Jumps in Bond Yields at Known Times*

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Abstract

We construct a no-arbitrage term structure model with jumps in the entire state vector at deterministic times but of random magnitudes. Jump risk premia are allowed for. We show that the model implies a closed-form representation of yields as a time-inhomogenous affine function of the state vector. We apply the model to the term structure of US Treasury rates, estimated at the daily frequency, allowing for jumps on days of employment report announcements. Our model can match the empirical fact that the term structure of interest rate volatility has a hump-shaped pattern on employment report days (but not on other days). The model also produces patterns in bond risk premia that are consistent with the empirical finding that much of the time-variation in excess bond returns accrues at times of important macroeconomic data releases.

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1 Introduction

Macroeconomic news comes out in a lumpy manner via scheduled news announcements, especially the monthly employment report that includes both nonfarm payrolls and the unemployment rate. These announcements are important for all asset prices, but especially for bond yields (Andersen, Bollerslev, Diebold, and Vega, 2007). Nevertheless, term structure models mostly assume that the factors driving the term structure of interest rates are continuous diffusions, and so that news comes out continuously. Some models allow for jumps, but these are typically jumps at random times, following a Poisson arrival process (Das, 2002; Duffie, 2001; Feldhutter, Schneider, and Trolle, 2008; Jiang and Yan, 2009; Johannes, 2004). Researchers using this approach find that many—though not all—of the jumps occur at times of news announcements (Andersen, Bollerslev, and Diebold, 2007). But, if we are thinking of the jumps as reflecting scheduled news announcements, then they are perhaps better viewed as jumps at deterministic times but of random magnitudes.[1] In this perspective, depending on how big the surprise component of a particular announcement is, the jump may be big or small. But every announcement leads to some jump, and its timing is known *ex ante*.

This paper takes a standard affine Gaussian term structure model, but augments it with jumps of random size at deterministic times. The closest related work is Piazzesi (2001, 2005), but unlike in those papers, we allow all elements of the state vector to jump, and allow the pricing kernel to jump as well.[2] So jump risk is priced. We

[1]Throughout, when we refer to jumps of random size/magnitude, the *sign* of the jumps is random too: they can be either positive or negative.

[2]Another difference is that Piazzesi (2005) models jumps in the federal funds target rate as Poisson jumps with jump intensity that is high and state-dependent within windows bracketing scheduled FOMC meeting events and low at other times (to allow for the small probability of unscheduled FOMC move). Meanwhile, Piazzesi (2001) augments that model with jumps in state variables corresponding to nonfarm payroll employment and CPI at deterministic times. On the other hand, we model all jumps as jumps at deterministic times.

show that the model implies a closed-form affine representation for yields, although one in which the loadings vary with the time until the next jump. We fit the model to daily data on the term structure of US Treasury yields, assuming that there are jumps on the days of employment reports.

The state variables are all latent factors, but we think of them as being driven by macroeconomic data. Changes in the state variables that are driven by news about the economy might consequently have different implications for future expected rates and term premia than other shifts in the state variables. Our model allows for this possibility. A conventional model with latent factors that follow a diffusion does not.

Empirically, the term structure of yield volatility has a hump shape on employment report days (low at the short maturities and peaking at about a two-year maturity), which is not present on other days (Fleming and Remolona, 1999).[3] Our term structure model is able to match this. Using the model we can also explore the daily structure of bond risk premia variation. We find that bond risk premia are notably bigger in absolute value on announcement days than on non-announcement days. The announcement-day bond risk premia are also bigger in absolute value than those that we obtain from estimation of a homogeneous (no-jump) model. These results are consistent with Faust and Wright (2008), who find that much of the time-variation in excess bond returns accrues during macro data release windows. We also decompose the model-implied changes in yields bracketing employment reports into components that are due to changes in term premia and changes to expectations, and find that the term structure of the volatility due to expectations component has different shape

[3]Fleming and Remolona (1999) also build a term structure model to match the hump shape in the term structure of yield volatility around announcements. Their model is in discrete time. It has 2K factors corresponding to K factors for expectations processes affecting interest rates for K different announcement types and another K factors as the "stochastic means" of these factors. They do not model the time-inhomogeneous nature of bond yields associated with announcement effects, and have *constant* bond risk premia.

for jumps compared with non-jump (diffusion) movements in yields.

The plan for the remainder of this paper is as follows. In section 2, we report some empirical facts about the behavior of yields on announcement and non-announcement days. In section 3, we describe the model with jumps at deterministic times, and derive an expression for bond prices in the model. In section 4, we discuss the methodology for model estimation, and section 5 discusses empirical results. Section 6 concludes.

2 Yields and Macro Announcements

First, we document some empirical facts about bond yields and macroeconomic announcements using the daily yield curve data which are used in the term structure model estimation. Table 1 shows the standard deviation of three-month, two-year and ten-year zero-coupon US Treasury daily yield changes, from the dataset of Gürkaynak, Sack, and Wright (2007), on the days of nonfarm payrolls announcements, on the days of certain other announcements, and on non-announcement days.[4] We see that employment report days show substantially higher volatility of interest rates than non-announcement days, or indeed days of any other types of macroeconomic announcements, consistent with earlier studies.[5] The difference between the volatility on employment report days and non-announcement days is overwhelmingly statistically significant.

Figure 1 plots the standard deviation of yield changes on employment report and non–announcement days against the maturity. On non-announcement days, the curve

[4]By non-announcement days, we mean days that have no employment report, CPI, durable goods, FOMC, GDP, PPI or retail sales announcement.

[5]For example, Fleming and Remolona (1997) document (in their Table 5) that among all kinds of announcements, the employment report has strongest effect on Treasury yields, and the results in Balduzzi, Elton, and Green (2001) (their Table 2) also indicate strongest response of bond yields to the employment report.

is fairly flat in maturity, reflecting the well-known fact that the vast majority of yield curve shifts are level shifts (Litterman and Scheinkman, 1991). But on employment-report days, the level of volatility is higher, but it is also hump-shaped in maturity—the most volatile yields on employment report release days are intermediate-maturity yields, and the volatility is notably lower at the short end of the yield curve (such as three months). This was earlier found by Fleming and Remolona (1999) and Piazzesi (2001). It can also be seen in Table 1 for each of the announcement types separately. This is an empirical fact that a standard diffusive term structure model cannot capture. It represents the effects of news today on expectations of future monetary policy, and also on risk premia. A more stark way of documenting this stylized fact is to look at the volatility in yield changes caused by employment report announcements, assuming that the only difference between employment report and non-announcement days is the existence of the employment report news[6]. We also show this in Figure 1. The jump-induced volatility has a particularly pronounced hump shape.

Faust and Wright (2008) document that excess returns on long-maturity bonds over their short-maturity counterparts on announcement days are predictable. This is another empirical fact that we attempt to capture.

[6]If $\sigma_{m,A}$ and $\sigma_{m,NA}$ are the standard deviations of bond yields at maturity m on employment report and non-announcement days, respectively, then we define the standard deviation of yields owing to the employment report as $\sqrt{\sigma_{m,A}^2 - \sigma_{m,NA}^2}$.

3 The Model and bond pricing

3.1 The Model

Our model specifies that x_t is an n-dimensional latent state vector. Under the physical measure, x_t, follows the jump-diffusion:

$$dx_t = K(\theta - x_t)dt + \Sigma dW_t + \xi_t dN_t \tag{3.1}$$

where W_t is an n-dimensional vector of independent standard Brownian motions, N_t is a counting process with jumps at deterministic times $t = T_i$, $i = 1, 2, 3, ...$ ($dN_t = 1$ for $t = T_i$, 0 at other times), and ξ_{T_i} is an n-dimensional vector of random jump sizes.[7]

The random jump size vector, ξ_{T_i}, is assumed to be normally distributed with a state-dependent mean: $\xi_{T_i} \sim \mathcal{N}(\mu(x_{T_i-}), \Omega)$, where $\Omega = \Upsilon\Upsilon'$, and μ is an affine function of the state vector right before the jump, i.e.,

$$\mu(x_{t-}) = \gamma + \Gamma x_{t-}. \tag{3.2}$$

The short-term interest rate is:

$$r_t = \rho_0 + \rho' x_t. \tag{3.3}$$

[7]For a nice pedagogical discussion of jumps at deterministic times, see Piazzesi (2009). Piazzesi notes in Chapter 3.5.2 that jumps in deterministic times lead to bond yields that are nonstationary (time-inhomogeneous).

Assume that the pricing kernel is

$$
\begin{aligned}
\frac{dM_t}{M_t} &= -r_t dt - \lambda_t' dW_t + J(\xi_t, x_{t-}) dN_t \\
J(\xi_t, x_{t-}) &= \exp(-\psi_{t-}' \Upsilon^{-1}(\xi_t - \mu(x_{t-})) - \frac{1}{2}\psi_{t-}'\psi_{t-}) - 1,
\end{aligned} \tag{3.4}
$$

where $\lambda_t = \lambda + \Lambda x_t$ and $\psi_{t-} = \psi + \Psi x_{t-}$.

Under the risk-neutral measure, x_t, follows the jump diffusion:

$$dx_t = K_Q(\theta_Q - x_t)dt + \Sigma dW_t^Q + \xi_t^Q dN_t$$

where the jump size vector $\xi_{T_i}^Q$ has the distribution $\mathcal{N}(\mu_Q(x_{T_i-}), \Omega)$, $\mu_Q(x_{t-}) = \gamma_Q + \Gamma_Q x_{t-}$, $K_Q = K + \Sigma\Lambda$, $\theta_Q = K_Q^{-1}(K\theta - \Sigma\lambda)$, $\gamma_Q = \gamma - \Upsilon\psi$ and $\Gamma_Q = \Gamma - \Upsilon\Psi$.

Apart from the deterministic jumps, this is a standard essentially affine term structure model (model $EA_0(3)$ in the terminology of Duffee (2002)).

A few remarks are in order. First, in this paper we do not model stochastic volatility of yields. While the time-varying volatility of yields is well known and well documented, empirical studies such as Jones, Lamont, and Lumsdaine (1998) find that the volatility associated with macroeconomic announcements effects are short-lived; therefore, our model with homoskedastic yields during non-announcement period and jumps at announcements can still be expected to capture some essential features of yield curve response to data releases.

Second, all macroeconomic announcements give rise to movements in interest rates that can be thought of as jumps (Andersen, Bollerslev, Diebold, and Vega, 2007). We could in principle extend the model to allow for jumps of multiple types, i.e., introduce different kinds of jumps corresponding to different types of announcement:

$$dx_t = K(\theta - x_t)dt + \Sigma dW_t + \xi_t^A dN_t^A + \xi_t^B dN_t^B + ... \tag{3.5}$$

However, working as we do with daily frequency data, it seems reasonable to treat employment report releases as the sole type of day on which we want to allow for jumps, in view of the especially strong effects of employment reports on yields.

3.2 Expression for bond prices

Let the time t price of a zero-coupon bond maturing at time T be $P(t,T)$. Then

$$P(t,T) = E_t^Q\left(\exp(-\int_t^T r_s ds)\right) \tag{3.6}$$

Proposition 1 provides an expression for this price.

Proposition 1. Suppose that between time t and T there are p jumps at $T_1, T_2, ..., T_p$, and that the short rate and risk-neutral dynamics of state variables are given by equations (3.3) and (3.1), respectively. Then

$$P(t,T) = \exp(a(t,T) + b(t,T)'x_t) \tag{3.7}$$

where

$$b(t,T) = \exp(-K_Q'(T_1 - t))((I + \Gamma_Q')b_1 + K_Q^{-1\prime}\rho) - K_Q^{-1\prime}\rho \tag{3.8}$$

$$a(t,T) = a_1 + b_1'\gamma_Q + \frac{1}{2}b_1'\Omega b_1 + A(T_1 - t; (I + \Gamma_Q')b_1) \tag{3.9}$$

and[8]

$$\begin{aligned} a_{i-1} &= a_i + b_i'\gamma_Q + \frac{1}{2}b_i'\Omega b_i + A(T_i - T_{i-1}; (I+\Gamma_Q')b_i) && (3.10)\\ b_{i-1} &= B(T_i - T_{i-1}; (I+\Gamma_Q')b_i) && (3.11)\end{aligned}$$

iterating backwards from the "initial" conditions

$$\begin{aligned} a_p &= A(T - T_p; 0_{n\times 1}) && (3.12)\\ b_p &= B(T - T_p; 0_{n\times 1}), && (3.13)\end{aligned}$$

and $A(\tau;\eta), B(\tau;\eta)$ given by

$$\begin{aligned} B(\tau;\eta) &\equiv \exp(-K_Q'\tau)(\eta + K_Q'^{-1}\rho) - K_Q'^{-1}\rho && (3.14)\\ A(\tau;\eta) &\equiv \int_0^\tau [(K_Q\theta_Q)'B(s;\eta) + \frac{1}{2}B(s;\eta)'\Sigma\Sigma' B(s;\eta) - \rho_0]ds && (3.15)\\ &= (K_Q\theta_Q)'\left[\int_0^\tau \exp(-K_Q's)ds\right](\eta + K_Q'^{-1}\rho) - (\rho_0 + \theta_Q'\rho)\tau \\ &\quad + \frac{1}{2}(\eta + K_Q'^{-1}\rho)'\left[\int_0^\tau \exp(-K_Q s)\Sigma\Sigma'\exp(-K_Q's)ds\right](\eta + K_Q'^{-1}\rho) \\ &\quad -\rho' K_Q^{-1}\Sigma\Sigma'\left[\int_0^\tau \exp(-K_Q's)ds\right](\eta + K_Q'^{-1}\rho) \\ &\quad -(\eta + K_Q'^{-1}\rho)'\left[\int_0^\tau \exp(-K_Q s)ds\right]\Sigma\Sigma' K_Q'^{-1}\rho + \tau\rho' K_Q^{-1}\Sigma\Sigma' K_Q'^{-1}\rho. \end{aligned}$$

The proof of Proposition 1 is in the appendix. Note that the integrals in (3.15) can be computed analytically.[9]

Note that even with jumps, prices are an exponential affine function of the state

[8] Note that throughout this paper, we define $\exp(A) = I + A + A^2/2 + A^3/6 + \cdots$ for any square matrix A.

[9] We have $\int_0^\tau \exp(-K_Q's)ds = K_Q'^{-1}(I - \exp(-K_Q'\tau))$ and $vec(\int_0^\tau \exp(-K_Q s)\Sigma\Sigma'\exp(-K_Q' s)ds) = ((I\otimes K_Q) + (K_Q\otimes I))^{-1}vec(\Sigma\Sigma' - \exp(-K_Q\tau)\Sigma\Sigma'\exp(-K_Q'\tau))$.

vector, and consequently yields are an affine function of the state vector, but the loadings depend not only on the time-to-maturity, but also on time itself.

When there is no state dependence in jumps ($\Gamma_Q = 0$), the expressions for $a(t,T)$ and $b(t,T)$ are particularly simple:

$$
\begin{aligned}
a(t,T) &= \tilde{a}(T-t) + \sum_{t<T_i<T} \Big(-\rho' K_Q^{-1}(I - e^{-K_Q(T-T_i)})\gamma_Q \\
&\quad + \frac{1}{2}\rho' K_Q^{-1}(I - e^{-K_Q(T-T_i)})\Omega(I - e^{-K_Q'(T-T_i)})K_Q^{-1'}\rho \Big), \qquad (3.16)\\
b(t,T) &= \tilde{b}(T-t), \qquad (3.17)
\end{aligned}
$$

where $\tilde{a}$ and $\tilde{b}$ are factor loadings for the standard affine-Gaussian model (without jumps), and the sum in equation (3.16) denotes summation over all T_i's between t and T. Note that when $\Gamma_Q = 0$, $b(t,T)$ is a continuous function of $T-t$ (as can be seen from equation (3.17)), thus the factor loading right after a jump, $b(T_i,T)$ and the factor loading right before the jump, $b(T_{i-},T)$ are the same.[10] But in general ($\Gamma_Q \neq 0$) they differ.

3.3 Yield curve implications

The bond pricing formulae derived above have interesting implications about the qualitative features of the yield curve. From the expression for price in equation (3.7), it can be shown that as maturity T approaches one of the jump dates (T_i's), the bond price is continuous, but not its first derivative. In other words,

$$
\begin{aligned}
\lim_{T\to T_i} P(t,T) &= \lim_{T\to T_i-} P(t,T) \qquad (3.18)\\
\lim_{T\to T_i} \frac{\partial}{\partial T}P(t,T) &\neq \lim_{T\to T_i-} \frac{\partial}{\partial T}P(t,T). \qquad (3.19)
\end{aligned}
$$

[10]Note that here and elsewhere in this paper, we denote $T_i - 0^+$ by T_i-, and $T_i + 0^+$ by T_i.

This implies that the yield curve is continuous but has kinks at locations corresponding to $T_1, T_2, ..., T_p$.

However, for realistic parameter values, these kink features are very slight so the yield curves based on the model still look smooth. This is comforting, as we know empirically that the yield curve is fairly smooth.

3.4 Economic meaning of the jumps in state variables

Many existing term structure models with jumps have focused on specifications in which only the short rate (or the target federal funds rate) has jumps.[11] A key aspect of our model is that we allow for jumps in all the state variables.

To motivate this, it is useful to consider a few simple term structure models that are special cases of our general specification. First, consider the following two-factor model with physical dynamics:

$$
\begin{aligned}
r_t &= x_{2t} \\
dx_{1t} &= \kappa_1(\theta_1 - x_{1t})dt + \sigma_1 dB_{1t} + \xi_{1t} dN_t \\
dx_{2t} &= \kappa_2(x_{1t} - x_{2t})dt + \sigma_2 dB_{2t} + \xi_{2t} dN_t
\end{aligned}
$$

Apart from the jumps, this is the so-called "central tendency" model, studied by Balduzzi, Das, and Foresi (1998) and Jegadeesh and Pennachi (1996). In this model, the second factor (x_{2t}) is the short rate, while the first factor (x_{1t}) is the time-varying "central tendency" to which the short rate x_{2t} mean-reverts. If there is a jump in x_{1t} (i.e., ξ_{1t}), it does not affect the short end of the yield curve today, but it does affect expected future short rates and hence the yield curve at longer maturities.[12]

[11] These include Das (2002), Johannes (2004), Jiang and Yan (2009) and Piazzesi (2005). Exceptions include Piazzesi (2001) and Feldhutter, Schneider, and Trolle (2008).

[12] This is the channel emphasized by Fleming and Remolona (1999).

In short, a jump in x_{1t} is like a so-called "path shock".[13]

For another motivating example, consider the following two-factor model, with physical dynamics:

$$
\begin{aligned}
r_t &= x_{2t} \\
dx_{1t} &= \kappa_1(\theta_1 - x_{1t})dt + \sigma_1 dB_{1t} + \xi_{1t} dN_t \\
dx_{2t} &= \kappa_2(\theta_2 - x_{2t})dt + \sigma_2 dB_{2t} + \xi_{2t} dN_t
\end{aligned}
$$

where the market price of non-jump risk is $\lambda_t = [0, \lambda_2 + \Lambda_{21} x_{1t}]'$. Apart from the jumps, this model is similar to the 2-factor model that Duffee (2002) used as an illustration.[14] In this model, again the second factor x_{2t} is the short rate. The other factor x_{1t} does not affect the (physical) path of the short term rate. However, because the market price of risk of x_{2t} depends on x_{1t}, the x_{1t} factor does affect the yield curve, and jump in x_{1t} will lead to a shift in the yield curve, reflecting a "risk premium" shock.

These two illustrative models are nested in our general model (equation (3.1)). In the general model, the state variables usually do not have simple labels, and clean identification of various jump effects is generally not feasible. However, allowing for jumps in state variables other than the short rate is potentially important: a surprisingly good employment report may not necessitate raising the policy rate immediately or at the next FOMC meeting, but may convince the market to price in more policy tightenings down the road ("path shock"), and it could also lead to a sudden rise in the term premium component of bond yields ("risk premium shock").

[13]This path shock is in the same sense as in Gürkaynak, Sack, and Swanson (2005a), who have discussed the patterns of yield/futures curve responses to FOMC announcements.

[14]Duffee's example has a CIR process for x_{1t}.

4 Estimating the Model

4.1 Estimation approach

The model described in section 3 implies that yields are a time-inhomogenous affine function of the latent state vector. Treating observed yields as being contaminated with small measurement error, the model can easily be estimated by maximum likelihood on daily data via the Kalman filter.

Specifically, we have the following observation equation and state equation:

$$\begin{aligned} y_{\tau,t} &= a_y(\tau;\delta(t)) + b_y(\tau;\delta(t))' x_t + e_{\tau,t} && (4.1) \\ x_t &= x_{t-1} + K(\theta - x_{t-1})\Delta t + \epsilon_t + \xi_t && (4.2) \\ & \quad \epsilon_t \sim \mathcal{N}(0_{n\times 1}, \Sigma\Sigma'\Delta t), && (4.3) \\ & \quad \xi_t \sim \mathcal{N}(0_{n\times 1}, \Omega) \text{ for } t = T_1, T_2, ... && (4.4) \end{aligned}$$

where $\tau \equiv T - t$ is time to maturity, $\delta(t) = T_1 - t$ is the time to the first jump (employment report), $a_y \equiv -a(t,T)/\tau$, $b_y \equiv -b(t,T)/\tau$, and $e_{\tau,t}$ is measurement error that is assumed to be i.i.d. over time and maturities. In order to simplify the implementation, we assume that the employment reports are equally spaced ($T_2 - T_1 = T_3 - T_2 = ... = \Delta = 1/12$), and let $\delta(t)$ take on 22 values only (approximately corresponding to the number of trading days in a month), ranging between 0 and $\Delta = 1/12$. In the state equation, Δt is one business day, i.e., $\Delta t = 1/250$. We restrict ξ_t vector to have zero mean in the physical measure, as the more general version $\xi_t \sim N(\gamma + \Gamma x_{t-1|t-1}, \Omega)$ becomes too unwieldy for estimation (ξ_t is still allowed to have a non-zero mean under the risk-neutral measure). Note that equation (4.4) implies that the conditional variance of x_t, $var(x_t|I_{t-1})$ has a deterministically varying pattern: it is $\Sigma\Sigma'\Delta t + \Omega$ on announcement days ($t = T_1, T_2, ...$) and $\Sigma\Sigma'\Delta t$ on non-announcement days. We fit the model to daily data on 3-month, 6-month and 1, 2, 4, 7 and 10-year zero-coupon US Treasury yields, using the dataset of Gürkaynak, Sack, and Wright (2007) for maturities of one year or greater, and T-bill yields for 3-month and 6-month yields. The data span 1990-2007 inclusive. At the zero lower bound, short- and even intermediate-term yields become insensitive to news (Swanson and Williams, 2014), but our model does not incorporate the zero lower bound. For this reason, we omit recent data from our estimation. In order to help pin down the parameters related to physical dynamics, we augment our Kalman filter based estimation with survey forecast data, as in Kim and Orphanides (2012).

4.2 Estimated specifications

As is standard in the literature, the number of factors, n, is set to 3. We first allow for jumps in all elements of the state vector and adopt the following normalizations for identification: we restrict ρ to be $[0,0,1]'$, specify K as lower triangular and θ as a vector of zeros, and let[15]

$$\Sigma = \begin{bmatrix} c & 0 & 0 \\ 0 & c & 0 \\ \Sigma_{31} & \Sigma_{32} & \Sigma_{33} \end{bmatrix}.$$

We shall denote this specification as the "J-Full" model.

This specification looks somewhat different from the usual specification in which K is lower-triangular, Σ is an identity matrix (or diagonal matrix of n free parameters), and ρ is a vector of n free parameters (or vector of ones). We chose our normalization

[15] c is a scale constant which we choose to be 0.01.

to make the third element of the state vector directly interpretable as the short rate.[16]

In order to compare with a specification in which there is jump in the short rate only, we also estimate a restricted model in which the Ω matrix is zero except for Ω_{33}. We shall denote this model as the "J-Short" model. Lastly, in order to compare models with and without jumps, we also estimate the homogeneous model (affine-Gaussian model), which shall refer to as the "No-Jump" model.

The parameter estimates for the three specifications (J-Full, J-Short, No-Jump) are given in Table 2.

5 Empirical results

5.1 Term structure of volatilities

The change in the τ-period yield across an employment report release (at time T_i) is given by

$$\Delta^J y(\tau) = b_y(\tau;\Delta)(x_{T_i-} + \xi_{T_i}) - b_y(\tau;0)x_{T_i-} + a_y(\tau;\Delta) - a_y(\tau;0). \tag{5.1}$$

Because the factor loadings right before an employment report (a_y, b_y for $\delta = 0$) are different from the factor loadings right after an employment report (a_y, b_y for $\delta = \Delta$), $\Delta^J y$ contains a predictable component. However, the predictable component is small; therefore we approximate the variance of $\Delta^J y$ as $var(\Delta^J y) \approx b_y(\tau;\Delta)'\Omega b_y(\tau;\Delta)$. We also compute the variance in the τ-period yield due to the diffusion (Brownian motion) component: $var(\Delta^D y) \approx b_y(\tau;\Delta)'\Sigma\Sigma' b_y(\tau;\Delta)\Delta t$.

[16] No loss of generality is incurred here, since our specification can be obtained from the "usual" specification by applying the invariant transformation $x_t = L\tilde{x}_t$, where $\tilde{x}_t$ is the state vector in the "usual" specification, x_t is our specification, and L is the matrix $L = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ \rho_1 & \rho_2 & \rho_3 \end{bmatrix}$.

A key motivation of our model is to try to match the different term structure of interest rate volatility associated with employment reports and at other times that is evident in the data (Figure 1). Figure 2 plots the term structure of interest rate volatility associated with employment report jumps ($\sqrt{var(\Delta^J y)}$), along with the term structure of daily interest rate volatility without jumps ($\sqrt{var(\Delta^D y)}$), implied by our estimated J-Full model. Our model can match the empirical fact that these two volatility term structures are different, and that the jump volatility term structure has a hump shape.

Piazzesi (2001) also estimated a term structure model which has jumps in state variables corresponding to nonfarm payroll employment and CPI at deterministic times (i.e. times of data releases). These jumps affect the yield curve through their effect on the intensity for the arrival of Poisson jumps that represent discrete changes in the federal funds target rate. She found that the term structure of the sensitivity of bond yields to nonfarm payroll surprises in her estimated model is monotonically downward sloping (Piazzesi 2001, Figure 8, right panel). On the other hand, in our model (J-Full) all state variables have jumps at the precise moment of data release, and it can produce the humped shape of jump volatility because the jumps in state variables beside the short rate captures the fact that employment report has little effect on short-term interest rate today but contains news about future expected monetary policy and can also shift the term premia implicit in the yield curve.

Figure 2 also shows the corresponding results from our J-Short model in dashed lines. In this model, the jump volatility term structure looks very different from the case where all three factors are allowed to jump. It does not have a hump shape, and instead slopes down.[17] The model with jumps in the short rate alone implies

[17]This is because the factor loading $[b_y(\tau;\delta(t))]_3$ for the short rate (the only state variable that has jumps in J-Short model) falls monotonically with increasing time-to-maturity τ.

that employment report announcements should have little impact on ten-year yields, which we know to be counterfactual.

The difference between the J-Full and J-Short models can be seen from the estimated Ω matrices. We obtain $\sqrt{\mathrm{diag}(\Omega)} = [0.00082, 0.00063, 0.00036]'$ for the J-Full model and $[0, 0, 0.00054]'$ for the J-Short model. Note that the J-Short model by design has nonzero standard deviation of jump in x_{3t} (short rate) only. On the other hand, in the J-Full model, the standard deviation of jump in x_{3t} (short rate) is the *smallest* of all the state variables.

We conclude that it is important to allow for jumps in more than just the short rate.

5.2 Expected excess returns

An important departure from the existing literature on term structure modeling with anticipated jump effects (including Fleming and Remolona (1999) and Piazzesi (2001, 2005)) is that in our model jump risk is priced. We now explore the implication of this for bond risk premia.

To examine bond risk premia, we compute one-day expected excess bond returns, i.e.,

$$\begin{aligned} & E_t(\log(P_{t+\Delta t,T}/P_{t,T}) - \log(1/P_{t,t+\Delta t}))/\Delta t = \\ \frac{1}{\Delta t} \quad & \{a(t+\Delta t,T)+b(t+\Delta t,T)E_t(x_{t+\Delta t})-a(t,T)-b(t,T)x_t+a(t,t+\Delta t)+b(t,t+\Delta t)x_t\} \end{aligned} \tag{5.2}$$

with daily filtered state variables (recall $\Delta t = 1$ day). Figure 3a plots this for ten-year bonds (expressed at an annualized rate) for the J-Full model and the No-Jump model. For a closer look, Figure 3b shows the same plot with a magnified y-axis.

It can be seen from Figures 3a,b that expected excess returns for the No-Jump model vary slowly over time, being positive for most of the 1990s and around 2005, but negative in the early 2000s. Incorporating jumps makes the expected excess returns much larger in absolute magnitude on employment report days (as can be seen from sharp spikes on employment report days). It can be also seen from Figures 3a,b that the average level of spikes moves in ways similar to the expected excess returns on non-announcement days, albeit with a different scale. Furthermore, the expected excess returns on non-employment report days are *smaller* in absolute value than the expected excess return from the homogeneous (No-Jump) model. These results indicate that part of the bond risk premium is earned on employment report days as compensation for jump risk. This is consistent with Faust and Wright (2008) who do not estimate a term structure model, but who do find that bond excess returns on days of macroeconomic news announcements are predictable. It is important to note, however, that the expected excess returns are relatively small in absolute magnitude, even on announcement days: a spike of typical size, say 0.25, corresponds to $0.25/250 = 0.1\%$ change in bond price.

Figure 3c shows the corresponding plot of one-day expected excess return based on the J-Short model. The pattern of expected excess return from this model doesn't have the aforementioned properties associated with Figures 3a and 3b (J-Full). Although the J-Short model still allows for jumps in the pricing kernel (short-rate jump risk is still priced), this is not sufficient to produce the kind of jump risk premia variation that we saw in the J-Full model.

To take a closer look, note that if there is no jump between t and $t + \Delta t$ then the expected one-day excess returns are well approximated by $b(t,T)'\Sigma(\lambda + \Lambda x_t)$.

Meanwhile, around jumps:

$$E_{T_i-}\left(\frac{P(T_i,T)-P(T_i-,T)}{P(T_i-,T)}\right)=\frac{E_{T_i-}(P(T_i,T))}{E^Q_{T_i-}(P(T_i,T))}-1=e^{b_i'(\mu(x_{T_i-})-\mu_Q(x_{T_i-}))}-1, \quad (5.3)$$

where the last equality follows from taking the expectation in equation (A.4) in the appendix under the risk-neutral measure and the same expectation under the physical measure. Taking a first order Taylor series expansion of equation (5.3), the expression in that equation is approximately $b_i'\Upsilon(\psi+\Psi x_{t-})$. Hence, the expected one-day annualized excess returns if there is one jump between t and $t+\Delta t$ are approximately:

$$b(t,T)'\Sigma(\lambda+\Lambda x_t)+\frac{1}{\Delta t}b(t,T)'\Upsilon(\psi+\Psi x_t) \quad (5.4)$$

Although the jump component in equation (5.4) is nonzero only on employment report days, we can think of there being an underlying process $b(t,T)'\Upsilon(\psi+\Psi x_t)$ and examine how it is related to the diffusion component $b(t,T)'\Sigma(\lambda+\Lambda x_t)$ (for a given time-to maturity $\tau=T-t$).[18] Table 3 shows the correlation of jump and diffusion components implied by our estimated models and daily filtered state variables, for two- and ten-year bonds. It also shows the correlation of daily changes in these components. It can be seen that in the case of the J-Full model, both the level and difference correlations are positive. This corroborates the above visual impression that bond risk premia associated with jumps move in ways that are similar to bond risk premia associated with diffusions. On the other hand, the J-Short model produces negative correlation between jump and diffusion contributions, underscoring the fact that the model with jumps in short rate alone is too restrictive to produce realistc variation in bond risk premia.

[18] As noted earlier, $b(t,T)$ also depends on time to the next employment report, but this effect is rather small, so we simply take the time to the next employment report δ as a fixed number (1/12).

Lastly, it is interesting to compare the *monthly average* of one-day expected excess returns for the J-Full model with the homogeneous model. As can be seen in Figure 4, the monthly averaging removes the spike patterns seen earlier, and produces bond risk premia that are similar, in pattern of variation and in scale, to the corresponding object from the homogeneous (No-Jump) model. This implies that the homogenous model can be viewed as a rough approximation of more granular models (such as the J-Full model) *for longer holding periods* (such as a month).

5.3 News: Term Premia and Expectations

Changes in interest rates around employment reports are large and generate a lot of attention from central banks, investors and journalists, as there is perhaps particular potential for crafting macroeconomic explanations for yield changes at these times. The volatility of long-term yields and forward rates surrounding macroeconomic announcements may suggest that inflation expectations are poorly anchored (Gürkaynak, Sack, and Swanson, 2005b). But it could also owe to changing expectations of future real short-term rates, or to changing term premia.

Beechey (2007) used the term structure model described in Kim and Wright (2005) and Kim and Orphanides (2012), and decomposed changes in yields on days of news announcements into revisions to expected future rates and revisions to term premia. Both were found to be important. But the exercise is in a certain sense internally inconsistent in that the underlying term structure model does not treat announcement and non-announcement days as being in any way different.

Our model allows us to decompose the model-implied term structure of interest rate volatility associated with employment report jumps and the model-implied term structure of the diffusive component of daily interest rate volatility into term premium and expected future short rate components.[19] The results of this exercise are included in Figures 5 and 6, for the J-Full model and the J-Short model, respectively. The J-Full model results show an interesting difference between jump volatility and diffusion volatility: The volatility of the expectations component of diffusion volatility declines monotonically with maturity, while the volatility of the expectations component of jump volatility first rises with maturity, peaks around 1-2 years, and then declines.

In the J-Full model, jump volatility at short maturities owes mainly to volatility of expected future rates, but at maturities beyond about three years the majority of the employment report jump volatility represents time-variation in term premia. On the other hand, in the J-Short model, jump volatility comes mainly from the expectations component at all maturities.

6 Conclusion

We treat news announcements as representing jumps in the term structure of interest rates of known time but random magnitude. We have proposed a model with jumps of this sort in all elements of the state vector, and with jumps in the pricing kernel as well. Along this dimension, the model is more flexible than the existing alternatives. This flexibility is important, because much of the variation in bond yields occurs right around news announcements. The model implies that yields are a time-inhomogenous affine function of the state vector.

Empirically, jumps associated with employment reports are most important for intermediate-term yields. This is a fact that our model can replicate. Our model also

[19]Since the expectations component of the bond yields in our model is also affine in the state vector, the jump in yields at employment report can be approximately expressed as $\Delta^J y \approx (b_y^E + b_y^{TP})\xi_{T_i}$. Therefore the contribution of expectations and term premium components to the variance are $b_y^{E'}\Omega b_y^E$ and $b_y^{TP'}\Omega b_y^{TP}$, respectively. Note that these do not add up to $var(\Delta^J y)$, since expectations and term premium components are generally correlated so there is an extra term $2b_y^{E'}\Omega b_y^{TP}$.

generates expected excess bond returns that are much more volatile on announcement days than on other days. We conclude that in understanding higher-frequency interest rate movements, separating out employment report and other days is both tractable and empirically important.

Appendix: Proof of Proposition 1

Using the Feynman-Kac formula, for any interval $[t, u]$ that doesn't include any jump event, we have:

$$E_t^Q(e^{-\int_t^u r_s ds + \eta' x_u}) = \exp(A(u-t;\eta) + B(u-t;\eta)' x_t) \tag{A.1}$$

where $B(\tau;\eta)$ and $A(\tau;\eta)$ are given by equations (3.14) and (3.15).

Between time t and T there are p jumps at $T_1, T_2, ..., T_p$. Consider $P(T_i, T)$ and $P(T_i-, T)$, where by T_i we mean $T_i + 0^+$, and by T_i- we mean $T_i - 0^+$. Using the law of iterated expectations, we have:

$$P(T_i-, T) = E_{T_i-}^Q(e^{-\int_{T_i-}^{T_i} r_s ds} E_{T_i}^Q(e^{-\int_{T_i}^{T} r_s ds})) = E_{T_i-}^Q(P(T_i, T)). \tag{A.2}$$

We know from equation (A.1) that at the time of the last jump:

$$P(T_p, T) = \exp(a_p + b_p' x_{T_p}).$$

where $a_p = A(T - T_p; 0)$ and $b_p = B(T - T_p; 0)$. Suppose that $P(T_i, T)$ is of the form:

$$P(T_i, T) = \exp(a_i + b_i' x_{T_i}). \tag{A.3}$$

From this, and equation (A.2), we have:

$$
\begin{aligned}
P(T_i-,T) &= E^Q_{T_i-}(e^{a_i+b_i'(x_{T_i-}+\xi_{T_i})}) \qquad \text{(A.4)}\\
&= e^{a_i+b_i'x_{T_i-}+b_i'(\gamma_Q+\Gamma_Q x_{T_i-})+\frac{1}{2}b_i'\Omega b_i}\\
&= e^{a_i+b_i'\gamma_Q+\frac{1}{2}b_i'\Omega b_i+[(I+\Gamma_Q')b_i]'x_{T_i-}},
\end{aligned}
$$

where we have used the fact that the jump vector is normally distributed. For the bond price at the time of jump $i-1$, we have:

$$
\begin{aligned}
P(T_{i-1},T) &= E^Q_{T_{i-1}}(e^{-\int_{T_{i-1}}^{T_i-} r_s ds}P(T_i-,T))\\
&= e^{a_i+b_i'\gamma_Q+\frac{1}{2}b_i'\Omega b_i}E^Q_{T_{i-1}}[e^{-\int_{T_{i-1}}^{T_i-} r_s ds+[(I+\Gamma_Q')b_i]'x_{T_i-}}],\\
&= e^{a_i+b_i'\gamma_Q+\frac{1}{2}b_i'\Omega b_i}e^{A(T_i-T_{i-1};(I+\Gamma_Q')b_i)+B(T_i-T_{i-1};(I+\Gamma_Q')b_i)'x_{T_i-}}
\end{aligned}
$$

where we have used equation (A.1) and the fact that there are no jumps between T_{i-1} and T_i in the last step. This means that $P(T_{i-1},T)=e^{a_{i-1}+b_{i-1}'x_{T_{i-1}}}$ where

$$
\begin{aligned}
a_{i-1} &= a_i+b_i'\gamma_Q+\frac{1}{2}b_i'\Omega b_i+A(T_i-T_{i-1};(I+\Gamma_Q')b_i)\\
b_{i-1} &= B(T_i-T_{i-1};(I+\Gamma_Q')b_i).
\end{aligned}
$$

We have thus proved equation (A.3) by induction over $i=p,p-1,p-2,...1$, where $\{a_i\}$ and $\{b_i\}$ are given by the recursions in equations (3.10), (3.11), (3.12) and (3.13). For the bond price at time t, we have:

$$P(t,T)=E^Q_t(e^{-\int_t^{T_1-} r_s ds}P(T_1-,T)).$$

This yields equation (3.7) and completes the proof of the Proposition. ■

Table 1: Standard Deviation of Yield Changes on Announcement Days

	Three-month	Two-year	Ten-year
Nonfarm payrolls	6.0*	10.1***	8.9***
Durable Goods	4.7	6.3***	5.8
Retail Sales	4.0**	6.9***	7.0***
PPI	3.8*	6.0	5.9
FOMC	5.9	6.7**	5.4
GDP	5.0	6.3***	6.3***
CPI	6.1	6.8***	6.5**
None	4.9	5.1	5.3

Notes: This table shows the standard deviation of three-month, two-year and ten-year zero-coupon yield changes (in basis points) on days of selected announcements, and on days of no announcements. For each type of announcement, cases in which the volatility is significantly different on that type of announcement day relative to non-announcement days at the 10, 5 and 1 percent significance level are marked with one, two and three asterisks, respectively. Newey-West standard errors are used. The sample period is January 1990 to December 2007.

Table 2: Parameter estimates

	J-Full	J-Short	No-Jump
K_{11}	0.0102 (0.0222)	0.0241 (0.0265)	0.0170 (0.0260)
K_{21}	-0.1463 (0.3120)	-0.8381 (0.4502)	-0.2318 (0.2605)
K_{31}	-0.1173 (0.3216)	0.6595 (0.4261)	-0.0294 (0.2956)
K_{22}	2.2006 (0.5740)	3.2498 (0.4670)	1.6373 (0.6506)
K_{32}	-2.3023 (0.4078)	-3.1530 (0.3993)	-1.9081 (0.4177)
K_{33}	0.6764 (0.2035)	0.3504 (0.0338)	0.6713 (0.2660)
Σ_{31}	0.0022 (0.0010)	0.0019 (0.0007)	0.0012 (0.0011)
Σ_{32}	-0.0051 (0.0006)	-0.0056 (0.0003)	-0.0043 (0.0011)
Σ_{33}	-0.0064 (0.0004)	-0.0061 (0.0001)	-0.0073 (0.0006)
ρ_0	0.0171 (0.0357)	0.0120 (0.0279)	0.0187 (0.0283)
λ_1	0.0635 (1.2979)	-0.9730 (0.5646)	-0.3967 (0.7636)
λ_2	-1.0458 (1.7400)	-1.0731 (1.5471)	0.1693 (0.8939)
λ_3	-4.9772 (6.9200)	-6.1942 (5.5682)	-5.4023 (6.1607)
$[\Sigma\Lambda]_{11}$	-0.1703 (0.2160)	0.1244 (0.0694)	-0.0024 (0.1606)
$[\Sigma\Lambda]_{21}$	0.3357 (0.1682)	0.5048 (0.2575)	0.1762 (0.1965)
$[\Sigma\Lambda]_{31}$	-0.7580 (0.1884)	-0.4027 (0.1804)	-0.7933 (0.1834)
$[\Sigma\Lambda]_{12}$	-0.3564 (0.4816)	-0.2089 (0.2469)	-0.0960 (0.4632)
$[\Sigma\Lambda]_{22}$	-0.6992 (0.3483)	-1.3224 (0.4230)	-0.5947 (0.2552)
$[\Sigma\Lambda]_{32}$	-0.7048 (0.3460)	-0.5794 (0.3664)	-0.9205 (0.2854)
$[\Sigma\Lambda]_{13}$	0.2796 (0.3003)	-0.0426 (0.0174)	0.0445 (0.2148)
$[\Sigma\Lambda]_{23}$	-0.2888 (0.1259)	0.1022 (0.0603)	-0.1466 (0.0155)
$[\Sigma\Lambda]_{33}$	0.5355 (0.3151)	-0.2088 (0.1102)	0.4724 (0.3826)
γ_{Q1}	-0.0006 (0.0009)		
γ_{Q2}	-0.0007 (0.0008)		
γ_{Q3}	-0.0003 (0.0005)	-0.0005 (0.0005)	
Γ_{Q11}	0.0071 (0.0104)		
Γ_{Q21}	0.0109 (0.0072)		
Γ_{Q31}	0.0023 (0.0059)	0.0109 (0.0055)	
Γ_{Q12}	0.0228 (0.0166)		
Γ_{Q22}	0.0149 (0.0136)		
Γ_{Q32}	-0.0245 (0.0102)	-0.0232 (0.0091)	
Γ_{Q13}	-0.0046 (0.0098)		
Γ_{Q23}	-0.0124 (0.0069)		
Γ_{Q33}	0.0079 (0.0058)	0.0011 (0.0031)	
Υ_{11}	0.0008 (0.0001)		
Υ_{21}	0.0005 (0.0001)		
Υ_{31}	0.0001 (0.0001)		
Υ_{22}	0.0004 (0.0001)		
Υ_{32}	0.0001 (0.0002)		
Υ_{33}	-0.0004 (0.0001)	0.0005 (0.0000)	

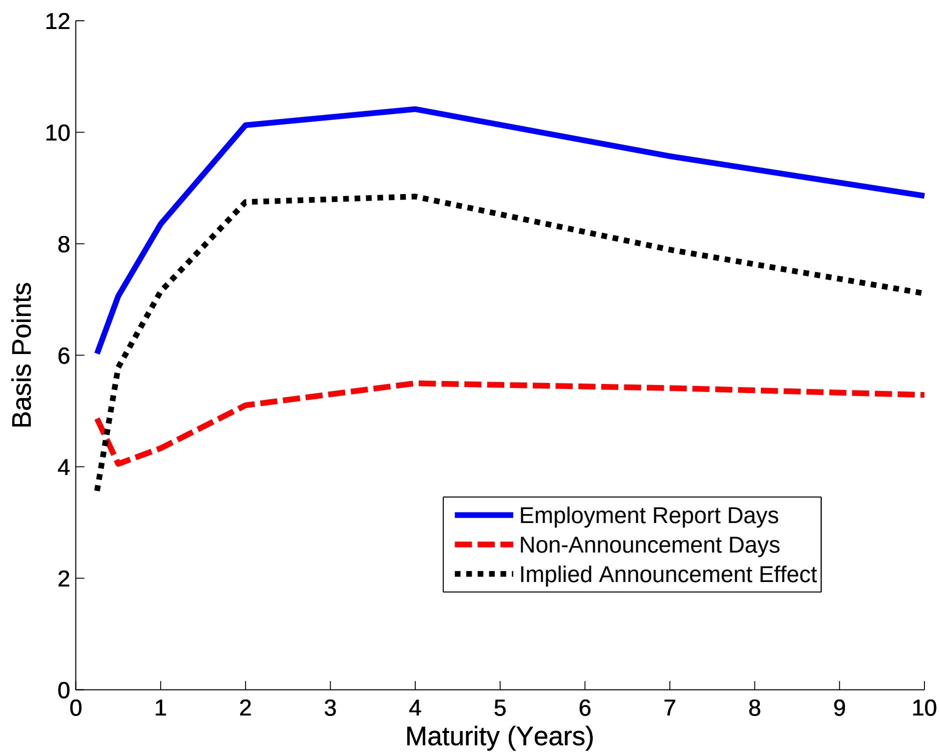
Notes: Parameter estimates for the J-Full, J-Short, and No-Jump models. Standard errors are given in parenthesis. We impose the following normalization restrictions: $K_{12} = K_{13} = K_{23} = 0$, $\Sigma_{11} = \Sigma_{22} = 0.01$, $\Sigma_{12} = \Sigma_{21} = \Sigma_{13} = \Sigma_{23} = 0$, $\rho = [0, 0, 1]'$, $\theta = [0, 0, 0]'$, $\Upsilon_{12} = \Upsilon_{13} = \Upsilon_{23} = 0$. In addition, for tractability we set $\gamma = [0, 0, 0]'$, and $\Gamma = 0_{3\times3}$.

Table 3: Correlation of jump and diffusion components of bond risk premia

		Two-year	Ten-year
J-Full	$\text{cov}(D, J)$	0.61	0.57
		(0.04)	(0.04)
	$\text{cov}(\Delta D, \Delta J)$	0.90	0.96
		(0.02)	(0.02)
J-Short	$\text{cov}(D, J)$	-0.74	-0.87
		(0.03)	(0.02)
	$\text{cov}(\Delta D, \Delta J)$	-0.96	-0.98
		(0.02)	(0.02)

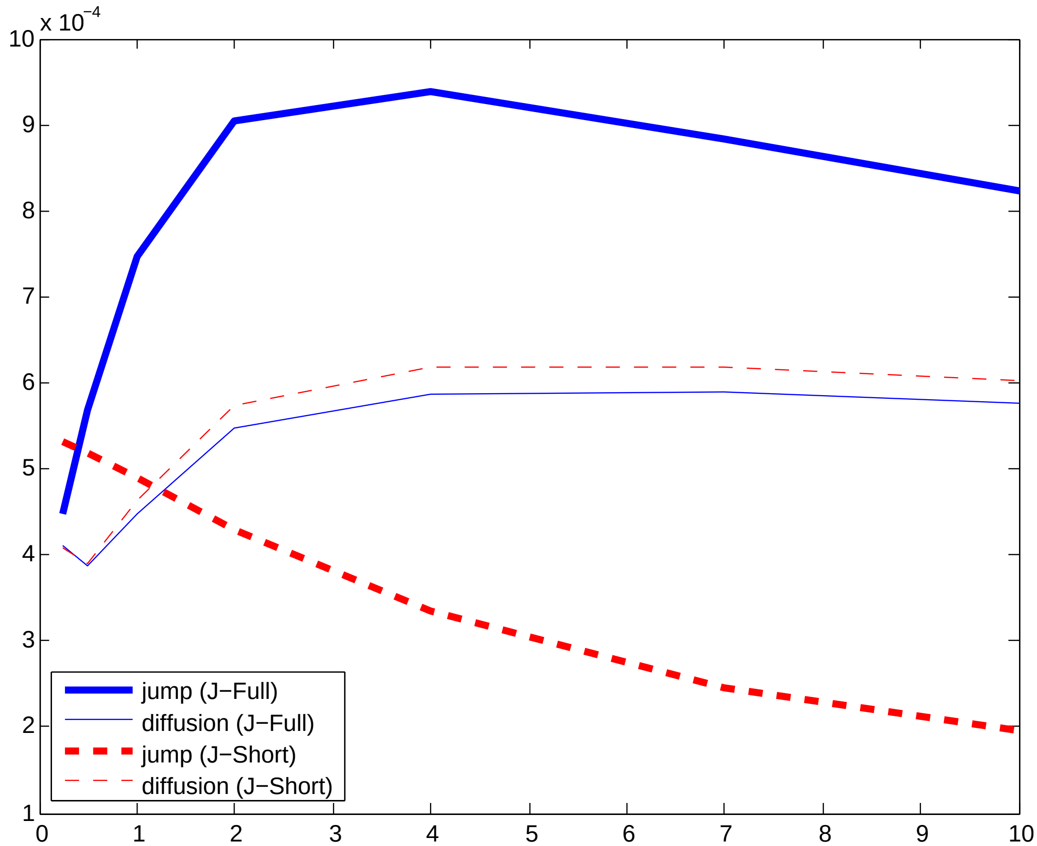
Notes: This table shows the simple correlation of the diffusion and jump components of bond risk premia ($D \equiv b(t,T)'\Sigma(\lambda + \Lambda x_t)$ and $J \equiv b(t,T)'\Upsilon(\psi + \Psi x_t)$) based on estimated parameters and state variables (daily series). Standard errors are in parentheses, computed using the Bartlett formula with 8 lags.

Figure 1: Volatility of Yield Changes



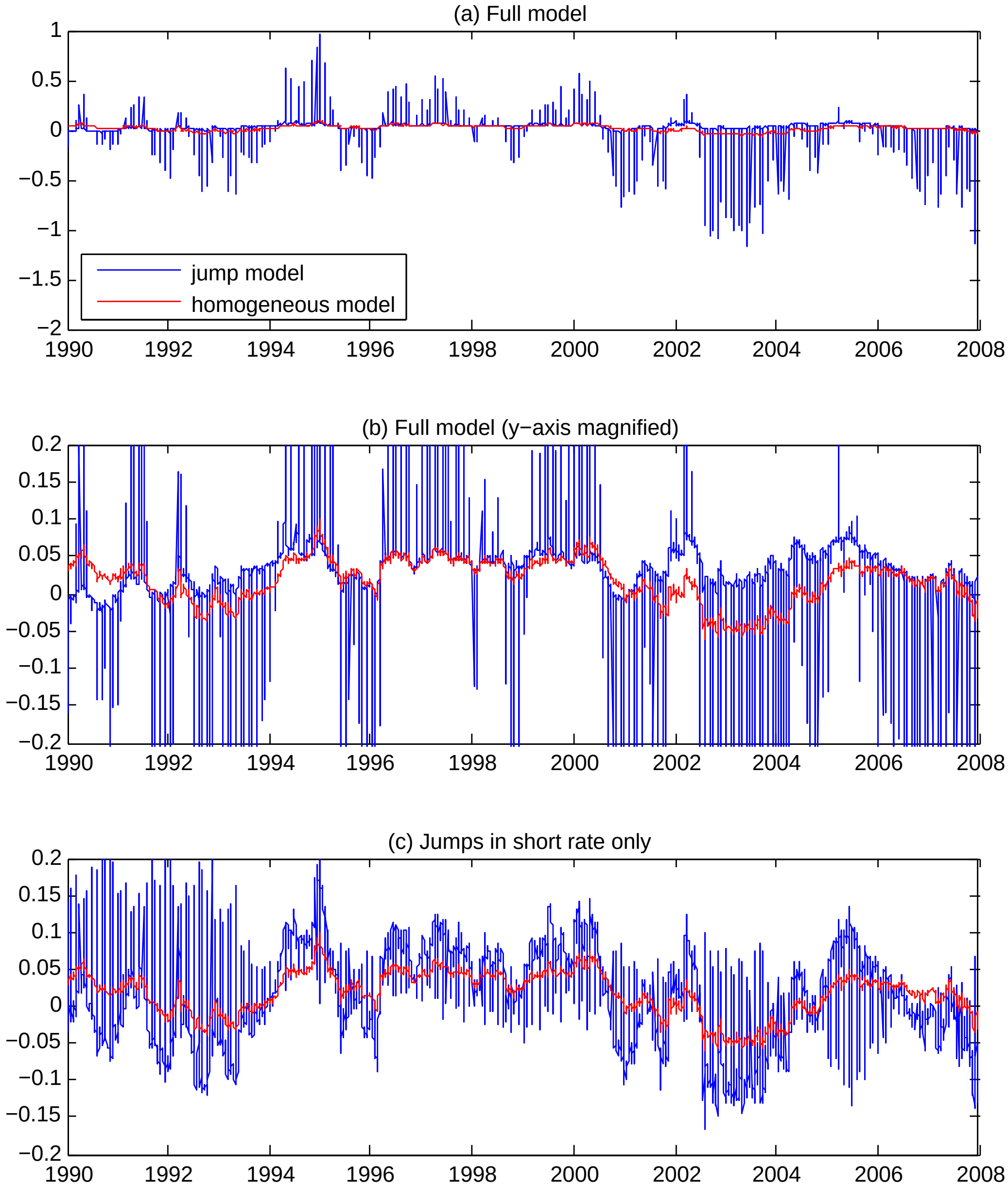
NOTE: This figure plots the standard deviation of daily changes in US Treasury zero-coupon yields on days of employment report releases and on non-announcement days against the bond maturity. The sample period is January 1990 to December 2007.

Figure 2: Model-implied term structure of volatility



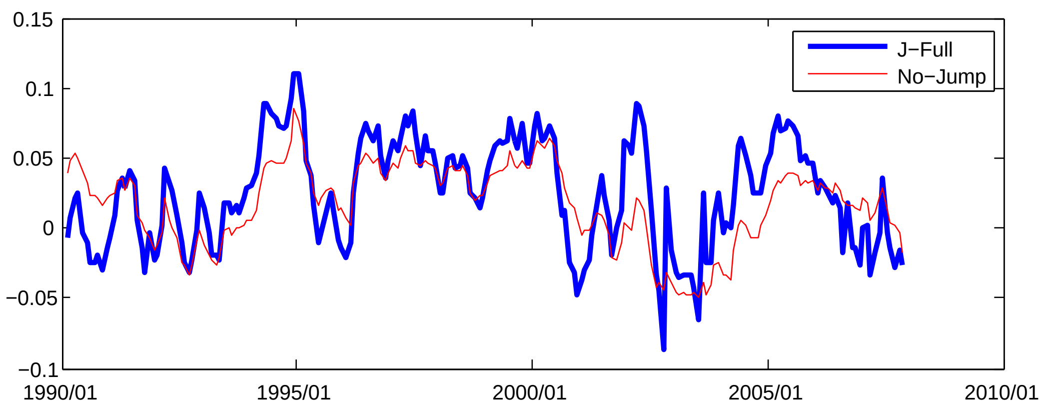
NOTE: This figure plots the model-implied term structure of interest rate volatility associated with employment report jumps, along with the model-implied term structure of daily interest rate volatility without jumps, both for the model with jumps in all state variables (solid lines) and the model with jumps in short rate alone (dashed lines).

Figure 3: One day expected excess return on ten-year bond



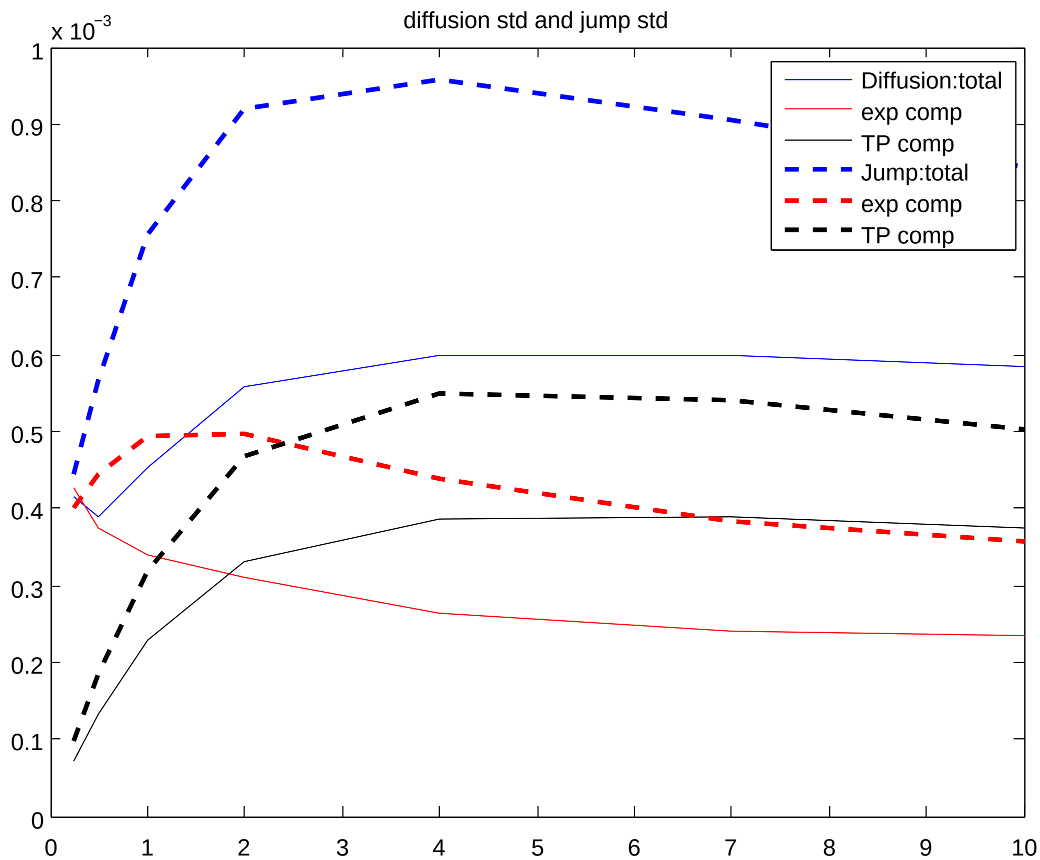
NOTE: This figure plots the one day holding period *ex ante* expected excess returns on holding a ten-year bond over a one-day bond. Results are shown both for the proposed model (with deterministic jumps) and for the corresponding homogenous model, that omits the jumps. Units are annualized returns. Figures (a) and (b) show the results for the full model, and Figure (c) show the results for the model with jumps in short rate alone.

Figure 4: Monthly average of one-day expected excess return on ten-year bond



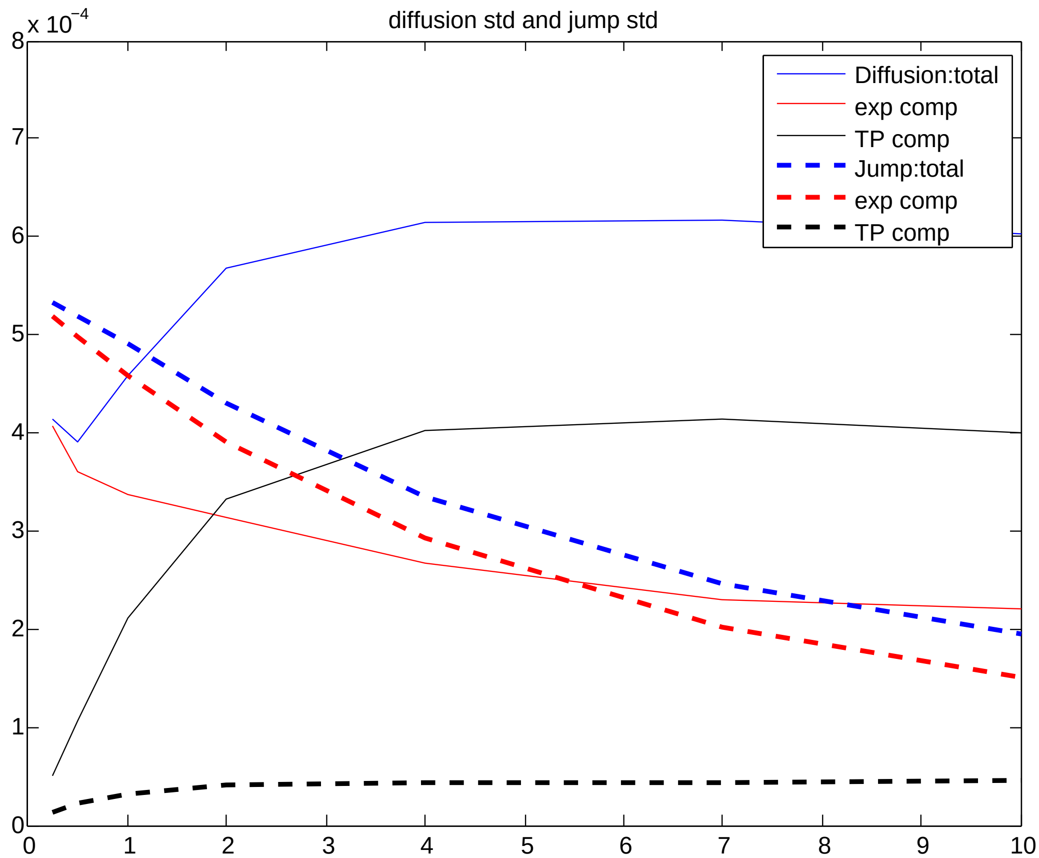
NOTE: This figure plots the monthly average of one-day expected excess returns from the J-Full model and the No-Jump model.

Figure 5: Model-implied term structure of volatility: Full model



NOTE: This figure plots the model-implied term structure of interest rate volatility associated with employment report jumps, along with the model-implied term structure of daily interest rate volatility without jumps. These volatilities are in turn decomposed into expected rate and term premium components. Results are based on the estimated version of the full model (with jumps in all state variables).

Figure 6: Model-implied term structure of volatility:
Jumps in Short Rates Alone



NOTE: This figure plots the model-implied term structure of interest rate volatility associated with employment report jumps, along with the model-implied term structure of daily interest rate volatility without jumps. These volatilities are in turn decomposed into expected rate and term premium components. Results are based on the estimated model with jumps in the short rate alone.

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