a_j(\tau - 1) \\
    b_j(\tau) &= \delta_{2,j} + (G_j - L_j \Phi_j)' b_j(\tau - 1)
\end{align*}
$$

where $L_j$ is the Cholesky decomposition of $\Omega_j$ and $\tau$ runs over the positive integers. These recursions are initialized by setting $a_{s_t}(0) = 0$ and $b_{s_t}(0) = 0_{3 \times 1}$ for all $s_t$. It is readily seen that the resulting intercept and factor loadings are determined by the weighted average of the two potential realizations in the next period where the weights are given by the transition probabilities $p_{jj}$ and $(1 - p_{jj})$, respectively. Thus, the bond prices in regime $s_t = j$ ($j \leq q$) incorporate the expectation that the economy in the next period will continue to stay in regime $j$, or that it will switch to the next possible regime $k = j + 1$, each weighted with the probabilities $p_{jj}$ and $1 - p_{jj}$, respectively.

Figure 2 summarizes the economy that we have just described in terms of a directed acyclic graph. In the beginning of period $t$, a regime realization occurs. This realization is governed with the regime in the previous period as indicated by the direction of the arrow connecting $s_{t-1}$ to $s_t$. Then given the regime at time $t$, the corresponding model parameters $\Theta_t$ are taken from the full collection of model parameters. These determine the functions $\alpha_{s_t}(\tau)$ and $b_{s_t}(\tau)$ according to the recursions in (2.11) and (2.12). Conditioned on the parameters and $f_{t-1}$, $f_t$ is generated by the regime-specific autoregressive process in (2.2). Finally, from (2.9), $\alpha_{s_t}(\tau)$, $b_{s_t}(\tau)$ and $f_t$ determine the yields of all maturities. Notice that in Dai et al. (2007) the dashed line in figure 2 is absent since $f_t$ is assumed to be drawn independently of $s_t$. 

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2.6 Regime-specific Term Premium

As is well known, under risk-neutral pricing, after adjusting for risk, agents are indifferent between holding a $\tau$-period bond and a risk-free bond for one period. The risk adjustment is the term premium. In the regime-change model, this term-premium is regime specific. For each time $t$ and in the current regime $s_t = j$, it can be calculated as

$$\text{Term premium} = (\tau - 1) \text{Cov} (\ln \kappa_{t,t+1}, R_{\tau-1,t+1} | f_t, s_t = j)$$

$$= -p_{jj} b_j (\tau - 1)' L_j \gamma_{t,j} - p_{jk} b_k (\tau - 1)' L_k \gamma_{t,j}$$

where $k = j + 1$. One can see that if $L_j$, which quantifies the size of the factor shocks in the current regime $s_t = j$, is large, or if $\gamma_{t,j}$, the market prices of factor risk, is highly negative, then the term premium is expected to be large. Even if $L_j$ in the current regime is small, one can see from the second term in the above expression that the term premium can be big if the probability of jumping to the next possible regime is high and $L_k$ in that regime is large.

In our empirical implementation below we calculate this regime-specific term premium for each time period in the sample.
3 Estimation

One common approach for estimating affine models is by maximum likelihood. This is a reasonable approach when the size of the model (as measured by the number of parameters) is small. In higher-dimensional models, it becomes virtually impossible to find the maximum likelihood estimates due to the complicated nature of the affine model and irregularities (boundary maxima, multi-modalities etc) of the likelihood surface. For this reason, interest in the alternative Bayesian approach implemented by Markov chain Monte Carlo (MCMC) methods (Ang et al. (2007) and Chib and Ergashev (2009)) has grown. This approach is particularly attractive because one of our models contains 209 parameters. Our approach to inference is grounded in the recent developments that appear in Chib and Ergashev (2009) and Chib and Ramamurthy (2009). The former paper deals with a 3 factor macro factor affine model without regime changes. It introduces the useful idea of building a prior distribution on the parameters that embodies the assumption of a positive term-premium. We follow the same strategy in the regime-change model. The latter paper introduces an implementation of the MCMC method (called the tailored randomized block M-H algorithm) that we adopt here to fit our model. The idea behind this implementation is to update parameters in blocks, where both the number of blocks and the members of the blocks are randomly chosen within each MCMC cycle. This strategy is especially valuable in high-dimensional problems and in problems where it is difficult to form the blocks on a priori considerations.

3.1 Empirical State Space Formulation

Let the collection of yields at each time $t$ be denoted by

$$\bar{R}_t = (R_{1t}, R_{2t}, \ldots, R_{16t})'$$

where $R_{it} = R_{\tau_i, t}$ and $\tau_i$ is the $i$th maturity (in quarters). In the application, the set of maturities is given by

$$\{1, 2, 3, 4, 5, 6, 7, 8, 10, 12, 16, 20, 24, 28, 36, 40\}$$

Following Chen and Scott (2003) and Dai et al. (2007), we assume that one basis yield ($R_{8t}$, the eighth in the above list) is priced exactly by the model. Let the remaining 15 yields (which
are measured with error) be denoted by $R_t$. Define $\bar{a}_{i,s_t}(\tau_i)/\tau_i$ and $\bar{b}_{i,s_t}(\tau_i)/\tau_i$ where $a_{s_t}(\tau_i)$ and $b_{s_t}(\tau_i)$ are obtained from the recursive equations in (2.11) - (2.12). Also let $\tilde{a}_{s_t} (\tilde{a}_{s_t})$ and $\tilde{b}_{s_t} (\tilde{b}_{s_t})$ be the corresponding intercept and factor loadings for $R_{8t}$ ($R_t$), respectively. Then, since the basis yield is priced without error, we have that $R_{8t}$ is given by

$$R_{8t} = \tilde{a}_{8,s_t} + \tilde{b}_{u,s_t} u_t + \tilde{b}_{m,s_t} (m_t - \mu_{m,s_t})$$  

(3.2)

where

$$\tilde{b}_{s_t} = \begin{pmatrix} \tilde{b}_{u,s_t} \\ \tilde{b}_{m,s_t} \end{pmatrix}$$

This implies that the latent factor can be expressed in terms of the observed variables as

$$u_t = (\tilde{b}_{u,s_t})^{-1} \left( R_{8t} - \tilde{a}_{8,s_t} - \tilde{b}_{m,s_t} (m_t - \mu_{m,s_t}) \right)$$  

(3.3)

Conditioned on $m_t$, this represents a one-to-one map between $R_{8t}$ and $u_t$. We now let

$$f_t = \begin{pmatrix} u_t \\ m_t \end{pmatrix} = \begin{pmatrix} (\tilde{b}_{u,s_t})^{-1} \left( R_{8t} - \tilde{a}_{8,s_t} - \tilde{b}_{m,s_t} (m_t - \mu_{m,s_t}) \right) \\ m_t \end{pmatrix}$$  

(3.4)

and

$$y_t = \begin{pmatrix} R_t \\ f_t \end{pmatrix}$$

Then, we express our set of measurement equations in vector-matrix form as

$$y_t = \begin{pmatrix} \tilde{a}_{s_t} \\ \mu_{s_t} \\ \tilde{b}_{s_t} \end{pmatrix} + \begin{pmatrix} 1 \\ 0_{3 \times 15} \end{pmatrix} (f_t - \mu_{s_t}) + \begin{pmatrix} I_{15} \\ 0_{3 \times 15} \end{pmatrix} \varepsilon_t, \quad \varepsilon_t \sim iidN(0, \Sigma_{s_t})$$  

(3.5)

where the yields $R_t$ are augmented by the identity $f_t = f_t$ to ensure that the Kalman updates of the factors corresponding to the macro-factors have no error, $\varepsilon_t \sim N_{15}(0, \Sigma_{s_t})$ and $\Sigma_{s_t} = \text{diag}(\sigma_{1,s_t}^2, \sigma_{2,s_t}^2, \ldots, \sigma_{s_t}^2, \sigma_{s_t}^2, \ldots, \sigma_{16,s_t}^2)$.

The transition equation is characterized by the evolution of the factors in (2.2). As initial conditions of the factors, we assume that $m_0$, the values of the macro variables at time 0, is known from the data, and $u_0$, the latent factor at time 0, which is assumed to be independent of $m_0$, follows the steady-state distribution in regime 0

$$u_0 \sim N(0, V_u)$$  

(3.6)

where $V_u = (1 - G_{11,0}^2)^{-1}$. The equations (3.5), and (2.2) complete the state-space form of our model.
3.2 Identification

We impose the standard identifying restrictions on the parameters of our model. First, we set $\mu_{u,s_t} = 0$ which means that $\delta_{1,s_t}$ is a free parameter. The mean of the short rate conditional on $s_t$ is thus $\delta_{1,s_t}$. Second, the (1,1) element of $L_{s_t}$ is also set to be 1/400 for normalization and the first element of $\delta_{2,s_t}$, namely $\delta_{21,s_t}$, is assumed to be non-negative.

Finally, to enforce stationarity of the factor process, we restrict the eigenvalues of $G_{s_t}$ to lie inside the unit circle. Thus, under the physical measure, the factors are mean reverting in each regime. These constraints are summarized as

$$R = \{ G_j, \delta_{21,j} | \delta_{21,j} \geq 0, |eig(G_j)| < 1 \text{ for } j = 1, 2, ..., q+1 \} \quad (3.7)$$

All the constraints are enforced through the prior distribution.

3.3 Prior Distribution

Let $\theta$ denote the free parameters in $(G_{s_t}, \mu_{m,s_t}, \delta_{s_t}, \gamma_{s_t}, \Phi_{s_t}, L_{s_t}, P)$. These along with the diagonal elements of $\{\Sigma_{s_t}\}$ (except for the basis variance in each state which are zero) form the set of unknown parameters. Because of the size of the parameter space, and the complex cross-maturity restrictions on the parameters, the formulation of the prior distribution can be a challenge. Chib and Ergashev (2009) have tackled this problem and shown that a defensible and reasonable prior distribution can be constructed by thinking about the term structure that is implied by the prior distribution. The implied yield curve can be determined by simulation: simulating parameters from the prior and simulating yields from the model given the parameters. The prior can be adjusted until the implied term structure is viewed as satisfactory on a priori considerations. Chib and Ergashev (2009) use this strategy to arrive at a prior distribution that incorporates the belief of a positive term premium and stationary but persistent factors. We adapt their approach for our model with change-points, ensuring that the yield curve implied by our prior distribution is upward sloping within each regime.

We arrive at our prior distribution in this way for each of the five models we consider - with 0, 1, 2, 3 and 4 change-points. It seems that this is a satisfactory and sensible solution to an otherwise challenging problem.

Broadly, our prior is constructed along the following lines.
• The parameters in \((G_{st}, \mu_{m,st}, \delta_{st}, \Gamma_{st}, \Phi_{st}, L_{st}, P)\) and those in \(\Sigma_{st}\) are assumed to be mutually independent.

• Normal and truncated normal distributions are used to represent the prior uncertainty of \(\theta\). For example, the prior on \(p_{jj}\) \((j = 1, \ldots, q)\) is normal with a mean of 0.98 and a standard deviation of 0.33, truncated to the interval \((0, 1)\), and the distribution on the free parameters in \((G_{st}, \delta_{21,st})\) is normal truncated to the region \(R\). Table 1 then summarizes the first and second moment of our normal prior on \(\theta\) in the \(C^3\) model. This prior is modified in obvious ways to arrive at the prior distribution of our models with \(C0, C1, C2\) and \(C4\) models.

• In order to ensure the positive definiteness of \(\Omega_{st}\), we restrict that all diagonal elements are positive in the following way.

\[
L_{st} = \begin{pmatrix}
1 & 0 & 0 \\
\ell_{21,st} & \exp(\ell_{22,st}) & 0 \\
\ell_{31,st} & \ell_{32,st} & \exp(\ell_{33,st})
\end{pmatrix}
\]

Thus the elements in \(\lambda_{st} = \{\ell_{21,st}, \ell_{22,st}, \ell_{31,st}, \ell_{32,st}, \ell_{33,st}\}\) are unrestricted achieving positive definiteness of \(\Omega_{st}\).

• Finally, the 15 free parameters of \(\Sigma_{st}\) are transformed into \(\Sigma^*_{st}\) through the transformation \(\sigma^2_{i,st} = d_{i,st} \sigma^2_{i,st}\) where the \(d_{i,st}\) are known multipliers introduced to ensure that the \(\sigma^2_{i,st}\) are much bigger than \(\sigma^2_{i,st}\). We let \(\sigma^* = \{\sigma^2_{i,st}\}\) denote the entire collection of these transformed variances. In a 4 possible regime(i.e. \(C^3\) model, the dimension of \(\sigma^*\) is 60\((= 15 \times 4)\). We then assume that each \(\sigma^2_{i,st}\) has an inverse-gamma prior distribution with a mean of 10 and standard deviation of 14.

To show what these assumptions imply for the outcomes in the 3 change-point model, we simulate the parameters 50,000 times from the prior, and for each drawing of the parameters, we simulate the factors and yields for each maturity and each of 50 quarters. The median, 2.5% and 97.5% quantile surfaces of the resulting term structure in annualized percents are reproduced in Figure 3. It can be seen that the simulated prior term structure is gently upward sloping on average in each regime. Also the assumed prior allows for considerable a priori variation in the term structure. The implied prior distribution of the term structure for the other models we consider can be found in appendix B.
Table 1: Prior normal distribution for the model parameters in $\theta$ for $C3$ model. This table presents the prior mean and standard deviation of the parameters in $\theta$. The prior mean is in bold face and standard deviations are in parenthesis.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Regime 1</th>
<th>Regime 2</th>
<th>Regime 3</th>
<th>Regime 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$</td>
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<td>3.00</td>
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<td>6.00</td>
<td>6.00</td>
<td>6.00</td>
<td>6.00</td>
</tr>
<tr>
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<td>(5.00)</td>
<td>(5.00)</td>
<td>(5.00)</td>
</tr>
<tr>
<td>$\delta_1$</td>
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<td>(0.40)</td>
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<td>$\times 400$</td>
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<td>6.00</td>
<td>6.00</td>
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</tr>
<tr>
<td>$\gamma$</td>
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<td>-0.50</td>
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</tr>
<tr>
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<td>(0.40)</td>
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</tr>
<tr>
<td>$\times 400$</td>
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<td>1.00</td>
<td>1.00</td>
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<td>(1.00)</td>
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</tr>
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<td>(0, 0, 0, 0, 1)'</td>
<td>(0, 0, 0, 0, 1)'</td>
</tr>
<tr>
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<td>(2.00)</td>
<td>(2.00)</td>
<td>(2.00)</td>
<td>(2.00)</td>
</tr>
</tbody>
</table>

3.4 Posterior Distribution and MCMC Sampling

Under our assumptions it is now possible to calculate the posterior distribution of the parameters by MCMC simulation methods. The use of these methods in our high-dimensional problem is made possible by the inclusion of the latent factors and the latent regime indicators in the prior-posterior analysis and by the use of the tailored randomized block (TaRB) MCMC algorithm developed in Chib and Ramamurthy (2009).

Let $S_n = \{s_t\}_{t=1,...,n}$. Then, the posterior distribution that we would like to explore is given by

$$
\pi(\theta, \sigma^2, u_0, S_n|y) \propto f(y|\theta, \sigma^2, S_n)p(S_n|\theta, u_0)\pi(u_0|\theta)\pi(\theta)\pi(\sigma^2)
$$

where $f(y|\theta, \sigma^2, S_n)$ is the distribution of the data given the regime indicators and the parameters, $p(S_n|\theta, u_0)$ is the density of the regime-indicators given the parameters and the initial latent factor, $\pi(u_0|\theta)$ is the density of the latent initial factor given the parameters, and $\pi(\theta)\pi(\sigma^2)$ is the prior density of $(\theta, \sigma^2)$.

The idea behind the MCMC approach is to sample this posterior distribution iteratively, such that the sampled draws form a Markov chain with invariant distribution given by the
target density. Practically, the sampled draws after a suitably specified burn-in are taken as samples from the posterior density. We construct our MCMC simulation procedure by sampling various blocks of parameters and latent variables in turn within each MCMC iteration. The distributions of these various blocks of parameters are each proportional to the joint posterior \( \pi(\theta, \sigma^2, u_0, S_n|y) \). In particular, after initializing the various unknowns, we go through 4 iterative steps in each MCMC cycle. Briefly, in Step 2 we sample \( \theta \) from the posterior distribution that is proportional to

\[
 f(y|\theta, \sigma^2, S_n)\pi(\theta)
\]

where \( f(y|\theta, \sigma^2, S_n) \) is obtained from the standard Kalman filtering recursions given the regime indicators \( S_n \). Note that by conditioning on \( S_n \) we avoid the calculation of the likelihood function \( f(y|\theta, \sigma^2, u_0) \) whose computation is more involved. We discuss the computation of
the likelihood function in the next section in connection with the calculation of the marginal likelihood. The sampling of $\theta$ from the latter density is done by the TaRB-MCMC method of Chib and Ramamurthy (2009). In Step 3 we sample $u_0$ from the posterior distribution that is proportional to

$$p(S_n|\theta, u_0)\pi(u_0|\theta)$$

In Step 4, we sample $S_n$ conditioned on $(\theta, u_0, \sigma^2)$ in one block by the algorithm of Chib (1996). We finish one cycle of the algorithm by sampling $\sigma^2$ conditioned on $(\theta, S_n)$ from the posterior distribution that is proportional to

$$f(y|\theta, \sigma^2, S_n)\pi(\sigma^2)$$

Our algorithm can be summarized as follows.

**Algorithm: MCMC sampling**

**Step 1** Initialize $(\theta, u_0, S_n, \sigma^2)$ and fix $n_0$ (the burn-in) and $n_1$ (the MCMC sample size)

**Step 2** Sample $\theta$ conditioned on $(y, u_0, S_n, \sigma^2)$

**Step 3** Sample $u_0$ conditioned on $(y, \theta, S_n)$

**Step 4** Sample $S_n$ conditioned on $(y, \theta, u_0, \sigma^2)$

**Step 5** Sample $\sigma^2$ conditioned on $(y, \theta, S_n)$

**Step 6** Repeat Steps 2-6, discard the draws from the first $n_0$ iterations and save the subsequent $n_1$ draws.

Full details of each of these steps are given in appendix C.

### 3.5 Marginal Likelihood Computation

One of our goals is to evaluate the extent to which the regime-change model is an improvement over the model without regime-changes. We are also interested in determining how many regimes best describe the sample data. Specifically, we are interested in the comparison of 5 models which in the introduction were named as $C0$, $C1$, $C2$, $C3$ and $C4$. The most general
model is C4 that has 4 possible change points, 1 latent factor and 2 macro factors. We do the comparison in terms of marginal likelihoods and their ratios which are called Bayes factors.

The marginal likelihood of any given model is obtained as

\[ m(y) = \int f(y|\theta, \sigma^{*2}, S_n)p(S_n|\theta, u_0)\pi(u_0|\theta)\pi(\theta)\pi(\sigma^{*2})d(\theta, \sigma^{*2}, S_n, u_0) \] (3.10)

This integration is obviously infeasible by direct means. It is possible, however, by the method of Chib (1995) which starts with the recognition that the marginal likelihood can be expressed in equivalent form as

\[ m(y) = f(y|\theta^*, \sigma^{*2}, u_0^*)\pi(u_0^*|\theta^*)\pi(\theta^*)\pi(\sigma^{*2})\pi(\theta^*, \sigma^{*2}, u_0^*) \] (3.11)

where \((\theta^*, \sigma^{*2}, u_0^*)\) is some specified (say high-density) point of \((\theta, \sigma^{*2}, u_0)\). Provided we have an estimate of posterior ordinate \(\pi(\theta^*, \sigma^{*2}, u_0^*|y)\) the marginal likelihood can be computed on the log scale as

\[ \ln \hat{m}(y) = \ln f(y|\theta^*, \sigma^{*2}, u_0^*) + \ln \{\pi(u_0^*|\theta^*)\pi(\theta^*)\pi(\sigma^{*2})\} - \ln \hat{\pi}(\theta^*, \sigma^{*2}, u_0^*|y) \] (3.12)

Notice that the first term in this expression is the likelihood. It has to be evaluated only at a single point which is highly convenient. The calculation of the second term is straightforward. Finally, the third term is obtained from a marginal-conditional decomposition following Chib (1995). The specific implementation in this context requires the technique of Chib and Jeliazkov (2001) as modified by Chib and Ramamurthy (2009) for the case of randomized blocks. We suppress the details.

We do show how the first term in the above expression, the likelihood ordinate would be calculated. To do this, we first begin with

\[ \ln L(y|\psi) = \sum_{t=1}^{n} \ln f(y_t|I_{t-1}, \psi) \] (3.13)

where \(\psi\) denotes the collection of the model parameters and

\[ f(y_t|I_{t-1}, \psi) = \sum_{i,j} f(y_t|I_{t-1}, \psi, s_{t-1} = i, s_t = j) Pr[s_{t-1} = i, s_t = j|I_{t-1}, \psi] \] (3.14)

is the one-step ahead predictive density of \(y_t\), and \(I_{t-1}\) consists of the history of the outcomes \(\tilde{R}_{t-1}\) and \(m_{t-1}\) up to time \((t-1)\). We now show how \(f(\psi|I_{t-1}, \psi, s_{t-1} = i, s_t = j)\) and \(Pr[s_{t-1} = i, s_t = j|I_{t-1}, \psi]\) can each be computed recursively.
From the measurement equation in (3.5) it is easy to see that \( y_t \) is Gaussian, conditioned on \((I_{t-1}, \psi, s_{t-1} = i, s_t = j)\). If we let

\[
E[f_t | I_{t-1}, \psi, s_{t-1} = i, s_t = j] = \mu_j + G_j (f_{t-1} - \mu_i)
\]

\[\equiv f_{ij}^{s_{t-1}}\]

then it follows that the needed moments of the latter Gaussian density are given by

\[
E(y_t | I_{t-1}, \psi, s_{t-1} = i, s_t = j) = a_j + B_j (f_{ij}^{s_{t-1}} - \mu_j)
\]

(3.15)

and

\[
Var(y_t | I_{t-1}, \psi, s_{t-1} = i, s_t = j) = B_j \Omega_j B_j' + \left( \begin{array}{cc}
\Sigma_j & 0 \\
0 & 0
\end{array} \right)
\]

(3.16)

Next, from the law of total probability we have that

\[
Pr[s_{t-1} = i, s_t = j | I_{t-1}, \psi] = p_{ij} Pr[s_{t-1} = i | I_{t-1}, \psi]
\]

(3.17)

where \(Pr[s_{t-1} = i | I_{t-1}, \psi]\) is obtained recursively starting with \(Pr[s_1 = 1 | I_0, \psi] = 1\) by the following steps. Once \(y_t\) is observed at the end of time \(t\), the probability of the regime \(Pr[s_t = j | I_{t-1}, \psi]\) from the previous step is updated to \(Pr[s_t = j | I_t, \psi]\) as

\[
Pr[s_t = j | I_t, \psi] = \sum_{i=1}^{q+1} Pr[s_{t-1} = i, s_t = j | I_t, \psi]
\]

(3.18)

where

\[
Pr[s_{t-1} = i, s_t = j | I_t, \psi] = \frac{f[y_t | I_{t-1}, s_{t-1} = i, s_t = j, \psi] Pr[s_{t-1} = i, s_t = j | I_{t-1}, \psi]}{f[y_t | I_{t-1}, \psi]}
\]

(3.19)

This completes the calculation of the likelihood function.

4 Results

We apply our modeling approach to analyze US data on quarterly yields of sixteen US T-bills between 1972:I and 2007:IV. These data are taken from Gurkaynak, Sack, and Wright (2007). We consider zero-coupon bonds of maturities 1, 2, 3, 4, 5, 6, 7, 8, 10, 12, 16, 20, 24, 28, 36, and 40 quarters. We let the basis yield be the 8 quarter (or 2 year) bond since it is the bond with the smallest pricing variance. Our macroeconomic factors are the quarterly GDP inflation
deflator and the real GDP growth rate in annualized percents. These data are from the Federal reserve bank of St. Louis.

Before proceeding we would like to explain our reasons for modeling 16 yields since these many yields have not been used in previous work. One reason is that our Bayesian estimation approach is capable of handling a large set of yields, more so than is possible by maximum-likelihood methods or less-tuned MCMC implementations than ours. The other reason is that in comparison with models with fewer yields, the model with 16 yields has the best out-of-sample predictive accuracy. To show this we fit the model up to 2006 and predict the yields and macro factors for each of the 4 quarters of 2007. We measure the predictive accuracy in terms of the posterior predictive criterion of Gelfand and Ghosh (1998) (PPC, henceforth). The technical details about simulating the Bayesian predictive density are given in section 4.6. For any given model $M_j$, the PPC criterion is defined as

$$PPC_j = D_j + W_j$$

where

$$D_j = \frac{1}{\lambda + 2} \sum_{i=1}^{\lambda+2} \sum_{t=1}^{T} \text{Var}(\tilde{y}_{i,t} | y, M_j)$$

and

$$W_j = \frac{1}{\lambda + 2} \sum_{i=1}^{\lambda+2} \sum_{t=1}^{T} [y_{i,t} - E(\tilde{y}_{i,t} | y, M_j)]^2$$

where $\lambda$ is the number of the maturities, $\{\tilde{y}_t\}_{t=1,2,...,T}$ are the predictions of the actual yields and macro factors $\{y_t\}_{t=1,2,...,T}$ under model $M_j$, and $y_{i,t}$ and $\tilde{y}_{i,t}$ are the $i$th component of $y_t$ and $\tilde{y}_t$, respectively. The first term has large values for models that are very simple or complex. The second term is a sum of squared residuals and measures goodness-of-fit in terms of how well the forecasts under model $M_j$ fit the actual observations. Table 2 clearly shows that the model with 16 maturities outperforms the models with fewer maturities. The reason for this superior performance is simple. The addition of a new yield introduces only one parameter (namely its pricing error variance) but because of the many cross-equation restrictions on the parameters, the additional observation helps to improve inferences about the common model parameters, which translates into improved predictive inferences.
The number No change point model of maturities($\lambda$) $D_j$ $W_j$ $PPC_j$

<table>
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<tr>
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<td>16</td>
<td>3.710</td>
<td>3.520</td>
<td>7.230</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Posterior predictive criterion PPC is computed by 4.1 to 4.3. We use the data from the most recent break time point, 1995:II to 2006:IV due to the regime shift, and out of sample period is 2007:I-2007:IV. Four yields are of 2, 8, 20 and 40 quarters maturity bonds (used in Dai et al. (2007)). Eight yields are of 1, 2, 3, 4, 8, 12, 16 and 20 quarters maturity bonds (used in Bansal and Zhou (2002)). Twelve yields are of 1, 2, 3, 4, 5, 6, 8, 12, 20, 28, 32 and 40 quarters maturity bonds. Sixteen yields are of 1, 2, 3, 4, 5, 6, 7, 8, 10, 12, 16, 20, 24, 28, 32 and 40 quarters maturity bonds.

4.1 Sampler Diagnostics

We base our results on 50,000 iterations of the MCMC algorithm beyond a burn-in of 5,000 iterations. We measure the efficiency of the MCMC sampling in terms of the metrics that are common in the Bayesian literature, in particular, in terms of the acceptance rates in the Metropolis-Hastings steps and the inefficiency factors (Chib (2001)) which, for any sampled sequence of draws, is defined as

$$1 + 2 \sum_{k=1}^{M} \rho(k),$$

(4.4)

where $\rho(k)$ is the $k$-order autocorrelation computed from the sampled variates and $M$ is a large number which we choose conservatively to be 500. For our biggest model, the average acceptance rate and the average inefficiency factor in the M-H step are 54.4% and 201.0, respectively. These values indicate that our sampler mixes well. It is also important to note that our sampler converges quickly to the same region of the parameter space regardless of the starting values.

4.2 The Number and Timing of Change Points

Table 3 contains the marginal likelihood estimates for our 5 contending models. As can been seen, the $C3$ is the model that gets the most support from the data. We now provide more detailed results for this model.

Our first set of findings relate to the timing of the change-points. Information about the change-points is gleaned from the sampled sequence of the states. Further details about
Table 3: Log likelihood (lnL), log marginal likelihood (lnML), posterior probability of each model (Pr[C\|y]) under the assumption that the prior probability of each model is 1/5, and change point estimates.

<table>
<thead>
<tr>
<th>Model</th>
<th>lnL</th>
<th>lnML</th>
<th>Pr[C|y]</th>
<th>change point</th>
</tr>
</thead>
<tbody>
<tr>
<td>C0</td>
<td>-1486.9</td>
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</tr>
<tr>
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<td>-1114.9</td>
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<td>0.00</td>
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</tr>
<tr>
<td>C2</td>
<td>-894.5</td>
<td>-1425.6</td>
<td>0.00</td>
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</tr>
<tr>
<td>C4</td>
<td>-273.4</td>
<td>-1136.2</td>
<td>0.00</td>
<td>1980:II, 1985:IV, 1995:II, 2002:III</td>
</tr>
</tbody>
</table>

how this is done can be obtained from Chib (1998). Of particular interest are the posterior probabilities of each of the states by time. These probabilities are given in Figure 4. The figure reveals that the first 32 quarters (the first 8 years) belong to the first regime, the next 23 quarters (about 6 years) to the second, the next 38 quarters (about 9.5 years) to the third, and the remaining quarters to the fourth regime. It is striking finding that this analysis picks up a breakpoint in 1995 since this has not been detected in previous regime-change models.

We would like to emphasize that our estimates of the change points from the models without macro factors are exactly the same as those from the change point models with macro factors. We do not report those results in the interest of space. In addition, the results are not sensitive to our choice of 16 maturities, as we have confirmed.

### 4.3 Parameter Estimates

Table 4 summarizes the posterior distribution of the parameters. One point to note is that the posterior densities are generally different from the prior given in table 1, which implies that the data is informative about these parameters. We focus on various aspects of this posterior distribution in the subsequent subsections.

#### 4.3.1 Factor Process

Figure 5 plots the average dynamics of the latent factors along with the short rate. This figure demonstrates that the latent factor movements are very close to those of the short rate.

The estimates of the matrix $G$ for each regime show that the mean-reversion coefficient matrix is almost diagonal. The latent factor and inflation rate also display very high and considerably different persistence across regimes. In particular, the relative magnitudes of
the diagonal elements indicates that the latent factor and the inflation factor are less mean-reverting in regime 2 and 4, respectively. For a more formal measure of this persistence, we calculate the eigenvalues of the coefficient matrices in each regime. These are given by

$$eig(G_1) = \begin{bmatrix} 0.874 \\ 0.636 \\ 0.155 \end{bmatrix}, \quad eig(G_2) = \begin{bmatrix} 0.983 \\ 0.805 \\ 0.370 \end{bmatrix}$$
Table 4: Estimates of C3 model parameters

This table presents the posterior mean and standard deviation based on 50,000 posterior draws beyond 5,000 burn-in. The 95% credibility interval of parameters in bold face does not contain 0. Standard deviations are in parenthesis. The yields are of 1, 2, 3, 4, 5, 6, 7, 8, 10, 12, 16, 20, 24, 28, 36 and 40 quarters maturity bonds. Values without standard deviations are fixed by the identification restrictions.

\[
eig(G_3) = \begin{bmatrix} 0.931 \\ 0.313 \\ 0.333 \end{bmatrix}, \quad eig(G_4) = \begin{bmatrix} 0.915 \\ 0.816 \\ 0.174 \end{bmatrix}
\]

It can be seen that the second regime has the largest absolute eigenvalue close to 1. Since the factor loadings for the latent factor \((\delta_{21,s_t})\) are significant whereas those for inflation \((\delta_{22,s_t})\) are not, the latent factor is responsible for most of the persistence of the yields.

Furthermore, the diagonal elements of \(L_3\) and \(L_4\) are even smaller than their counterparts in \(L_1\) and \(L_2\). This suggests that a reduction in factor volatility starting from the middle of the
1980s, which coincides with the period that is called the great moderation (Kim, Nelson, and Piger (2004)).

4.3.2 Factor Loadings

The factor loadings in the short rate equation, $\delta_{2,s_t}$, are all positive, which is consistent with the conventional wisdom that central bankers tend to raise the interest rate in response to a positive shock to the macro factors. It can also be seen that $\delta_{2,s_t}$ along with $G_{s_t}$ and $L_{s_t}$ are different across regimes, which makes the factor loadings regime-dependent across the term structure as revealed in figure 6. This finding lends support to our assumption of regime-dependent factor loadings.

4.3.3 Term Premium

Figure 7 plots the posterior distribution of the term premium of the two year maturity bond over time. It is interesting to observe how the term premium varies across regimes. In particular, the term premium is the lowest in the most recent regime (although the .025 quantile of the term premium distribution in the first regime is lower than the .025 quantile of term premium distribution in the most current regime). This can be attributed to the lower value of factor volatilities in this regime.
4.3.4 Pricing Error Volatility

In Figure 8 we plot the term structure of the pricing error standard deviations. As in no-change point model of Chib and Ergashev (2009), these are hump-shaped in each regime. One can also see that these standard deviations have changed over time, primarily for the short-bonds. These changes in the volatility also help to determine the timing of the change-points.

4.4 Forecasting and Predictive Densities

A principle objective of this paper is to compare the forecasting abilities of the affine term structure models with and without regime changes. In the Bayesian paradigm, it is relatively straightforward to calculate the predictive density during the course of the MCMC iterations. This is because the predictive density of the future observations, conditional on the data, is obtained by simply integrating out the parameters with respect to the posterior distribution. Denoting $y_f$ as the future observations, the predictive density under model $Cq$ can be calculated as

$$f(y_f|Cq, y) = \int f(y_f|Cq, y, \psi)\pi(\psi|Cq, y)d\psi$$

(4.5)

where the predictive draws are sampled under the terminal regime $q + 1$.

Specifically, note that each MCMC iteration (beyond the burn-in period) provides us with the factors $\{f_t\}_{t=1,\ldots,n}$ and the parameters of the model from the posterior distribution. There-
Figure 7: Term premium. The figure plots the 2.5%, 50% and 97.5% quantile of the posterior term premium which correspond to “Low,” “Median” and “High” based on 50,000 draws beyond a burn-in of 5,000 iterations.

Figure 8: Term Structure of the Pricing Error Volatility. The figures display the 2.5%, 50% and 97.5% quantile of the posterior standard deviation of the pricing errors which correspond to “Low,” “Median” and “High.”

Therefore, conditioned on $f_n$ and the underlying parameters in regime $q + 1$, we draw the forecasts of factors $f_{n+1}$ based on the transition equation. Then given $f_{n+1}$, the yields in the forecast period $R_{n+1}$ are drawn using the relationship described in the measurement equation. By repeating these two steps recursively, we can draw $f_{n+i}$ and $R_{n+i}$ (equivalently, $m_{n+i}$ and $\tilde{R}_{n+i}$) for $i = 1, 2, \ldots, T$. The resulting collection of the simulated macro factors and yields is taken as a sample from the Bayesian predictive density.

We plot the out of sample forecasts in Figure 9. The top panel gives the forecast intervals.
Figure 9: The MCMC forecasts of the yield curve. The figures present four quarters ahead forecasts of the yields on the T-bills. The top panel is based on no change point model and the bottom panel on the three change point model. In each case, the 2.5%, 50% and 97.5% quantile curves, labeled “Low”, “Median” and “High” respectively, are based on 50,000 forecasted values for the period of 2007:I-2007:IV. The observed curves are labeled “Real.”

from the $C0$ model and the bottom panel has the forecast intervals from the $C3$ model. Note that in both cases the actual yield curve in each of the four quarters of 2007 is bracketed by the corresponding 95% credibility interval though the intervals from the $C3$ model are tighter.

For a more formal forecasting performance comparison, we tabulate the PPC for each case in Table 5. We also include in the last column of this table an interesting set of results that make use of the regimes isolated by our $C3$ model. In particular, we fit the no-change point model to the data in the last regime but ending just before our different forecast periods
Table 5: Posterior predictive criterion  PPC is computed by (4.1) to (4.3).

(2005:I-2005:IV, 2006:I-2006:IV and 2007:I-2007:IV). As one would expect, the forecasts from the no-change point model estimated on the sample period of the last regime are similar to those from the $C3$ model. Thus, given the regimes we have isolated, a poor-man’s approach to forecasting the term-structure would be to fit the no-change arbitrage-free yield model to the last regime. Of course, the predictions from the $C3$ model produce a smaller value of the PPC than those from the no-change point model that is fit to the whole sample. This, combined with the in-sample fit of the models as measured by the marginal likelihoods, suggests that the change point model outperforms the no-change-point version. These findings not only reaffirm the finding of structural changes, but also suggest that it is essential to incorporate regime changes when forecasting the term structure of interest rates.

5 Concluding Remarks

In this paper we have developed a new model of the term structure of zero-coupon bonds with regime changes. Our work complements the recent work in this area since it is organized around a different model of regime changes than the Markov switching model that has been
used to date. Our work also complements the recent work on affine models with macro factors which has been done in settings without regime changes. The models we fit involve more bonds than in previous work which allows us to capture more of the term structure. This enlargement of the model is made possible by our tuned econometric methods which rely on some recent developments in Bayesian econometrics.

Our empirical analysis suggests that the term structure has gone through three change points, and that the term structure and the risk premium is materially different across regimes. Our analysis also shows that there are gains in predictive accuracy by incorporating regime changes when forecasting the term structure of interest rates.

A Bond Prices under Regime Changes

By the assumption of the affine model, we have

\[ P_t(s_t, \tau) = \exp \left( -a_{s_t}(\tau) - b_{s_t}(\tau)' (f_t - \mu_{s_t}) \right) \]

and

\[ P_{t+1}(s_{t+1}, \tau - 1) = \exp \left( -a_{s_{t+1}}(\tau - 1) - b_{s_{t+1}}(\tau - 1)' (f_{t+1} - \mu_{s_{t+1}}) \right) \].

Let \( h_{\tau,t+1} \) denote

\[
\frac{P_{t+1}(s_{t+1}, \tau - 1)}{P_t(s_t, \tau)} = \exp \left[ -a_{s_{t+1}}(\tau - 1) - b_{s_{t+1}}(\tau - 1)' (f_{t+1} - \mu_{s_{t+1}}) + a_{s_t}(\tau) + b_{s_t}(\tau)' (f_t - \mu_{s_t}) \right]
\]

It immediately follows from the bond pricing formula that

\[
1 = E \left[ \kappa_{t,t+1} \frac{P_{t+1}(s_{t+1}, \tau - 1)}{P_t(s_t, \tau)} | f_t, s_t \right] = E \left[ \kappa_{t,t+1} h_{\tau,t+1} | f_t, s_t \right].
\]

Then by substitution

\[
\kappa_{t,t+1} h_{\tau,t+1} = \exp \left[ -\tau_{t,s_t} - \frac{1}{2} \gamma'_{t,s_t} \gamma_{t,s_t} - \gamma'_{t,s_t} L_{s_{t+1}}^{-1} \eta_{t+1} - a_{s_{t+1}}(\tau - 1) - b_{s_{t+1}}(\tau - 1)' (f_{t+1} - \mu_{s_{t+1}}) + a_{s_t}(\tau) + b_{s_t}(\tau)' (f_t - \mu_{s_t}) \right]
\]

\[
= \exp \left[ -R_{t,s_t} - \frac{1}{2} \gamma'_{t,s_t} \gamma_{t,s_t} - \left( \gamma'_{t,s_t} L_{s_{t+1}}^{-1} + b_{s_{t+1}}(\tau - 1)' \right) \eta_{t+1} + \zeta_{\tau,s_t,s_{t+1}} \right]
\]

\[
= \exp \left[ -R_{t,s_t} - \frac{1}{2} \gamma'_{t,s_t} \gamma_{t,s_t} - \left( \gamma_{t,s_t} + b_{s_{t+1}}(\tau - 1)' L_{s_{t+1}} \right) \omega_{t+1} + \zeta_{\tau,s_t,s_{t+1}} \right]
\]

\[
= \exp \left[ -R_{t,s_t} - \frac{1}{2} \gamma'_{t,s_t} \gamma_{t,s_t} + \frac{1}{2} \Gamma_{t,\tau} \Gamma_{t,\tau} + \zeta_{\tau,s_t,s_{t+1}} \right] \exp \left[ -\frac{1}{2} \Gamma_{t,\tau,\tau} \right]
\]
Thus we have

\[ \zeta_{\tau,s_{t},s_{t+1}} = a_{s_{t}}(\tau) + b_{s_{t}}(\tau)(f_{t} - \mu_{s_{t}}) - a_{s_{t+1}}(\tau - 1) - b_{s_{t+1}}(\tau - 1)'G_{s_{t+1}}(f_{t} - \mu_{s_{t}}) \]
\[ \Gamma_{t,\tau} = \gamma_{t,s_{t}} + b_{s_{t+1}}(\tau - 1)'L_{s_{t+1}} \]

and \( \omega_{t+1} = L_{s_{t+1}}^{-1} \eta_{t+1} \sim N(0, I_{k+m}) \). Given \( f_{t}, s_{t+1} \) and \( s_{t} \), the only random variable in \( \kappa_{t,t+1}h_{t,t+1} \) is \( \omega_{t+1} \). Then since

\[ E\left( \exp[-\frac{1}{2} \Gamma_{t,\tau} \Gamma_{t,\tau}' - \Gamma_{t,\tau} \omega_{t+1}] \right) = 1 \]

we have that

\[ E[\kappa_{t,t+1}h_{t,t+1}|f_{t}, s_{t+1}, s_{t}] = \exp[-R_{t,s_{t}} - \frac{1}{2} \gamma'_{t,s_{t}} \gamma_{t,s_{t}} + \frac{1}{2} \Gamma_{t,\tau} \Gamma_{t,\tau}' + \zeta_{\tau,s_{t},s_{t+1}}] \]

Using log-approximation \( \exp(y) \approx y + 1 \) for a sufficiently small \( y \) leads to

\[ E[\kappa_{t,t+1}h_{t,t+1}|f_{t}, s_{t+1}, s_{t}] \]
\[ = \exp[-R_{t,s_{t}} - \frac{1}{2} \gamma'_{t,s_{t}} \gamma_{t,s_{t}} + \frac{1}{2} \left( \gamma'_{t,s_{t}} + b_{s_{t+1}}(\tau - 1)'L_{s_{t+1}} \right) \left( \gamma_{t,s_{t}} + b_{s_{t+1}}(\tau - 1)'L_{s_{t+1}} \right) + \zeta_{\tau,s_{t},s_{t+1}}] \]
\[ \approx -R_{t,s_{t}} + \gamma'_{t,s_{t}} L'_{s_{t+1}} b_{s_{t+1}}(\tau - 1) + \frac{1}{2} \left( b_{s_{t+1}}(\tau - 1)'L_{s_{t+1}} L'_{s_{t+1}} b_{s_{t+1}}(\tau - 1) \right) + \zeta_{\tau,s_{t},s_{t+1}} + 1 \]
\[ = - \left( \delta_{1,s_{t}} + \delta'_{2,s_{t}}(f_{t} - \mu_{s_{t}}) \right) + \left( \tilde{\gamma}_{s_{t}} + \Phi_{s_{t}}(f_{t} - \mu_{s_{t}}) \right)'L'_{s_{t+1}} b_{s_{t+1}}(\tau - 1) \]
\[ + \frac{1}{2} \left( b_{s_{t+1}}(\tau - 1)'L_{s_{t+1}} L'_{s_{t+1}} b_{s_{t+1}}(\tau - 1) \right) + \zeta_{\tau,s_{t},s_{t+1}} + 1 \]

Given the information at time \( t \), i.e. \( f_{t} \) and \( s_{t} = j \), integrating out \( s_{t+1} \) yields

\[ E[\kappa_{t,t+1}h_{t,t+1}|f_{t}, s_{t} = j] = \sum_{s_{t+1} = j,k} p_{j,s_{t+1}} \{ E[\kappa_{t,t+1}h_{t,t+1}|f_{t}, s_{t+1}, s_{t} = j] \} \]
\[ = 1 \text{ where } k = j + 1. \]

Thus we have

\[ 0 = \sum_{s_{t+1} = j,k} p_{j,s_{t+1}} \{ E[\kappa_{t,t+1}h_{t,t+1}|f_{t}, s_{t+1}, s_{t} = j] - 1 \} \text{ since } \sum_{s_{t+1} = j,k} p_{j,s_{t+1}} = 1 \]
\[ = p_{jj} (E[\kappa_{t,t+1}h_{t,t+1}|f_{t}, s_{t+1} = j, s_{t} = j] - 1) + p_{jk} (E[\kappa_{t,t+1}h_{t,t+1}|f_{t}, s_{t+1} = k, s_{t} = j] - 1) \]
\[ \approx -p_{jj} (\delta_{1,j} + \delta'_{2,j}(f_{t} - \mu_{s_{t}})) + p_{jj} (\tilde{\gamma}_{j} + \Phi_{j}(f_{t} - \mu_{s_{t}}))'L'_{j} b_{j}(\tau - 1) \]
\[ + \frac{1}{2} p_{jj} (b_{j}(\tau - 1)'L_{j} L'_{j} b_{j}(\tau - 1)) + p_{jj} \zeta_{\tau,j,j} \]
\[ - p_{jk} (\delta_{1,j} + \delta'_{2,j}(f_{t} - \mu_{s_{t}})) + p_{jk} (\tilde{\gamma}_{j} + \Phi_{j}(f_{t} - \mu_{s_{t}}))'L'_{k} b_{k}(\tau - 1) \]
\[ + \frac{1}{2} p_{jk} (b_{k}(\tau - 1)'L_{k} L'_{k} b_{k}(\tau - 1)) + p_{jk} \zeta_{\tau,j,k} \]
Matching the coefficients on \( f_i \) and constant terms equal to zero we obtain the recursive equation for \( a_s(t) \) and \( b_s(t) \) given the initial condition of \( a_s(0) = 0 \) and \( b_s(0) = 0_{3 \times 1} \) implied by no arbitrage condition. Finally imposing the restriction on the transition probability establishes the proof.

### B Prior distribution

<table>
<thead>
<tr>
<th></th>
<th>No change point</th>
<th>One change point</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Regime 1</td>
<td>Regime 2</td>
</tr>
<tr>
<td>( G )</td>
<td>diag(0.95, 0.8, 0.4)</td>
<td>diag(0.95, 0.8, 0.4)</td>
</tr>
<tr>
<td></td>
<td>(0.33)</td>
<td>(0.33)</td>
</tr>
<tr>
<td>( \mu \times 400 )</td>
<td>0.00 5.00 3.00</td>
<td>0.00 6.50 3.00</td>
</tr>
<tr>
<td>( \delta_1 \times 400 )</td>
<td>6.00 (0.60)</td>
<td>6.00 (0.60)</td>
</tr>
<tr>
<td>( \delta_2 )</td>
<td>0.80 (0.40)</td>
<td>0.80 (0.40)</td>
</tr>
<tr>
<td></td>
<td>(0.40)</td>
<td>(0.40)</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>0.50 (0.33)</td>
<td>0.50 (0.33)</td>
</tr>
<tr>
<td></td>
<td>(0.33)</td>
<td>(0.33)</td>
</tr>
<tr>
<td>( \Phi )</td>
<td>1.00 (1.00)</td>
<td>1.00 (1.00)</td>
</tr>
<tr>
<td></td>
<td>(1.00)</td>
<td>(1.00)</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>(0, 0, 0, 0, 1)'</td>
<td>(0, 0, 0, 0, 1)'</td>
</tr>
<tr>
<td></td>
<td>(2.00)</td>
<td>(2.00)</td>
</tr>
</tbody>
</table>

**Table 6: Prior distribution of the parameters in the 0 and 1 change point model** This table presents the prior mean and standard deviation of the parameters in \( \theta \). The prior mean are indicated in bold face and the standard deviations are in parenthesis.

### C MCMC Sampling

This section provides the details of the MCMC algorithm (steps 2-5) outlined in section 3.4.

**Step 2 Sampling \( \theta \)**

We sample \( \theta \) conditioned on \((u_0, S_n, \sigma^2)\) by the tailored randomized block M-H (TaRB-MH) algorithm introduced in Chib and Ramamurthy (2009). The schematics of the TaRB-MH algorithm are as follows. The parameters in \( \theta \) are first randomly partitioned into various sub-blocks at the beginning of an iteration. Each of these sub-blocks is then sampled in sequence by drawing a value from a tailored proposal density constructed
<table>
<thead>
<tr>
<th>Regime 1</th>
<th>Regime 2</th>
<th>Regime 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G$</td>
<td>diag(0.95, 0.8, 0.4) (0.33)</td>
<td>diag(0.95, 0.8, 0.4) (0.33)</td>
</tr>
<tr>
<td>$\mu$</td>
<td>0.00 (2.00)</td>
<td>6.50 (1.00)</td>
</tr>
<tr>
<td>$\times 400$</td>
<td>(2.00)</td>
<td>(1.00)</td>
</tr>
<tr>
<td>$\delta_1$</td>
<td>6.00 (5.00)</td>
<td>6.00 (5.00)</td>
</tr>
<tr>
<td>$\times 400$</td>
<td>(5.00)</td>
<td>(5.00)</td>
</tr>
<tr>
<td>$\delta_2$</td>
<td>0.80 (0.40)</td>
<td>0.40 (0.40)</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>-0.50 (0.33)</td>
<td>-0.50 (0.33)</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>1.00 (1.00)</td>
<td>1.00 (1.00)</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>(0, 0, 0, 0, 1)' (2.00)</td>
<td>(0, 0, 0, 0, 1)' (2.00)</td>
</tr>
</tbody>
</table>

Table 7: Prior distribution of the parameters in the 2 change point model. This table presents the prior mean and standard deviation of the parameters in $\theta$. The prior means are indicated in bold face and standard deviations are in parenthesis.

for that particular block; this proposal is then accepted or rejected by the usual M-H probability of move (Chib and Greenberg (1995)). For instance, suppose that in the $g$th iteration, we have $h_g$ sub-blocks of $\theta$

$$\theta_1, \theta_2, \ldots, \theta_{h_g}$$

Then the proposal density $q(\theta_i|\theta_{-i}, y)$ for the $i$th block, conditioned on the most current value of the remaining blocks $\theta_{-i}$, is constructed by a quadratic approximation at the mode of the current target density $\pi(\theta_i|\theta_{-i}, y)$. In our case, we let this proposal density take the form of a student $t$ distribution with 15 degrees of freedom

$$q(\theta_i|\theta_{-i}, y) = St(\theta_i|\hat{\theta}_i, V_{\hat{\theta}_i}, 15)$$

where

$$\hat{\theta}_i = \arg \max_{\theta_i} \ln \{ f(y|\theta_i, \theta_{-i}, S_n) \pi(\theta_i) \}$$

and

$$V_{\hat{\theta}_i} = \left( -\frac{\partial^2 \ln \{ f(y|\theta_i, \theta_{-i}, S_n) \pi(\theta_i) \}}{\partial \theta_i \partial \theta_i'} \right)_{\theta_i=\hat{\theta}_i}^{-1}. $$

Because the likelihood function tends to be ill-behaved in these problems, we calculate $\hat{\theta}_i$ using a suitably designed version of the simulated annealing algorithm. In our experience,
<table>
<thead>
<tr>
<th>Regime 1</th>
<th>Regime 2</th>
<th>Regime 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G$</td>
<td>diag(0.95, 0.8, 0.4)</td>
<td>diag(0.95, 0.8, 0.4)</td>
</tr>
<tr>
<td>$\mu$</td>
<td>0.00</td>
<td>6.50</td>
</tr>
<tr>
<td>$\times 400$</td>
<td>(2.00) (1.00)</td>
<td>(2.00) (1.00)</td>
</tr>
<tr>
<td>$\delta_1$</td>
<td>6.00</td>
<td>6.00</td>
</tr>
<tr>
<td>$\times 400$</td>
<td>(5.00)</td>
<td>(5.00)</td>
</tr>
<tr>
<td>$\delta_2$</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>$\times 400$</td>
<td>(0.40)</td>
<td>(0.40)</td>
</tr>
<tr>
<td>$\gamma$</td>
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<td>-0.50</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>(0, 0, 0, 1)’</td>
<td>(0, 0, 0, 1)’</td>
</tr>
<tr>
<td>$\times 400$</td>
<td>(2.00)</td>
<td>(2.00)</td>
</tr>
</tbody>
</table>

<table>
<thead>
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<th>Regime 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G$</td>
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</tr>
<tr>
<td>$\mu$</td>
<td>0.00</td>
</tr>
<tr>
<td>$\times 400$</td>
<td>(2.00) (1.00)</td>
</tr>
<tr>
<td>$\delta_1$</td>
<td>3.00</td>
</tr>
<tr>
<td>$\times 400$</td>
<td>(5.00)</td>
</tr>
<tr>
<td>$\delta_2$</td>
<td>0.80</td>
</tr>
<tr>
<td>$\times 400$</td>
<td>(0.40)</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>-0.50</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>1.00</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>(0, 0, 0, 1)’</td>
</tr>
<tr>
<td>$\times 400$</td>
<td>(2.00)</td>
</tr>
</tbody>
</table>

Table 8: Prior distribution of the parameters in the 4 change point model. This table presents the prior mean and standard deviation of the parameters in $\theta$. The prior means are indicated in bold face and standard deviations are in parenthesis.

This stochastic optimization method works better than the standard Newton-Raphson class of deterministic optimizers.

We then generate a proposal value $\theta^i_k$ which, upon satisfying all the constraints, is accepted as the next value in the chain with probability

$$\alpha \left( \theta^{(g-1)}_i, \theta^i_k | \theta_{-i}, y \right)$$
Step 3 Sampling the initial factor

Given the prior in section 1, \(u_0\) is updated conditioned on \(\theta\), \(m_0\) and \(f_1 = (u_1' \ m_1')'\), where \(m_0\) is given by data and \(u_1\) is obtained from the equation (3.3). In the following, it is assumed that all the underlying coefficients are those in regime 0. Then \(u_0|f_1, \theta \sim N_1(u_0, U_0)\)

where

\[
U_0 = U_0 (\Sigma_u^{-1} + H^*\Omega_{11,0}^* u_1^*), \quad U_0 = (\Sigma_u^{-1} + H^*\Omega_{11,0}^* H^*)
\]

and on letting

\[
G_0 = \begin{pmatrix} G_{11,0} & G_{12,0} \\
G_{21,0} & G_{22,0} \end{pmatrix}, \quad \Omega_0 = \begin{pmatrix} \Omega_{11,0} & \Omega_{12,0} \\
\Omega_{21,0} & \Omega_{22,0} \end{pmatrix}
\]

\[
H^* = G_{11,0} - \Omega_{12,0}\Omega_{22,0}^{-1} G_{21,0}, \quad \Omega_{11,0}^* = \Omega_{11,0} - \Omega_{12,0}\Omega_{22,0}^{-1} \Omega_{21,0}
\]

\[
u_1^* = u_1 - G_{12,0} (m_0 - \mu_{m,0}) - \Omega_{12,0}\Omega_{22,0}^{-1} (m_1 - \mu_{m,0}) + \Omega_{12,0}\Omega_{22,0}^{-1} G_{22,0} (m_0 - \mu_{m,0})
\]

Step 4 Sampling regimes

In this step one samples the states from \(p[S_n|I_n, \psi]\) where \(I_n\) is the history of the outcomes up to time \(n\). This is done according to the method of Chib (1996) and Chib (1998) by sampling \(S_n\) in a single block from the output of one forward and backward pass through the data.

The forward recursion is initialized at \(t = 1\) by setting \(Pr[s_1 = 1|I_1, \psi] = 1\). Let \(f_{i[t-1]}^{j,k}\) denote \(E[f_i|I_{t-1}, s_{t-1} = j, s_t = k]\). Then one first obtains \(Pr[s_t = k|I_t, \psi]\) for all \(k = 1, 2, ..., q + 1\) and \(t = 1, 2, ..., n\) by calculating

\[
Pr[s_t = k|I_t, \psi] = \sum_{j=k-1}^{k} Pr[s_{t-1} = j, s_t = k|I_t, \psi]
\]
where
\[
\Pr[s_{t-1} = j, s_t = k|I_t, \psi] = \frac{f[y_t|I_{t-1}, s_{t-1} = j, s_t = k, \psi] \Pr[s_{t-1} = j, s_t = k|I_{t-1}, \psi]}{f[y_t|I_{t-1}, \psi]}
\]
and the three terms on the right hand side of this expression are obtained as
\[
f[y_t|I_{t-1}, s_{t-1} = j, s_t = k, \psi] = -\frac{1}{\sqrt{2\pi}} |\Lambda^k|^{-1/2} \times \exp \left[-\frac{1}{2} \sqrt{\eta_{t|t-1}^k} (\Lambda^k)^{-1} \eta_{t|t-1}^k \right]
\]
for
\[
f_{j|t-1}^{jk} = \mu_k + G_k (f_{t-1} - \mu_j)
\]
\[
\eta_{t|t-1}^{jk} = y_t - a_k - b_k (f_{t|t-1}^{jk} - \mu_k)
\]
and \(\Lambda^k = b_k \Omega_k b_k^T + T \Sigma_k T^T\)

\[
\Pr[s_{t-1} = j, s_t = k|I_t, \psi] = \sum_{j=1}^{q+1} \sum_{k=j}^{q+1} f[y_t|I_{t-1}, s_{t-1} = j, s_t = k, \psi] \Pr[s_{t-1} = j, s_t = k|I_{t-1}, \psi]
\]

In the backward pass, one simulates \(S_n\) by the method of composition. One samples \(s_n\) from \(\Pr[s_n = 1|I_n, \psi]\). We remark that in this sampling step, \(s_n\) can take any value in \(\{1, 2, ..., q+1\}\). For instance, if \(s_n\) turns out to be \(q\) and not \((q+1)\), then \(q\) is taken to be the absorbing regime and the parameters of regime \((q+1)\) are drawn from the prior in that iteration. In our data, however, \((q+1)\) is always drawn because the last change-point occurs in the interior of the sample and, therefore, the distribution \(\Pr[s_n = 1|I_n, \psi]\) has almost a unit mass on \((q+1)\). Then for \(t = 1, 2, ..., n-1\) we sequentially calculate
\[
\Pr[s_t = j|I_t, s_{t+1} = k, S^{t+2}, \psi] = \Pr[s_t = j|I_t, s_{t+1} = k, \psi]
\]
\[
= \frac{\Pr[s_{t+1} = k|s_t = j] \Pr[s_t = j|I_t, \psi]}{\sum_{k=j}^{q+1} \Pr[s_{t+1} = k|s_t = j] \Pr[s_t = j|I_t, \psi]}
\]
where \(S^{t+1} = \{s_{t+1}, ..., s_n\}\) denotes the set of simulated states from the earlier steps. A value \(s_t\) is drawn from this distribution and it is either the value \(k\) or \((k-1)\) conditioned on \(s_{t+1} = k\).

**Step 5 Sampling the variances of the pricing errors**

A convenient feature of our modeling approach is that, conditional on the history of the regimes and factors, the joint distribution of the parameters in \(\Sigma^*\) is analytically tractable.
and takes the form of an Inverse Gamma density. Thus, for \( i \in \{1, 2, \ldots, 7, 9, \ldots, 16\} \) and \( j = 1, 2, \ldots, q + 1 \), \( \sigma_{i,j}^2 \) is sampled from

\[
\text{IG} \left\{ \frac{\bar{v} + \sum_{t=1}^{n} I(s_t = j)}{2}, \frac{\bar{d} + \sum_{t=1}^{n} d_{i,j} I(s_t = j)}{2} \left( R_{it} - \bar{a}_{i,j} - \bar{b}_{i,j}^{\prime} (f_{it} - \mu_j) \right)^2 \right\}
\]

where \( I(\cdot) \) is the indicator function.

References


