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Expectations and Risk Premia at 8:30am: Deciphering the Responses of Bond Yields to Macroeconomic Announcements

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Abstract

What explains the sharp movements of the yield curve in response to major U.S. macroeconomic announcements? To answer this question, we estimate an arbitrage-free dynamic term structure model with macroeconomic fundamentals as risk factors. We assume that the yield curve reacts to announcements primarily because of the information these contain about the fundamentals of output, inflation and the Fed's inflation target. We model the updating process by linking the factor shocks to announcement surprises. Fitting this process to data on yield curve movements in 20-minute event windows, we find that most major announcements, especially those concerning the labor market, are informative largely about the output gap rather than inflation. The resulting changes in short-rate expectations account for the bulk of observed yield movements. But adjustments in risk premia are also sizable. In partly offsetting the effects of short-rate expectations, these adjustments help to account for the well-known hump-shaped pattern of yield reactions across maturities.

Keywords: affine models, bond excess returns, economic announcements, term structure of interest rates.

JEL classification: G0, G1, E0, E4

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1. Introduction

At exactly 8:30am Eastern Standard Time, on the first Friday of the month, the U.S. Employment Report is released. The world's government bond markets react strongly and swiftly. The price reaction is as strong as it ever gets in these markets, and it is over in a few minutes. Something similar happens at the release times of other scheduled U.S. macroeconomic announcements. These times are evidently the most important information events in the bond markets. While several studies have recorded how the yield curve reacts during these events, little is known about why it reacts the way it does.

The stylized facts of how the yield curve reacts are well established. Bond yields across the maturity spectrum and related derivative prices show pronounced movements around the release times of news related to macroeconomic variables (see, inter alia, Fleming and Remolona, 1997; 1999; 2001; Green, 2004; Andersen et al., 2007; Pasquariello and Vega, 2007). The strength of bond yield reactions depends upon the type of announcements with the non-farm payrolls number in the U.S. Employment Report being the most important.[1] In investigating the impact of announcements on bonds of different maturities, studies report that the largest yield movements tend to cluster around the intermediate maturities, leading to a pronounced hump-shaped announcement reaction curve (Balduzzi et al. 2001; Fleming and Remolona, 2001; Faust et al., 2007).[2]

What explains these strong reactions to macroeconomic news? The yield curve moves at these times presumably because the announcements lead investors to update their expectations of the path of future interest rates and to reassess the risks about those expectations. But two important questions remain. First, exactly what information about macroeconomic fundamentals is contained in the announcements? Second, how does this information affect risk premia? The first question arises from the fact that the announcements are typically not directly about inflation or the output gap, which are considered the fundamental factors behind the rate-setting behavior of the U.S. Federal Open Market Committee (FOMC). Investors therefore need to assess the implications for inflation, the output gap and the reaction of the FOMC. If we can map the information content of these various announcements to fundamental variables, we can understand how investors revise their expectations in the light of salient new information. The second question is similarly important, since risk premia must explain a rather large part of yield movements if they are to resolve the expectations puzzle (see, inter alia, Dai and Singleton, 2002; Duffee, 2002). However, it is not yet understood what happens to these risk premia when macroeconomic news arrive.

[1] Other important announcements include the ISM/NAPM survey and the unemployment rate.

[2] Nonetheless, the reaction is quite strong even at long maturities, a fact emphasized by Gurkaynak et al. (2005).

In this paper, we address these two questions by fitting an arbitrage-free dynamic term structure model to high-frequency estimates of yield changes around the release times of major U.S. macroeconomic announcements. The model we fit belongs to the general class of affine arbitrage-free models of the term structure. At its core is a monetary policy reaction function driven by fundamental macroeconomic variables, namely inflation and the output gap, as well as the long-run inflation objective of the central bank. These factors also represent risk factors for the pricing of bonds.[3] At high frequencies, announcement surprises can be seen as shocks to these factors. With market prices of risk specified to be affine in the factors (see, inter alia, Duffee, 2002; Gürkaynak and Wright, 2012), the factor loadings serve to link announcement shocks directly to macroeconomic fundamentals and risk premia.

The empirical analysis proceeds in three steps. In the first step, we categorize the announcements into five groups and estimate in 20-minute windows the effect of announcement surprises on yields of six different maturities along the yield curve.[4] In the second step, we estimate the parameters of the macro term structure model using monthly time series data. Finally, in the third step we combine the results obtained from the first two steps in order to estimate the parameters of an updating process for the arrival of new information. These parameters link the announcement surprises to shocks in each of the macroeconomic risk factors. In effect, these parameters measure the information content of the announcements with respect to the fundamentals. They tell us how market participants would update their expectations and risk premia. We carry out the empirical investigation using data for the period 1985-2007, which spans the tenure of Alan Greenspan as Chairman of the Federal Reserve, and can be reasonably treated as a single monetary regime in which the Fed's long-run inflation objective was uncertain (see e.g. Sims and Zha, 2006).[5]

We find a number of interesting results: First, our estimates show a clear distinction between announcements that are relevant to output expectations and announcements that are relevant to inflation expectations. Indeed, four out of our five groups of announcements, namely the ones related to the labour market, production, the housing market and consumer behaviour, largely inform output expectations. Only the group of announcements about prices indices informs inflation expectations. Second, there is a consistent pattern

[3] As detailed in Section 2, the monetary policy rule also includes a monetary policy shock, which constitutes a fourth pricing factor. As such, the model is similar to one used by Hördahl and Tristani (2014) to explain yield movements in the United States and in the euro area.

[4] To minimize the noise associated with individual macroeconomic news, we assign announcements to five groups that are likely to convey similar information content with respect to broad underlying macroeconomic data. The details of group formation are reported in Section 4.1.

[5] The full sample period applies when daily yield data are used in the estimation. High-frequency data availability limits our estimates of announcement effects at the 20-minutes frequency to the shorter sample period of January 1993-December 2000. See Sections 4.1 and 5.1 and the internet appendix for further details.

across announcement groups in that changes in bond yields are caused mostly by revisions to the expected path of future short-term interest rates. Third, changes in risk premia are sizable but move largely in the opposite direction, thus partly offsetting the expectations effect on the yield curve. Hence, an announcement that surprises on the side of a stronger economy would typically lead to a lower risk premia even as the yield curve steepens. Indeed, it is this countercyclical behaviour of risk premia that resolves the expectations puzzle. Fourth, the strength of the expected short-rate's effect relative to that of risk premia changes with maturity. At short maturities, the two effects reinforce each other, but the effect of risk premia becomes relatively stronger at longer maturities, thus helping to account for the common hump-shaped pattern of yield curve reactions to macroeconomic news.

Related literature. Our study brings together two major strands of the literature on bond markets. The first strand is on the high-frequency reaction of bond yields to macroeconomic announcements (see, inter alia, Fleming and Remolona, 1997; 1999; 2001; Balduzzi et al. 2001; Green, 2004; Andersen et al., 2007; Pasquariello and Vega, 2007; Faust et al., 2007). The recurring theme is that the behavior of bond yields is best captured using data at the highest possible frequency, if possible tick-by-tick. The second strand of the literature deals with modelling yield curves with arbitrage-free affine models that incorporate macroeconomic variables as risk factors (see, inter alia, Ang and Piazzesi, 2003; Diebold et al., 2006; Hördahl et al., 2006; Dewachter and Lyrio, 2006; Rudebusch and Wu, 2008; Bekaert et al., 2010). Our contribution is to reconcile the two strands of the literature. We explain exactly why bond yields change at announcement times, explaining these changes in terms of risk premia and expectations about future short-term interest rates and in the process uncovering how macroeconomic fundamentals are updated.

Our study is closely related to those of Faust and Wright (2012) and Bansal and Shaliastovich (2012) and Kim and Wright (2014) who explore bond risk premia from similar perspectives. More specifically, Faust and Wright (2012) look at the predictability of bond risk premia and decompose returns into those earned in short windows around macroeconomic announcements (most of which are released at 8:30am) and those earned at other times. They find that the predictability of returns is due largely to price movements around news announcements and they propose a trading strategy that involves taking positions only around those announcements. Bansal and Shaliastovich (2012) investigate the predictability of bond (and foreign ex-change) risk premia and propose a long-run risk model that associates risk premia with the volatilities of inflation and the output-gap. Kim and Wright (2014) propose a no-arbitrage term structure model that al-lows for jump risk premia. The authors find that their model can match the main stylized facts of the term structure of US rates and record that interest rate volatility exhibits a hump-shaped pattern on employment report dates. Our analysis differs from these studies in two respects: First, we do not focus on the pre-dictability of bond risk premia. Second, we look at high-frequency responses of bond yields to a broad set of macroeconomic announcements and relate them to revisions in expectations and risk premia in an arbitrage-free affine model with macroeconomic risk factors.

Our paper is also related to the recent studies by Lu and Wu (2009), Beechey and Wright (2009), and Goldberg and Grisse (2013), which explore the fundamental relationship between a number of macro-economic releases and asset prices. Lu and Wu (2009) extract two systematic economic factors from a wide array of noisy and sparsely observed macroeconomic releases and find that the two factors predict more than 77 percent of the daily variation in LIBOR and swap rates from one-month to 10-year maturities. Beechey and Wright (2009) and Goldberg and Grisse (2013) document the time variation in the responses of the yield curve to macroeconomic announcements and find that it is explained by economic and risk conditions.[6] We build upon those findings by using bond yield data sampled at high frequencies to esti-mate yield curve responses more precisely. Most importantly, we link the movements in bond yields to a full-fledged term-structure model that allows us to reveal the underlying macroeconomic fundamentals.[7]

The remainder of the paper is as follows: Sections 2 and 3 introduce the term structure model, discuss how it is adjusted to capture announcement effects and provide details of the empirical framework. Section 4 describes the data used in this study and reports the main empirical results. Section 5 discusses various robustness checks and a final section concludes.

2. A Macro-Finance Model of the US Term Structure with Announcement Data

To interpret the reaction of the yield curve to announcements in terms of macroeconomic fundamentals, we propose a model that explicitly links the term structure of interest rates to macroeconomic factors. In particular, we employ a variant of the model used by Hördahl and Tristani (2014) to explain movements in US Treasury yields.[8] The remainder of this section describes the model in detail.

[6] Beechey and Wright (2009) decompose the reaction of nominal yields into changes affecting the real rate and the inflation compensation using nominal and index-linked bonds. They find, consistent with the findings of our study, that the news impact on the nominal term structure of interest rates represents changes in expected future real short term interest rates and/or risk premia (p. 535).

[7] Another study that contemporaneously and independently pursues a similar line of research is Kisacikoglu (2016). This study complements the results reported in our paper by investigating the information content of news announcement and proposing a structural model of the pricing kernel.

[8] See also Hördahl *et al.* (2006) and Ang and Piazzesi (2003).

2.1 The Macroeconomy

The modelling approach adopted in this section is one in which the dynamics of the relevant macroeconomic variables are consistent with a New Keynesian framework. The model includes two equations describing the evolution of inflation, π_t, and the output gap, x_t, as follows:

$$\pi_t = \mu_\pi E_t\left[\pi_{t+1}\right] + \left(1-\mu_\pi\right)\pi_{t-1} + \delta_x x_t + \varepsilon_t^\pi, \tag{1}$$

$$x_t = \mu_x E_t\left[x_{t+1}\right] + \left(1-\mu_x\right)x_{t-1} - \zeta_r\left(r_t - E_t\left[\pi_{t+1}\right]\right) + \varepsilon_t^x, \tag{2}$$

with ε_t^π and ε_t^x denoting respectively supply and demand shocks which are assumed to be normally distributed with zero means and with variances equal to σ_π^2 and σ_x^2, respectively:

$$\begin{aligned}\varepsilon_t^\pi &= \phi_\pi \varepsilon_{t-1}^\pi + v_t^\pi,\\ \varepsilon_t^x &= \phi_x \varepsilon_{t-1}^x + v_t^x,\end{aligned}$$

and where r_t is the short-term nominal interest rate. Although this setup is quite simple, it nevertheless incorporates a number of standard channels of transmission of shocks and of monetary policy.[9] To close the model, it is assumed that agents' perceptions of the Federal Reserve's behavior can be described by the following monetary policy rule:

$$r_t = (1-\rho)\left\{\beta\left(\pi_t - \pi_t^*\right) + \gamma x_t\right\} + \rho r_{t-1} + \eta_t \tag{3}$$

where π_t^* is the perceived inflation target and where η_t is a monetary policy shock that is serially uncorrelated and normally distributed with zero mean and variance equal to σ_η^2. The perceived inflation target is assumed to follow the dynamics

$$\pi_t^* = \phi_{\pi^*}\pi_{t-1}^* + \varepsilon_t^{\pi^*}, \tag{4}$$

with uncorrelated $\varepsilon_t^{\pi^*} \sim N\left(0, \sigma_{\pi^*}^2\right)$ .The inflation target is an unobservable variable that can be understood as the perceived target that investors have in mind when pricing bonds. It is estimated as part of a system that includes bond yields across a wide range of maturities. All variables of the model are specified in

[9] For example, inflation can increase because of demand shocks that raises output above potential and create excess demand, or because of supply shocks (such as cost-push shocks) that directly impact prices. The central bank can counteract unwanted movements in inflation due to shocks by changing the short-term interest rate, thereby stimulating or restricting aggregate demand.

deviations from their long-run means. Equation (3) is a variant of the Taylor (1993) rule, where the policy rate responds to deviations of inflation from the inflation target and to the output gap. The policy rule also allows for interest rate smoothing, which is an important feature of actual policy rates.[10]

In solving for the rational expectations equilibrium, the model is written in state-space form and solved using standard numerical methods (Hördahl et al., 2006 and the references therein).[11] As part of the solution, we obtain the law of motion of the state variables, denoted $\mathbf{Z}_t$,

$$\mathbf{Z}_t = \mathbf{M}\mathbf{Z}_{t-1} + \boldsymbol{\Sigma}\boldsymbol{\xi}_t, \tag{5}$$

where $\mathbf{Z}_t = [x_{t-1}, \pi_{t-1}, \pi_t^*, \eta_t, \varepsilon_t^\pi, \varepsilon_t^x, r_{t-1}]'$ is a 7×1 vector containing the model's relevant variables and shocks, $\mathbf{M}$ is a 7×7 matrix of parameters, $\boldsymbol{\xi}_t$ is a 7×1 vector of i.i.d. N(0,1) error terms and $\boldsymbol{\Sigma}$ is a 7×7 matrix of standard deviations.[12] We also obtain an equation for the levels of the two observable macroeconomic factors, $\mathbf{X}_t = [x_t, \pi_t]'$ in terms of $\mathbf{Z}_t$,

$$\mathbf{X}_t = \mathbf{C}'\mathbf{Z}_t, \tag{6}$$

where $\mathbf{C}$ is a 7×2 matrix of parameters.[13] The short-term interest rate is also obtained as a function of the state variables,

$$r_t = \boldsymbol{\Psi}'\mathbf{Z}_t, \tag{7}$$

where $\boldsymbol{\Psi}$ is a 7×1 vector of parameters.

2.2 The Term Structure

Equations (5) and (7) show that the state variables follow a first-order VAR and that the short-term interest rate is a linear function of the state vector $\mathbf{Z}_t$, respectively. As a result, closed-form bond-pricing solutions can be easily obtained in line with the vast literature on affine models of the term structure of interest rates.[14] First, we need to impose the assumption of absence of arbitrage opportunities and specify a process for the stochastic discount factor. We choose a standard specification for the stochastic discount factor (with

[10] It is worth noting that the model assumes that agents do not know the state of the economy directly. If this assumption did not apply, agents could recover the state of the economy from yields without the need of macroeconomic news announcements (Nimark, 2008).

[11] In particular, we use the methodology based on the Schur decomposition (Söderlind, 1999).

[12] Note that four of the state variables are contemporaneous, while three are lagged.

[13] Full model details are reported in the internet appendix.

[14] However, standard affine models are typically based on unobservable state variables, and both the short-rate equation and the law of motion of the state variables are postulated exogenously. On the other hand, in our framework, the state variables are macroeconomic factors, and their law of motion as well as the short rate equation are obtained endogenously as functions of the parameters of the underlying structural macroeconomic model.

a log-normal Radon-Nikodym derivative), and assume that the 7×1 vector of market prices of risk $\boldsymbol{\lambda}_t$ are affine in the state vector (Duffee, 2002)[15]

$$\boldsymbol{\lambda}_t = \boldsymbol{\lambda}_0 + \boldsymbol{\lambda}_1 \mathbf{Z}_t, \tag{8}$$

where $\boldsymbol{\lambda}_0$ and $\boldsymbol{\lambda}_1$ are a 7×1 vector and a 7×7 matrix of price of risk parameters, respectively. Given this setup, the continuously compounded yield $y_t^{(n)}$ on a zero coupon bond with maturity n can be written as an affine function of the state vector as follows:

$$y_t^{(n)} = A_n + \mathbf{B}_n' \mathbf{Z}_t, \tag{9}$$

where A_n is a scalar and $\mathbf{B}_n$ is a 7×1 vector derived using recursive relations.[16] When considering a collection of yields with m different maturities, equation (9) can be written as:

$$\mathbf{Y}_t = \mathbf{A} + \mathbf{B}' \mathbf{Z}_t, \tag{10}$$

where $\mathbf{Y}_t$ is the $m \times 1$ vector of yields, $\mathbf{A}$ and $\mathbf{B}$ are an $m \times 1$ vector and a $7 \times m$ matrix of parameters, respectively.

2.3 The Updating Process when Information Arrives

How do we link our term structure model to the announcement of macroeconomic news? We assume that the immediate reaction of the yield curve to announcements primarily reflects the information that these announcements contain about the fundamentals that drive the term structure. The yield curve moves as market participants instantaneously update their perceptions about the state of the economy, and hence

[15] A microfounded stochastic discount factor is not exploited because the macro model is specified at the aggregate level, without any explicit assumptions about its microfoundations. While this leaves us unable to directly link prices of risk and risk premia to individuals' preferences, the advantage of this approach is that it provides added flexibility to capture important features of the data. The stochastic discount factor m_{t+1} is defined as $m_{t+1} = \exp(-r_t)\,\psi_{t+1}/\psi_t$, where ψ_{t+1} is the Radon-Nikodym derivative assumed to follow the log-normal process $\psi_{t+1} = \psi_t \exp\left(-\frac{1}{2}\boldsymbol{\lambda}_t'\boldsymbol{\lambda}_t - \boldsymbol{\lambda}_t'\boldsymbol{\xi}_{1,t+1}\right)$. See Hördahl *et al.* (2006) for further details.

[16] In particular, defining $\bar{A}_n \equiv -nA_n$ and $\bar{\mathbf{B}}_n' \equiv -n\mathbf{B}_n'$, we can write

$$\begin{aligned} \bar{A}_{n+1} &= \bar{A}_n - \bar{\mathbf{B}}_n' \boldsymbol{\Sigma} \boldsymbol{\lambda}_0 + \tfrac{1}{2} \bar{\mathbf{B}}_n' \boldsymbol{\Sigma} \boldsymbol{\Sigma}' \bar{\mathbf{B}}_n, \\ \bar{\mathbf{B}}_{n+1}' &= \bar{\mathbf{B}}_n' (\mathbf{M} - \boldsymbol{\Sigma} \boldsymbol{\lambda}_1) - \boldsymbol{\Psi}', \end{aligned}$$

with initial conditions $\bar{A}_1 = 0$ (the short rate mean is subtracted from all yields initially) and $\bar{\mathbf{B}}_1' = -\boldsymbol{\Psi}'$. Full details are reported in the internet appendix.

adjust their expectations and risk assessments in the light of the new information. In our model, surprises in the announcements would therefore represent shocks to the relevant state variables. We compute these announcement surprises as the difference between the released number and the most recent forecast of that number. We assume that the relevant state variables that may react are the output gap, inflation and the perceived inflation target of the Fed, each of which therefore serve as a macroeconomic risk factor. Each announcement could potentially contain information about each of the three factors. Our estimation technique allows us to estimate how much information is contained in these macroeconomic announcements. For each group of announcements, we estimate a set of information-content parameters that serve to reconcile observed movements in the yield curve with the factor loadings derived from the term structure model.

To be more specific, we assume that three of the four contemporaneous state variables in $\mathbf{Z}_t$, namely the perceived inflation target, inflation and the output gap are updated once an announcement is released.[17] We label this reduced 3×1 state vector as $\widetilde{\mathbf{Z}}_t = [\pi^*_t, \varepsilon^\pi_t, \varepsilon^x_t]$. At a specific announcement release time t, each state variables i in the vector $\widetilde{\mathbf{Z}}_t$ will be shocked by $u_{ij,t}$ as the surprise $S_{j,t}$, corresponding to the macroeconomic announcement type j, is made public. Moreover, we assume that the shock to each of the state variables in $\widetilde{\mathbf{Z}}_t$ is proportional to the announcement surprises. This implies that

$$\mathbf{u}_{j,t} = \boldsymbol{\alpha}_j S_{j,t}, \tag{11}$$

where $\mathbf{u}_{j,t} = [u_{\pi^* j,t}, u_{\varepsilon^\pi j,t}, u_{\varepsilon^x j,t}]'$ is 3×1 vector of state variable shocks and $\boldsymbol{\alpha}_j$ is a 3×1 vector of sensitivity parameters for each state variable i to announcement surprise j. Since macroeconomic data are released with a lag, the set-up above implies that investors update their perceptions about the current (time t) state of the world based on the most recent data releases, even when these pertain to the previous month, or earlier. For example, when assessing what inflation today is likely to be, investors rely on the most recent release of CPI, PPI, unemployment, etc., which all refer to the situation in the previous month.

Next, the model yield expression in (10) implies that yield changes over a short intraday time interval h

[17] Since our data set does not include monetary policy announcements, we restrict the responses so that the monetary policy shock η_t is unaffected by all macro announcements. This also helps us reduce the number of parameters to be estimated, which is already sizeable given the number of announcement types we consider.

that spans an announcement is given by[18]

$$\Delta \mathbf{Y}_{j,t} = \mathbf{B}' \Delta \mathbf{Z}_{j,t+h}, \tag{12}$$

where $\Delta \mathbf{Y}_{j,t} = \mathbf{Y}_{j,t+h} - \mathbf{Y}_{j,t}$ is the vector of observed yield changes associated with announcement surprise j and where $\Delta \mathbf{Z}_{j,t+h} = \mathbf{Z}_{j,t+h} - \mathbf{Z}_{j,t}$ is the shock to the state vector during this short time interval. As only the three state variables in $\widetilde{\mathbf{Z}}$ will react to announcement surprises in our setting, we can rewrite equation (12) as $\Delta \mathbf{Y}_{j,t} = \widetilde{\mathbf{B}}' \Delta \widetilde{\mathbf{Z}}_{j,t+h}$ where $\widetilde{\mathbf{B}}$ is a $3 \times m$ matrix containing the entries of $\mathbf{B}$ corresponding to the relevant reduced state vector.

Furthermore, since $\mathbf{u}_{j,t}$ is the vector of shocks resulting from announcement j, we have that $\Delta \widetilde{\mathbf{Z}}_{j,t+h} = \mathbf{u}_{j,t}$, and we can write

$$\begin{aligned} \Delta \mathbf{Y}_{j,t} &= \widetilde{\mathbf{B}}' \mathbf{u}_{j,t} \\ &= \widetilde{\mathbf{B}}' \boldsymbol{\alpha}_j S_{j,t}. \end{aligned} \tag{13}$$

where the second equality follows from equation (11).

3. The Empirical Framework

We obtain estimates of the parameters discussed in Section 2 in three steps. In the first step, we estimate the response of bond yields to macroeconomic announcement shocks as in Fleming and Remolona (2001). This gives us estimates of $\Delta \mathbf{Y}_{j,t}$. In the second step, we estimate the term structure model described by equations (1)-(9) using the maximum likelihood (ML) methodology, which provides us with an estimate of $\widetilde{\mathbf{B}}$.

In the final step, we combine the two sets of parameter estimates from the previous two steps to obtain an estimate of the parameters $\boldsymbol{\alpha}_j$. In what follows, we discuss the details of the empirical framework adopted in each of the three steps.

[18] We consider h to be negligible compared to n, so the vector $\mathbf{A}$ and the matrix $\mathbf{B}$ do not change when bond maturities change from n to $n-h$ (and hence, $\mathbf{A}$ will cancel out when first differences are taken).

3.1 Step 1: Bond Yield Responses to Announcement Surprises

We estimate the response of bond yields to macroeconomic announcement surprises by replicating the procedure outlined in Fleming and Remolona (2001). We define the macroeconomic announcement surprise j at time t, $S_{j,t}$, as the difference between announcement realization, $R_{j,t}$ and its corresponding prevailing forecast, $F_{j,t}$. Since all macroeconomic announcements are expressed in different measurement units, we follow the existing literature and standardize by dividing each of the surprises by their sample standard deviation, σ_j (see, inter alia, Fleming and Remolona, 1997; Pasquariello and Vega, 2007 and the references therein):

$$S_{j,t} = \frac{R_{j,t} - F_{j,t}}{\sigma_j}. \tag{14}$$

We then estimate the impact of macroeconomic announcement surprises on bond yields with the following regression:

$$\Delta y_{j,t}^{(n)} = \phi_j^{(n)} S_{j,t} + e_{j,t}^{(n)}, \tag{15}$$

where $\Delta y_{j,t}^{(n)}$ denotes the 20-minute changes in bond yields with maturity n computed on the dates when macroeconomic variable j announcements are released (see Section 4.1 for details), $\phi_j^{(n)}$ are maturity-specific reaction parameters and $e_{j,t}^{(n)}$ is a zero-mean, serially uncorrelated error term.[19] In vector form, we can write the regression above as

$$\Delta \mathbf{Y}_{j,t} = \mathbf{\Phi}_j S_{j,t} + \mathbf{e}_{j,t}, \tag{16}$$

where the $m \times 1$ vector $\mathbf{\Phi}_j$ gathers the reaction parameters $\phi_j^{(n)}$ for all maturities, and $\mathbf{e}_{j,t}$ is the corresponding vector of errors.

3.2 Step 2: Macro-Finance Term Structure Model

We estimate the arbitrage-free term structure model presented in Section 2 by ML, and we construct the likelihood function using a Kalman filter methodology. To implement the ML estimation of the model, we first define a vector $\mathbf{W}_t$ containing the observable contemporaneous variables,

$$\mathbf{W}_t \equiv \begin{bmatrix} \mathbf{Y}_t \\ \mathbf{X}_t \end{bmatrix},$$

[19] In the empirical analysis we have also estimated the system of equations (16) with an intercept term. The results, not reported to save space, are qualitatively and quantitatively similar to the ones reported in the subsequent Section 4.

where $\mathbf{Y}_t$ is the $m \times 1$ vector of zero-coupon yields and $\mathbf{X}_t$ is a 2×1 vector of observable macroeconomic fundamentals.

We then define the system of observation equations as

$$\begin{aligned}\mathbf{W}_t &= \begin{bmatrix}\mathbf{A} \\ \mathbf{0}\end{bmatrix} + \begin{bmatrix}\mathbf{B}' \\ \mathbf{C}'\end{bmatrix}\mathbf{Z}_t \\ &\equiv \mathbf{K} + \mathbf{H}'\mathbf{Z}_t,\end{aligned}$$

where $\mathbf{0}$ is a 2×1 vector of zeros, $\mathbf{K}$ is $(m+2) \times 1$ vector and $\mathbf{H}$ a $7 \times (m+2)$ matrix of parameters, respectively. The system of state equations is as given by the law of motion from the model solution in equation (5):

$$\mathbf{Z}_t = \mathbf{M}\mathbf{Z}_{t-1} + \mathbf{\Sigma}\boldsymbol{\xi}_t,$$

By introducing a vector of measurement errors corresponding to the observable variables $\mathbf{W}_t$, and making assumptions about their covariances, we can express the log-likelihood function based on the forecasts of the states and the associated Mean Square Errors (MSE) that are generated by the Kalman filter (see the internet appendix and Hördahl and Tristani, 2014, for details).[20] As part of the estimation result we obtain $\mathbf{B}$ and therefore $\widetilde{\mathbf{B}}$ for the restricted state vector, which will be used in the next step.

3.3 Step 3: Factor Sensitivity Parameters

In the third step, we estimate the factor sensitivity parameters $\boldsymbol{\alpha}_j$ in equation (13) by combining the results from the two previous steps. Specifically, we note that the model-based bond yield responses in equation (13) should correspond to the actual yield responses in equation (16), and equating the right-hand side of the two expressions (ignoring the regression errors $\mathbf{e}_{j,t}$) we get[21]

$$\mathbf{\Phi}_j S_{j,t} = \widetilde{\mathbf{B}}'\boldsymbol{\alpha}_j S_{j,t}$$

[20] Note that the inclusion of measurement errors on all observable variables means that the state of the economy cannot be directly recovered by the econometrician using only term structure information.

[21] To avoid excessive notation we do not denote in what follows that $\mathbf{\Phi}_j$ and $\widetilde{\mathbf{B}}$ are estimated sets of parameters. However, we discuss later in this section the implication of dealing with generated regressors and regressands.

for each announcement j. This is equivalent to

$$\mathbf{\Phi}_j = \widetilde{\mathbf{B}}'\boldsymbol{\alpha}_j.$$

In principle, we could therefore estimate the unknown parameters in $\boldsymbol{\alpha}_j$ by regressing the yield responses $\mathbf{\Phi}_j$ from the announcement analysis on the loadings $\widetilde{\mathbf{B}}'$ that are obtained from the estimation of the affine term-structure model, i.e.

$$\mathbf{\Phi}_j = \widetilde{\mathbf{B}}'\boldsymbol{\alpha}_j + \varepsilon_j, \tag{17}$$

where ε_j is a cross-sectionally uncorrelated error term.

3.4 Econometric issues and standard errors

It is instructive to note that Equation (17) cannot be estimated using conventional least square estimators since both regressor and regressand are obtained from prior estimations, and are therefore measured with sampling error. Although several methods have been proposed in the literature to take into account these types of biases (see, *inter alia*, Pagan, 1984 and Murphy and Topel, 1985, Lewis and Linzer, 2005 and the references therein), equation (17) is particularly challenging since i) both generated regressor and regressand are included in the estimation and ii) the complexity of the first-step estimations, especially with regards to $\widetilde{\mathbf{B}}$, does not allow for an easy applicability of the corrections suggested in the literature.[22]

In our baseline set of estimations, we try to mitigate the effect of generated regressor and regressand biases in equation (17) by incorporating the uncertainty surrounding the values of $\mathbf{\Phi}_j$ and $\widetilde{\mathbf{B}}$ in the estimation of the parameters in $\boldsymbol{\alpha}_j$. In particular, we compute the distribution of the parameter $\boldsymbol{\alpha}_j$ by simulation using observations drawn from the distributions of both the estimated regressors and regressands. Specifically, for each announcement type, we draw a set of yield responses $\mathbf{\Phi}$ from the distribution obtained in the first step. We then draw a set of parameters for the term structure model from the distribution obtained in the second step. Next we use these parameters to generate new factor loadings $\widetilde{\mathbf{B}}$, and proceed to estimate a new set of α parameters. We repeat this 100,000 times and use the resulting distribution of $\boldsymbol{\alpha}_j$ to obtain point estimates and to make inference about statistical significance. This procedure relies on the

[22] One obvious difficulty in applying Murphy and Topel's (1985) approach to our case is that the function generating the regressor must be known and twice differentiable in the parameter values (Murphy and Topel, 1985 p.374). Although the function generating the regressor and regressand can be written in closed form, the first derivatives of the same functions (with respect to the estimated parameters values) cannot be written in closed form. In fact in the case of $\widetilde{\mathbf{B}}$ its values are constructed by means of a recursion (see the internet appendix for further details).

assumption, relatively common in the literature on two-step econometric modeling, that both Φ_j and $\widetilde{\mathrm{B}}$ are generated by models that are able to produce consistent estimates of both first-step parameters and their asymptotic covariance matrix (Murphy and Topel, 1985 p. 371).

We also compute standard errors of the estimated parameters ${}_j$ using a bootstrap approach that does not rely on any specific distribution assumption for the parameter estimates obtained in step 1. More specifically, we set up a bootstrap procedure in which the set of all shocks that occur within a month, including announcement surprises and bond yield responses, are resampled with replacement. This bootstrap procedure generates an empirical distribution for the estimated values of Φ_j which are then used in conjunction with the distribution of $\widetilde{\mathrm{B}}$ parameters obtained in step 2 to generate a empirical distribution for the parameter ${}_j$.

A final empirical concern relates to the fact that in the empirical estimation, as detailed in the following Section 4.1, the individual announcements are pooled in five groups. This implies that for each group, individual announcement surprises are potentially correlated with each other as some announcement news are released at the same time. In these circumstances, the disturbances included in a panel model, or as in our case, in a pooled regression carried out in step 1 cannot be assumed to be cross-sectionally independent. To ensure that valid inference for Φ_j is used, we also compute the Driscoll and Kraay (1998) nonparametric estimator of the variance-covariance matrix. This methodology is particularly suitable in our case as it produces standard errors that are robust to general forms of temporal as well as cross-sectional dependence in the data (Hoechle, 2007).

4. Empirical Results

4.1 Data

We estimate the parameters in the first step using US Treasury bond and US macroeconomic announcements data. The first dataset consists of transaction-level data for the most recently issues (on-the-run) US Treasury securities obtained from GovPX, a joint venture setup by the primary dealers and interdealer brokers in 1991 (see, *inter alia*, Pasquariello and Vega, 2007; 2009 and the references therein). Our tick-by-tick data set contains the transaction prices and the size of each trade, plus best bid and offer tradable quotes. We focus on on-the-run securities, since they are the ones characterized by greater liquidity and where the majority of informed trading takes place (Pasquariello and Vega, 2007). Bond yield changes on announcement dates are computed in the spirit of Fleming and Remolona (2001), i.e. as changes in yields from the last transaction before the announcement time to the first transaction after the subsequent 20 minutes.[23] This relatively narrow time frame is chosen to pin down the genuine effect of macroeconomic announcements without any contamination from other sources (Ederington and Lee, 1993; Fleming and Remolona, 1999). We use yields from transaction prices across six maturities available in the GovPX data set: 3- and 6-month T-bill rates, and 1-, 2-, 5-, and 10-year Treasury yields.[24]

The second dataset includes real-time macroeconomic forecasts of the relevant US macroeconomic variable and actual published data. We collect this information for eleven variables which we assume relate to US macroeconomic fundamentals, namely (1) NAPM index, (2) Unemployment rate, (3) Nonfarm payrolls,(4) Industrial production, (5) Producer price index, (6) Retail sales, (7) Consumer price index, (8) Housing starts, (9) New durable goods orders, (10) New homes sales and (11) Consumer confidence index.[25] The data are obtained from Money Market Services (MMS) Inc.[26]

In order to minimize the noise of bond yield responses associated with individual macroeconomic news, we assign the individual macroeconomic announcements to five groups made up of two or three announce-ments that are likely to have similar informational content with respect to broad underlying macroeconomic data categories. The formation of groups aimed at reducing the noise associated with individual entities is similar in spirit, and consistent with, the conventional practice of portfolio construction routinely carried out in the asset pricing literature (see Fama and MacBeth, 1973). We specify the five groups as follows:

1. *Labor market:* Unemployment rate and Nonfarm payrolls;
2. *Production:* NAPM index, Industrial production, and New durable goods orders;
3. *Prices:* Producer price index and Consumer price index;
4. *Housing market:* Housing starts and New homes sales;

[23]We assessed the robustness of the cut-off time by computing a fraction of the empirical results using yield changes over 20, 25 and 30 minutes windows. The results, not reported to save space but available upon request, are qualitatively and quantitatively similar to the ones reported in the main text of this study.

[24]We conducted a similar analysis using mid-quotes and the results, not reported to save space, are qualitatively and quantitatively similar to the ones discussed in this section.

[25]An important aspect of these macroeconomic releases is their characteristic of being widely and instantaneously disclosed to all market participants. Lock-up conditions are indeed imposed from government statistical agencies in order to guarantee the simultaneous release of key information to all market participants at regularly scheduled dates. See on this issue Fleming and Remolona (1999; 2001).

[26]The time series properties of the professional forecasts reported in the MMS database have been extensively investigated in previous studies (e.g. Fleming and Remolona, 1997). As reported in Pasquariello and Vega (2007), MMS International was acquired by Informa in 2003 and no longer exists. Action Economics LLC now provides commentary and analysis to support decision-making in the global fixed income and currency markets and also provides similar survey services.

5. *Consumer behavior:* Retail sales and Consumer confidence index.

In the first group we include the Unemployment rate (with an opposite sign, so that positive announcement surprises within this category represent higher-than expected improvements in the employment situation) and Nonfarm payrolls.[27] [28] The second group is meant to capture the overall state of the industrial sector: the NAPM index is based on a survey of purchasing and supply executives and encompasses a variety of sectors of the manufacturing sector; Industrial production measures output of the industrial sector of the economy; and New durable goods orders provides data on new orders received from more thousands of manufacturers of factory hard goods (durable goods). The third group captures price pressures in the economy as a whole by combining announcements on consumer and producer price indices. The fourth group reflects information relating to the housing sector. The last group captures announcements relating to consumer behavior: Retail sales is an indicator that tracks the value of retail products sold to consumers in the past month, whereas the Consumer confidence index is an indicator based on a survey of thousands of households, meant to capture the financial health and the confidence of the average consumer.[29] Because of the availability of the high-frequency bond yields data set, the macroeconomic announcement database is constructed over the period January 1993 - December 2000.[30]

We estimate the term structure model in the second step using monthly data on zero-coupon Treasury yields, inflation, and a measure of the output gap. The term structure data consists of zero-coupon yields available from the Federal Reserve Board (Gürkaynak et al., 2007). Nine maturities, ranging from 1 month

[27] Although Unemployment rate and Nonfarm payrolls announcements are routinely used in empirical research to proxy for news pertaining the US labour market, they are temporally preceded by ADP Nonfarm Employment announcements. Since the latter are scheduled on the first Wednesday of each month, and they are generally highly correlated with Nonfarm payrolls announcements, they may be potentially included in our labour market group. However, as further investigation is required to uncover the unique information content of each announcement, we leave this as an avenue for future research. We thank an anonymous referee to point this to us.

[28] It is worthwhile noting that labour market announcements in the US occur simultaneously with Canadian labour market announcements on the first Friday of each month. Although there is no established evidence suggesting a significant impact of Canadian announcement shocks on US bond yields, we acknoweldge that this simultaneity may represent a potential source of contamination for our baseline estimates.

[29] Since we group the announcements as described above, this means that there will not be a one-for-one correspondence between any of the macro state variables and any of the macro announcements. In particular, we have inflation as one of the state variables (and we include CPI changes in the observation equation when estimating the term structure model) and CPI announcements are also among the ones included in the first estimation step, but the announcement of a given change in CPI would not translate one-for-one into changes in the state variable inflation since the responses are also affected by PPI announcements. Another reason is that CPI enters the observation equation with an observation error, so CPI is not identical to the inflation state variable in the model.

[30] As discussed in Boni and Leach (2002) and Mizrach and Neely (2006), GovPX intermediated volume began to decrease in 1999 as alternative electronic trading venue came into being. For this reason we end our sample at the end of 2000. Although this sample period does not allow us to investigate the institutional change that occurred in early 2000 because of the migration of US Treasuries trading to electronic venues (Boni and Leach, 2002; Mizrach and Neely, 2006; Fleming et al, 2017), recent studies have shown that the 1990-2000 period is not much different from the more recent 2009-2010 period, in particular for medium- and long maturities which are the main focus of this study (see Swanson and Williams, 2014 and the references therein).

to 10 years, are used in the estimation. Inflation is computed as the month-on-month log-difference of consumer price index (CPI, seasonally adjusted). The output gap is computed as the quarterly log-difference of real GDP and the US Congressional Budget Office's (CBO) estimate of potential real GDP. As the term structure model is estimated at the monthly frequency, we construct a monthly time series of the output gap by fitting an ARMA(1,1) model to the quarterly time series.[31] In the estimation process, inflation and the output gap are directly entered as deviation from their mean.[32]

In order to broadly match the sample period of the high-frequency data set, the term structure model is estimated over the period August 1987 to January 2006. We have chosen this specific sample period as it corresponds to the tenure of Alan Greenspan as Chairman of the Federal Reserve and because of the existing empirical findings that have suggested that the 1985-2007 period can be adequately treated as a single regime (see e.g. Sims and Zha, 2006).

It is worthwhile to note that we use two different data sets on yields in our empirical analysis. In the first step, where we estimate the yield responses to macro announcements, we only have access to yield-to-maturity data from GovPX. In the second step, where we estimate the term structure model, we rely on commonly used zero-coupon yields, as described above. In order to ensure that the two sets of yield data are comparable, we match the average Macaulay duration of the high-frequency GovPX yields with the corresponding maturity of the zero coupon yields for the monthly yield series. We therefore assume that, for example, the 10-year Treasury note – which has an average duration of 91 months in our sample – reacts in a similar manner as a 91-month zero-coupon bond would, in response to a given macroeconomic announcement surprise.[33]

4.2 Estimation and Economic Interpretation

We begin our empirical investigation by first estimating equation (15) to obtain the actual responses of bond yields to standardized macroeconomic shocks within each announcement group. The results are reported in Table 1. In line with Fleming and Remolona (2001), announcement surprises for all groups impact bond yields significantly for all maturities. In fact virtually all of the parameter estimates $\phi_j^{(n)}$ are significant at the 1% statistical level, irrespective of whether we rely on asymptotic, bootstrapped or Driscoll and Kraay's (1998) standard errors. The labour market announcement surprises exhibit the largest impact across all bond maturities and all announcement surprises have a positive impact on bond

[31] More specifically, we forecast the output gap one quarter ahead, and compute one- and two-month ahead values by means of linear interpolation. This exercise is conducted in real time, i.e. the ARMA(1,1) model is estimated at the end of each quarter using data only up to that quarter.

[32] We also subtract the sample mean of the short-term policy rate r from all yields.

[33] Average durations and other sample statistics are reported in the accompanying internet appendix.

yields. The next important announcements, in terms of impact on bond yields, are the ones related to prices and consumer behaviour, respectively; with magnitudes that range between one half and one third of the impact exerted by labor market announcements. Furthermore, across all announcement groups except the price group, there is a clear hump-shaped pattern of announcement effects: the same news elicits a larger reaction in terms of bond yield changes from intermediate maturities, with a peak generally associated with 2-year to 5-year maturities.

The parameters of the term structure model are presented in Table 2, Panels A and B. The estimates of the term structure model are empirically plausible. In fact, the parameters of the central bank's interest rate rule are in line with estimates found in the literature, including the responses to inflation deviations from the policy objective and to the output gap (and γ). The policy rule is also characterized by some, albeit not extreme, interest rate smoothing, with a smoothing coefficient (ρ) just below 0.9. We also find very strong backward-lookingness of inflation and the output gap, with μ_π and μ_x coefficients close to zero. This suggests that shocks to macroeconomic factors have a large impact on expectations of future values, which in turn exhibit an important role for bond yields in the model.

The yield fit of the model is excellent across all maturities: the model-implied and the actual bond yields are virtually indistinguishable from each other. The two top panels of Figure 1 illustrates this for two of the maturities in the sample.[34] The bottom four panels in Figure 1 displays the estimated dynamics of the state variables implied by the term structure model. Overall, the fit is satisfactory, especially in light of the fact that the implied dynamics of the factors are jointly obtained with the dynamics of bond yields. Of the two observable macroeconomic factors, the model does a particularly good job in fitting the output gap. The dynamics of inflation differs somewhat more when comparing the estimated model with the data. However, the model-implied year-on-year inflation dynamics capture the broad contours of the low-frequency movements in actual year-on-year CPI inflation. This low-frequency component of inflation therefore seems to be what bond market investors care about. Or to put it differently, the yield data calls for the inflation variable to be substantially more persistent than our CPI inflation measure, and the Kalman filter therefore extracts a slow-moving component from the inflation data as the most suitable inflation state variable.

[34] Given the flexibility of the market price of risk specification, our model, like all essentially affine models, is potentially prone to over-fitting (Duffee, 2010). We have checked this issue by computing maximal Sharpe ratios implied by our model estimates. The average value over the sample period is around 1.2 and it is in line with the evidence recorded in existing studies (see, Adrian et al., 2013 and the references therein).

Similar to yields for longer maturities, the model fit of the policy rate (here taken to be the 1-month rate) is virtually identical to the actual data. The lower right-hand panel of Figure 1 displays the filtered perceived inflation target, which is an unobservable variable in the term structure model. The features of the estimated target rate seem plausible: it is quite persistent and it falls slowly from a level just below 3.2% to around 2.8% over the sample period, in line with the notion that the Federal Reserve gradually gained credibility in keeping inflation low during the Greenspan Era. Moreover, the estimated target level at the end of the sample (2.8% in CPI terms) is consistent with the anecdotal evidence at the time that the Fed had adopted an implicit PCE (personal consumption expenditures) inflation target of 2.5%.

Having estimated both actual bond yield responses and the term structure model in the first two steps of our empirical setup, we next estimate the factor sensitivities $_j$ for the five announcement groups in our sample. The results are reported in Table 3. The signs of the estimated factor sensitivities are as expected: Positive surprise announcements are all associated with upward revisions to inflation, the inflation target and the output gap state variables. However, the magnitude and the statistical significance of the responses vary across announcement groups and state variables. Among the five groups, announcements related to the labor market exhibit the greatest impact on both inflation and output gap with magnitudes that are at least twice as large as the sensitivities exhibited by the other groups. A one standard deviation upward shock in this group, for example, implies a 3.3 basis point (annualized) rise in the perceived inflation rate used by agents to price bonds, and an increase of 4.6 basis points for the output gap. While these numbers are quite small, they nevertheless imply sizeable increases in expected future inflation and output gaps. The prices group is the second most important set of announcements but, in contrast with the labor market group, its effect is concentrated on inflation and the inflation target. Interestingly, standardized surprises in this group move perceived annualized inflation less than shocks to announcements related to the labor market. However, the parameter estimates are statistically insignificant at conventional level. The remaining three announcement groups only exhibit significant sensitivities to the output gap with magnitudes that are similar across groups.

Given the full set of parameter estimates reported in Tables 2 and 3, we can examine the transmission of macroeconomic surprises to interest rates and bond yields. The estimated model-implied responses of bond yield changes to the standardized macroeconomic announcement surprises are shown in Figure 2, along with the estimates of the high-frequency bond yield responses reported in Table 1. The model captures the average responses well. Furthermore, it also replicates the hump-shaped pattern generally seen in the data for all announcement groups.

As discussed in Section 2, the yield responses in Figure 2 are due to changes in the expected average short-term interest rate and/or changes in risk premia. The two top panels in Figure 3 provide a decomposition of the yield responses into these two components for two of the announcement groups.[35] We can identify a uniform pattern: the expected interest rate effect dominates across all maturities. The risk premium component does affect yield responses but it moves in the opposite direction of the expected interest rate effect, especially over medium- to long-term maturities, confirming the counter-cyclical nature of risk premia.[36] [37]

The relative importance of the state variables in terms of contributing to the overall yield responses is displayed in the two bottom panels of Figure 3, again for two of the announcement groups. Consistent with the results reported in Table 3, the response of bond yields to labour market announcements are due mostly to perceived changes to the output gap (this holds also for production, housing, and consumer behaviour announcements). For labour market announcements changes in the perceived inflation target also play a significant role, although less than that of the output gap. The yield changes associated with Price index announcements show even stronger responses that are due to perceived changes in the inflation target. This suggests that price-related announcements significantly affect bond prices because they induce investors to revise their views of the long-term inflation outlook, as captured by the inflation target. Price index announcements also induce revisions to the inflation factor, are seen as transitory and therefore less important for bond prices, in particular for longer maturities. Taken together, these results suggest that perceived changes to inflation do not account much for the response of bond yields across all of the announcement groups.

Announcements in all groups lead to substantial adjustments in risk premia, which account for the common hump-shaped pattern of yield curve reactions. At the same time, the behavior of risk premia across the curve depends critically on the nature of the information shock. This becomes clear if we examine the decomposition of yield responses into an expectations and a premium component for each of the three

[35] Here, as well as in Figure 4, we show only the decompositions for the Labour market and the Price index groups in order to save space. The remaining three groups (Production, Housing, and Consumer behaviour announcements) are qualitatively similar to the Labour market in terms of these decompositions. Full results are available upon request.

[36] The results pertaining the risk premia component of bond yield changes are consistent with, among others, Campbell and Shiller (1991), Dai and Singleton (2002) and Duffee (2002). The different sign of the risk premia components exhibited by maturities up to two years confirms the difficulty of term structure models in fitting the short-end of the yield curve, as documented in previous studies (Dai and Singleton, 2002 and the references therein).

[37] We report the 95% confidence bands for the two components of yield responses in Figure A1 in the internet appendix. In most of the cases, both the expected interest rates and the risk premium components are statistically significant and different from each other at conventional levels over maturities longer than 2 years.

state variable shocks at a time (while holding the others fixed at zero). Specifically, for each announcement group, we isolate the effect of a standardised announcement surprise on one of the state variables (e.g. the output gap) and decompose the resulting yield response into an expectations component and a premium component.

When the yield curve moves because of output gap shocks (top two panels in Figure 4), the move-ments at the short to intermediate maturities are dominated by revisions to the expected short-term interest rate. The risk premium component associated with the output gap becomes gradually more important from around the 4th year onwards, progressively reducing the effect of the expected short-term interest rate. This pattern is virtually the same regardless of the announcement that gives rise to the output gap shock, although the effect is stronger for some announcements (e.g. Labour market) than others (e.g. Prices). A similar pattern is recorded when the yield curve moves because of inflation shocks (middle two panels in Figure 4). Differently, when the yield curve moves because of inflation target shocks (bottom two panels in Figure 4), the movement across the entire curve is dominated by adjustments in the risk premium, whereas the expected short-rate component is generally very small across all announcement groups. However, this effect on risk premia is only statistically significant for price index announcements. This indicates that, as higher-than expected inflation news lead investors to revise their perceptions about the long long-term inflation outlook via the perceived target, they also require higher risk premia to compensate for this.

Taken together, the results reported in this section suggest that bond yield reactions around major macroeconomic announcements are mostly due to revision of expectations regarding the path of the future short-term interest rates. However, risk premia reactions associated with macroeconomic risk factors are sizable, statistically significant, and with differing magnitude across the maturity spectrum. These risk premia move in the opposite direction of the effect exerted by the revision of expectations about short-term interest rates. Moreover, the offsetting effect is stronger the longer the maturity, thereby giving rise to the hump-shaped pattern of the yield responses to macroeconomic announcement news.

5. Robustness

This section checks the robustness of the baseline results reported in Section 4. We first check whether our results hold if we extend our sample period until the start of the zero lower bound period in 2008. We then check the robustness of our baseline findings against an alternative empirical proxy for the output gap. We also check whether the estimates of the term structure model suffer from small-sample bias due to well-known difficulties in accurately estimating the dynamics of highly persistent variables.[38] We show that our baseline results are robust to all these issues.[39]

5.1 Extending the Sample Period

As explained in Section 4.1, our intraday analysis ends at the end of 2000, since reliable yield data from GovPX became unavailable around this time. We nevertheless want to make sure that our baseline results are not specific to the 1993-2000 period, but that they extend beyond that interval. To this end, we examine the performance of our model using *daily* yield response data (i.e. end-of-day yields after a macro announcement minus closing yields before the announcement) over the period January 1990-September 2008. We are mindful that the zero lower bound (ZLB) period from late 2008 onwards is likely to be a period with yield characteristics that are quite different from those before this period. We therefore exclude the ZLB period and end our sample period in September 2008.

While this daily yield data has the advantage that it is of the same type as that used in the estimation of the term structure model (i.e. zero-coupon yields), a clear disadvantage is that daily yield responses will be significantly affected by market developments other than the announcements of interest. While this is likely to negatively affect the statistical significance of the estimates, the results will nevertheless be useful in gauging whether the main features of our baseline hold up over this extended sample.[40]

The outcome of this exercise, reported in Tables A2-A3 of the internet appendix, shows that the results hold up quite well, although, as expected, the statistical significance suffers.[41] More specifically, the yield responses $\phi_j^{(n)}$ are quantitatively similar to those obtained using the 20-minute intervals over the shorter sample period, but a number of them are now statistically insignificant, even at the 10% level. A similar picture emerges for the factor sensitivity parameters α_j, which are all positive, and generally of similar magnitude as for the intraday data, but the level of statistical significance drops considerably. Taken together, this shows that (i) the main results presented in Section 4 hold up well in terms of the sign and magnitude of the estimated parameters, but also that (ii) yield response data over very short intraday time intervals are crucial in order to accurately pin down the statistical properties of yield responses to macroeconomic

[38] In a previous version of this study we have also examined whether our results change if we condition the value of the factor sensitivity parameters on variables that proxy for different economic environments at the time of news arrivals. The results, not reported but available upon request, suggest that there is very little evidence for state-dependence of announcement effects.

[39] We discuss the main results of the robustness checks in this section and report the various tables and graphs in the internet appendix.

[40] For consistency we also estimate the term structure model extending the initial sample up to September 2008.

[41] To save space, we report only one set of standard errors in the internet appendix; the other two sets of standard errors, available upon request, corroborate these results.

announcements.[42]

5.2 Alternative proxy for the output gap

The baseline results reported in the paper are based on a measure of output gap that uses the CBO estimate of potential output; a quantity that cannot be observed in real time and that is subject to large revisions over time. In order to assess the robustness of our results against our reliance on the CBO measure, we have carried out the analysis as described in Section 3 using an alternative proxy for the output gap. This alternative gap measure is computed as the deviation of real log-GDP from a linear-quadratic trend. The trend is estimated in real time, so that the trend parameter estimates are updated at each point in time. The results, reported in Table A4 of the internet appendix, confirm that our baseline findings are robust against this issue.[43]

5.3 Bias-Corrected Model Estimates

An additional concern is the possibility that the estimates of the affine term structure model suffer from small-sample bias due to well-known difficulties in accurately estimating the dynamics of highly persistent variables. Bauer et al. (2012) show that this is a common problem with affine term structure models, and that the bias may result in substantial errors in estimated risk premia and expected future short-term interest rates. They suggest ways to correct for the small-sample bias using a so-called inverse bootstrap method. Unfortunately, their proposed methods are not directly applicable to our case, as it requires the assumption of bond yields being perfectly observable without error to invert the model for the latent state variables. In our case this assumption would not help in solving the problem since we are still be unable to quickly estimate the parameters from equation (4).[44]

We adopt an alternative approach to check for the robustness of our baseline results with respect to small-sample bias. This approach is similar to the bootstrap bias correction method suggested by Tang and

[42] We have also carried out an additional robustness check using high-frequency data for the period between January 2005 and October 2008. The intraday data are from BrokerTec. As BrokerTec's data format, as well as security coverage, is different from those in GovPX, we have obtained yield changes from zero-coupon curves interpolated from on-the-run bond prices (see Cieslak and Povala, 2016 internet appendix). The results, in a number of cases, are broadly consistent with those of the baseline. However, given the very short sample length and the differences in the characteristics of the two data sets, some notable differences also emerge. More specifically, the standard errors based on BrokerTec data tend to be higher, probably as a result of the additional noise generated by the yield responses calculated from interpolated curves. The full set of results are available from the authors upon request.

[43] We have reported in the internet appendix only one set of standard errors of the parameter estimates. However, the results using the other two sets of standard errors, not reported to save space, are in line with the ones reported in Table A4 of the internet appendix.

[44] The reason is that we need to solve the macro model first before extracting the VAR parameters. See the internet appendix for further details.

Chen (2009). Specifically, we use our baseline model estimates (denoted $\hat{\theta}$) to generate N new samples of macro variables and yields (of the same length as the original sample) with the help of a parametric bootstrap procedure. For each new generated sample we reestimate the term structure model using ML, resulting in N sets of bootstrap parameter estimates $\hat{\theta}^*_B$, $B = 1, ..., N$. Letting $\bar{\theta}^*$ denote the median of the bootstrapped estimates, we obtain the bias-corrected estimator as[45]

$$\hat{\theta}_{BC} = 2\hat{\theta} - \bar{\theta}^*$$

We implement the procedure described above for $N = 5,000$ generated samples to obtain bias-corrected parameter estimates of the term structure model. The results reported in Figures A2-A3 of the internet appendix suggest that the bias correction has very little impact on our baseline results.[46]

6. Conclusions

This paper investigates the reaction of bond yields to macroeconomic news with the aim of quantifying the revision in investors' expectations regarding the path of future interest rates and their reassessment of the risks associated with such expectations. Our empirical framework relies on an arbitrage-free dynamic term structure model with macroeconomic factors together with estimates of changes in the US yield curve during a 20-minute window around the release times of major US macroeconomic announcements. At the core of the term structure model is a monetary policy reaction function driven by macroeconomic variables as in a Taylor rule. These same variables also serve as the key factors that drive changes in risk premia following the release of announcement news.

Using data for 11 major macroeconomic variables and high-frequency responses of yields to announcement suprises, we find several novel results. First, our estimates show a clear distinction between announcement news that are relevant to output expectations and those that are relevant to inflation expectations. Second, there is a consistent pattern across announcement groups in that changes in bond yields are mostly caused by revisions to the expected path of future short-term interest rates. However, bond yields also react to announcement surprises because of risk premia responses. Changes in risk premia

[45] Alternatively, the correction can also be computed on the average of the bootstrapped estimates, rather than the median. However, Bauer et al. (2012) report that median-based corrections tend to do slightly better in terms of capturing the true persistence for samples generated using a known data generating process. Moreover, earlier studies have argued that median-unbiased estimators have better properties when the distribution VAR estimator is highly skewed, which is typically the case in models for persistent processes (Rudebusch, 1992).

[46] As shown in the internet appendix, the bias-corrected responses of these variables are very close to the baseline estimates, and that they are always within the estimated 95% confidence limits of the benchmark responses.

are less sizable and move in the opposite direction, thus partly offsetting the effect due to revisions in short-rate expectations. Third, the strength of the expectations effect relative to the premium effect changes with bond maturity. At short maturities, the two effects reinforce each other, but the risk premium effect becomes rel-atively stronger at longer maturities, thus helping to account for the common hump-shaped pattern of yield curve reactions to macroeconomic news. The results are robust to various checks, including an extension of the sample period, an alternative measure of the output gap and to potential small-sample biases in the estimation of the term structure model.

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Table 1. Impact of Announcement Surprises on Treasury Yields

The table reports the estimates of the reaction of bond yields at different maturities to standardized macroeconomic announcement shocks. $\phi_j^{(n)}$ denotes the slope parameter estimate in equation (15) of the main text where n denotes the maturity of the on-the-run benchmark used in the estimation. The estimates are carried out over the sample period January 1993 - December 2000. Below each estimate are three sets of standard errors: in parenthesis asymptotic standard errors; in brackets Driscoll and Kraay (1998) standard errors; and in curly brackets based on a bootstrapped distribution (using 100,000 draws) as detailed in Section 3.4 of the main text.

	$n =$					
$\phi_j^{(n)}$	3 months	6 months	12 months	24 months	60 months	120 months
1. Labour market	1.794	1.822	3.308	4.227	4.000	3.444
	(0.273)	(0.371)	(0.416)	(0.500)	(0.512)	(0.461)
	[0.347]	[0.421]	[0.500]	[0.590]	[0.578]	[0.493]
	{0.348}	{0.422}	{0.500}	{0.592}	{0.577}	{0.493}
2. Production	0.367	0.674	1.190	1.533	1.494	1.275
	(0.076)	(0.086)	(0.116)	(0.143)	(0.153)	(0.140)
	[0.112]	[0.117]	[0.152]	[0.180]	[0.193]	[0.177]
	{0.112}	{0.116}	{0.152}	{0.179}	{0.193}	{0.178}
3. Prices	0.575	1.036	1.234	1.447	1.623	1.627
	(0.142)	(0.186)	(0.207)	(0.238)	(0.262)	(0.234)
	[0.146]	[0.220]	[0.216]	[0.258]	[0.298]	[0.272]
	{0.149}	{0.221}	{0.218}	{0.258}	{0.298}	{0.272}
4. Housing market	0.266	0.449	0.801	0.980	1.008	0.857
	(0.147)	(0.108)	(0.120)	(0.137)	(0.142)	(0.130)
	[0.102]	[0.100]	[0.146]	[0.172]	[0.166]	[0.142]
	{0.104}	{0.100}	{0.147}	{0.172}	{0.166}	{0.143}
5. Consumer behavior	0.513	0.661	1.239	1.661	1.702	1.508
	(0.099)	(0.126)	(0.181)	(0.204)	(0.215)	(0.185)
	[0.114]	[0.164]	[0.214]	[0.223]	[0.229]	[0.194]
	{0.114}	{0.164}	{0.216}	{0.225}	{0.231}	{0.194}

Table 2. Model Estimates

The table reports parameter estimates of the macro-finance term structure model discussed in Section 2. Figures in parentheses are asymptotic standard errors from the estimated Hessian.

Panel A) The macroeconomy

Parameter	Estimate	St.err. $\times 10^2$
ρ	0.891	(0.135)
β	1.444	(0.088)
γ	0.678	(0.053)
$\mu_\pi \times 10^2$	0.002	(0.012)
δ_x	0.015	(0.058)
μ_x	0.015	(0.082)
ζ_r	0.046	(0.069)
ϕ_{π^*}	0.995	(0.114)
ϕ_π	0.871	(0.211)
ϕ_x	0.963	(0.338)
$\sigma_{\pi^*} \times 10^3$	0.008	(0.000)
$\sigma_\eta \times 10^3$	0.282	(0.002)
$\sigma_\pi \times 10^3$	0.030	(0.000)
$\sigma_x \times 10^3$	0.030	(0.000)

Panel B) Market prices of risk: λ_1 ($\times 10^{-4}$) *parameters in* $\lambda_t = \lambda_0 + \lambda_1 \mathbf{Z}_t$:[47]

	driver of time-variation			
Priced risk	$\varepsilon_t^{\pi^*}$	η	ε_t^{π}	ε_t^{x}
inf. target shock $\left(\varepsilon_t^{\pi^*}\right)$	-0.046	-0.005	0.052	-0.167
	(0.006)	(0.011)	(0.006)	(0.010)
policy shock (η)	-0.772	0.096	-1.001	-0.284
	(0.002)	(0.005)	(0.025)	(0.005)
inflation shock (ε_t^{π})	-0.427	0.283	0.427	-0.930
	(0.001)	(0.003)	(0.004)	(0.002)
output gap shock (ε_t^{x})	-0.160	-0.083	0.353	0.449
	(0.005)	(0.009)	(0.006)	(0.005)

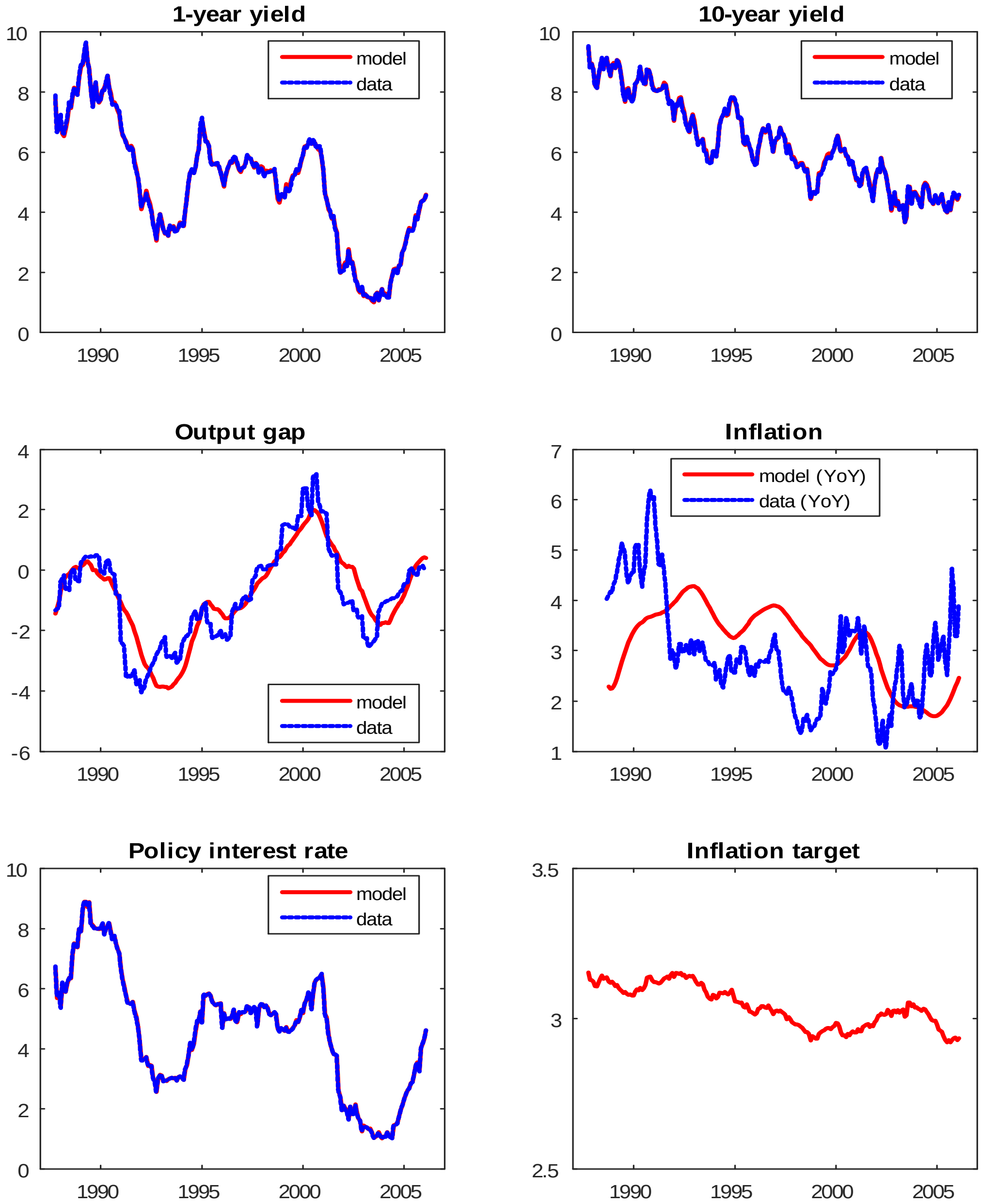
[47] This reports only the non-zero 4×4 block of λ_1 corresponding to the contemporaneous risk factors. Note that the constant λ_0 parameters do not matter for our analysis as they cancel out when we calculate the model-implied responses. For the sake of completeness, the estimated (non-zero) $\lambda_0 \times 10^{-4}$ values are equal to (with standard errors in parenteses): -0.1343 (0.0221); 0.2610 (0.0488); -0.6753 (0.0211); 0.1097 (0.0263).

Table 3. Factor Sensitivities to Macroeconomic Announcement Surprises

The table reports the estimates of the sensitivity parameters α_j of bond yields reactions to announcement shocks with respect to the three relevant macroeconomic risk factors (inflation target, inflation and output gap). These correspond to the slope parameter estimate in equation (17) of the main text, reported as the median of the distribution of the parameter obtained by simulation using observations drawn from the distributions of both the estimated model-free yield responses Φ_j and the factor loadings $\tilde{B}$ (see Section 3.3). The figures reported in the table are based on 100,000 draws. Below each estimate are three sets of standard errors from the simulated distribution of $\hat{\alpha}_j$: in parenthesis based on draws from the asymptotic distribution of Φ_j and $\tilde{B}$; in brackets based on Driscoll and Kraay (1998) standard errors; and in curly brackets based on bootstrapped responses Φ_j.

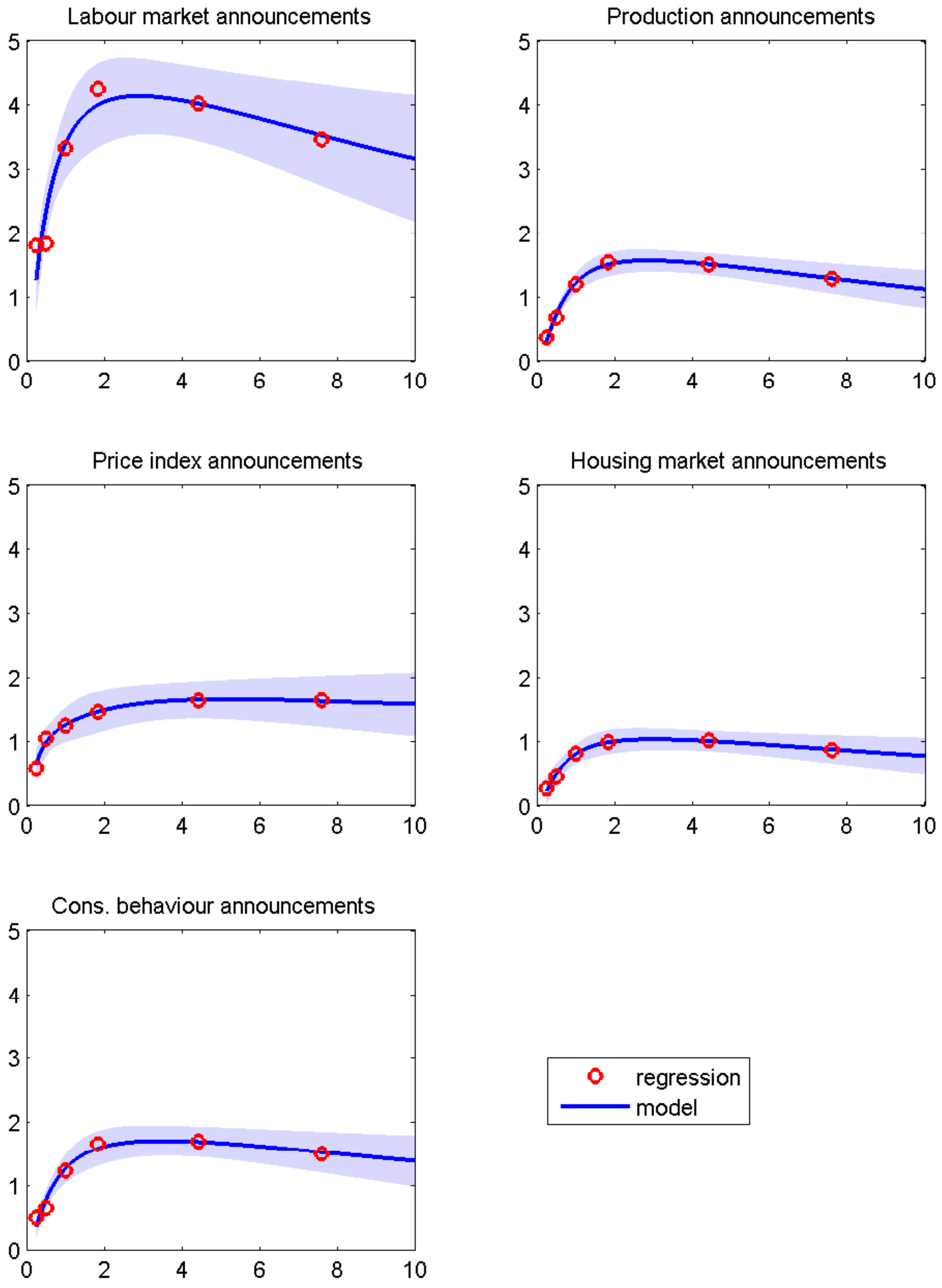
Announcement group	Macroeconomic risk factors		
	inflation target	inflation	output gap
1. Labor market	0.041	0.276	0.382
	(0.058)	(0.133)	(0.182)
	[0.067]	[0.157]	[0.211]
	{0.067}	{0.158}	{0.212}
2. Production	0.001	0.027	0.199
	(0.017)	(0.036)	(0.054)
	[0.021]	[0.047]	[0.067]
	{0.022}	{0.048}	{0.068}
3. Prices	0.057	0.185	0.032
	(0.029)	(0.068)	(0.090)
	[0.032]	[0.074]	[0.096]
	{0.033}	{0.075}	{0.099}
4. Housing market	0.005	0.029	0.118
	(0.018)	(0.050)	(0.059)
	[0.019]	[0.043]	[0.060]
	{0.019}	{0.044}	{0.062}
5. Consumer behavior	0.019	0.049	0.171
	(0.024)	(0.049)	(0.073)
	[0.025]	[0.057]	[0.079]
	{0.026}	{0.058}	{0.081}

Figure 1: Model fit: yields and macro factors



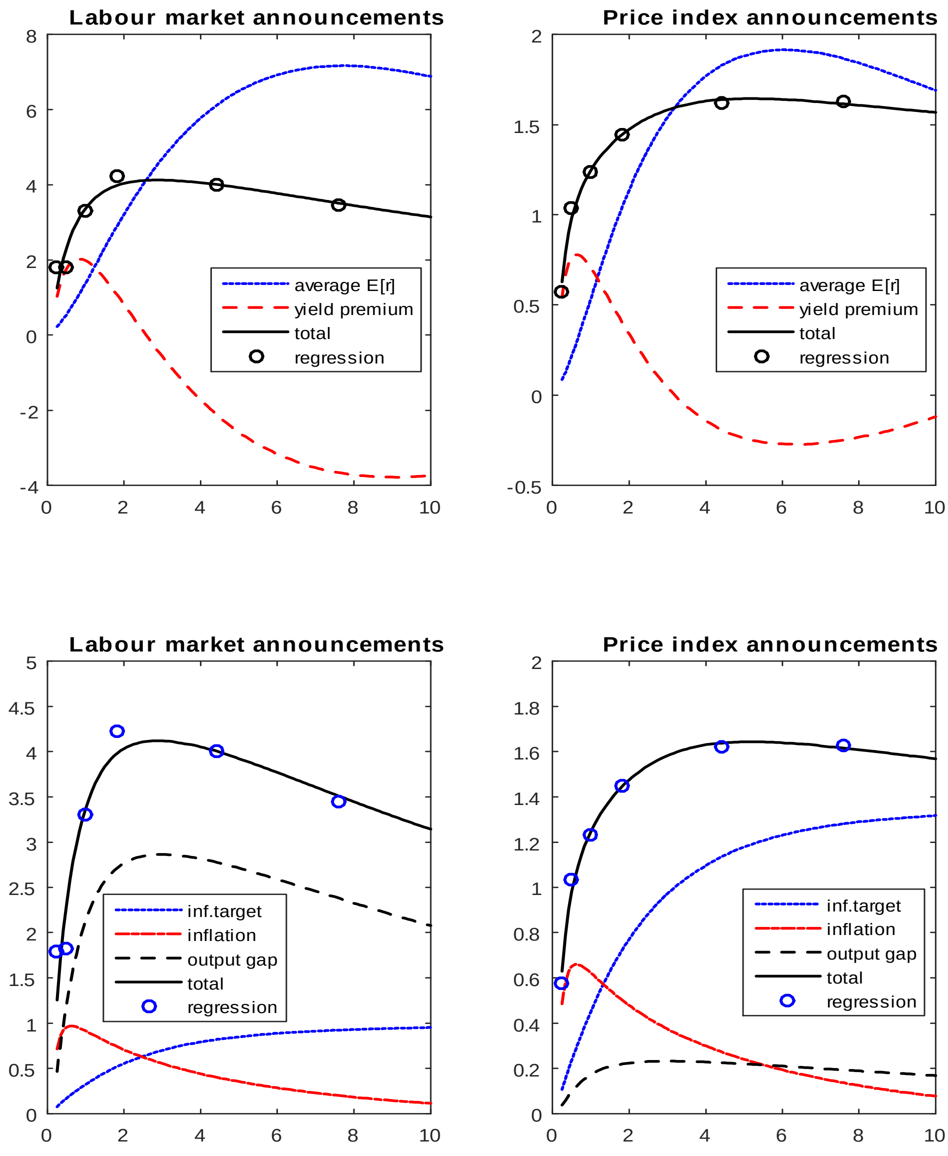
Solid lines show yields and factor dynamics implied by the term structure model, based on the ML estimates obtained in the first estimation step. Dotted lines show the observed yield, macro and policy rate (1-month rate) data (percent per year; monthly data). Inflation figures have been converted to year-on-year rates.

Figure 2: Estimated term structure responses to macro announcement surprises



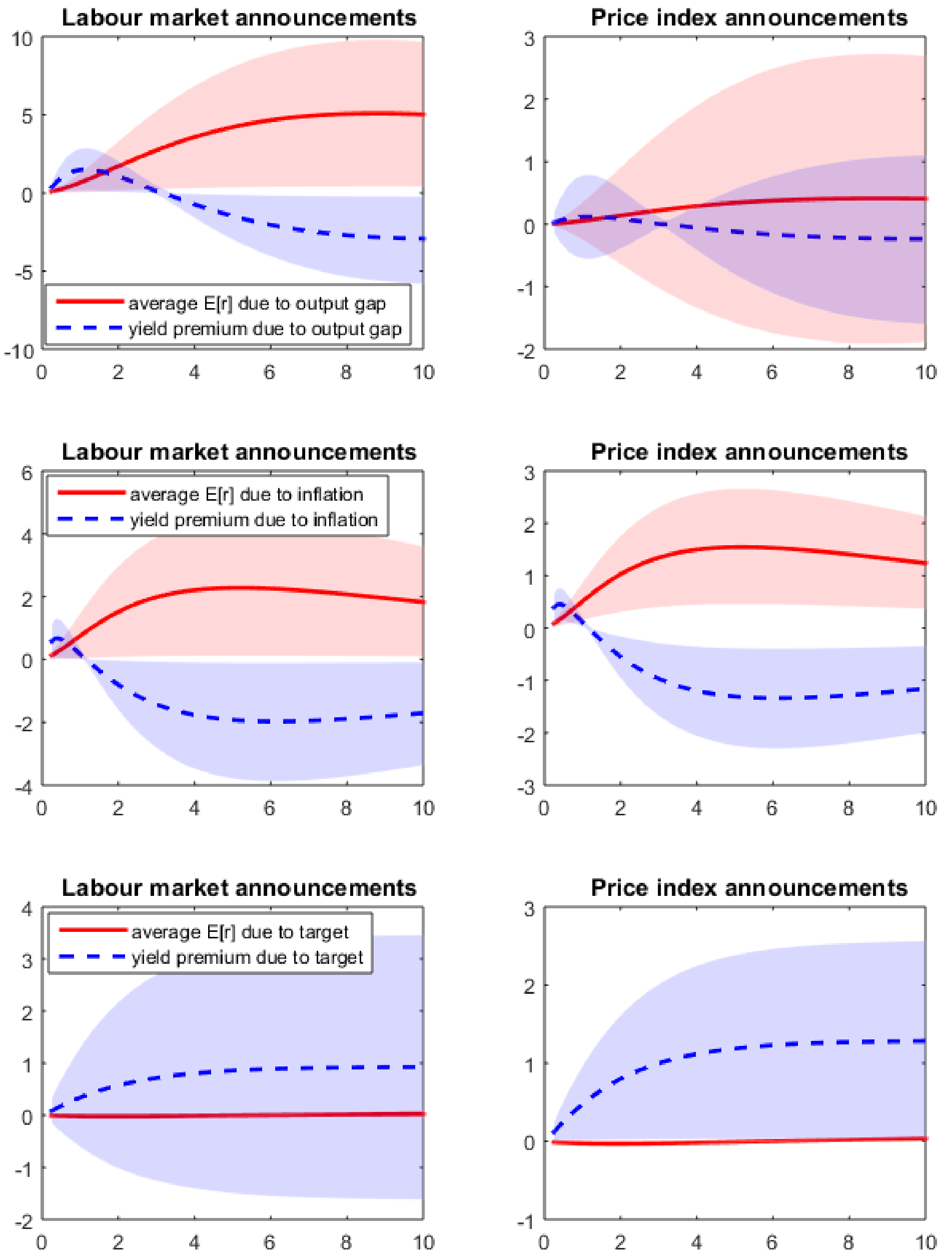
The curves show model-implied responses of the term structure of interest rates to macroeconomic announcement surprises (one standard deviation). The dots represent coefficients from OLS regressions of yield changes on announcement surprises. The vertical axis shows responses in basis points; the horizontal axis shows the maturity in years. Shaded areas represent 95 percent MC confidence bands based on 100,000 parameter draws,

Figure 3: Estimated term structure responses to announcement surprises and decompositions



Bold solid curves are total responses to macro announcement surprises (same as in Figure 2). The circles represent coefficients from OLS regressions of observed yield changes on announcement surprises. In the two top panels, the dotted curves and dashed curves represent the components of the total responses that are due to the average expected short term interest rate and the yield premium, respectively. In the two bottom panels, the dotted curves, dashed-dotted curves, and dashed curves represent the components of the total responses that are due to changes in the perceived inflation target, in inflation, and in the ouput gap, respectively. The vertical axis measures the responses in basis points; the horizontal axis shows the maturity in years.

Figure 4: Average expected short rate and term premium announcement responses due to changes in each of the state variables



The curves show the model-implied responses of average expected short-term interest rates (solid curves) and of term (yield) premia (dashed curves) to adjustments in each of the three relevant state variables that result from macroeconomic announcement surprises (a one standard deviation surprise). The two top panels show the responses that are due to revisions to the perceived output gap; the two middle panels show the responses that are due to revisions in perceived inflation; the two bottom panels show the responses that are due to revisions in the perceived inflation target. The vertical axis shows responses in basis points; the horizontal axis shows the maturity in years. Shaded areas represent 95 percent MC confidence bands based on 100,000 parameter draws,

Internet Appendix to

Expectations and Risk Premia at 8:30AM: Deciphering the Responses of Bond Yields to Macroeconomic Announcements

A1 Term Structure Model: Solution and Bond Prices

In order to solve the macro model presented in Section 2.1, we cast it in state-space form such that

$$\begin{bmatrix} \mathbf{Z}_{t+1} \\ \mathrm{E}_t\mathbf{X}_{t+1} \end{bmatrix} = \mathbf{J} \begin{bmatrix} \mathbf{Z}_t \\ \mathbf{X}_t \end{bmatrix} + \mathbf{S}r_t + \begin{bmatrix} \mathbf{v}_{t+1} \\ \mathbf{0} \end{bmatrix},$$

where $\mathbf{Z}_t = [x_{t-1}, \pi_{t-1}, \pi_t^*, \eta_t, \varepsilon_t^\pi, \varepsilon_t^x, r_{t-1}]'$ is the vector of predetermined variables of the model, and $\mathbf{X}_t = [x_t, \pi_t]'$ is the vector of nonpredetermined variables, and $\mathbf{v}_{t+1} = \mathbf{\Sigma}\boldsymbol{\xi}_{t+1}$ represents a vector of shocks. Moreover, the policy rule is written in feedback form from the other variables as $r_t = \mathbf{G}_1'\mathbf{Z}_t + \mathbf{G}_2'\mathbf{X}_t$. Solving the model through standard numerical methods[1] yields

$$\begin{aligned} \mathbf{Z}_{t+1} &= \mathbf{M}\mathbf{Z}_t + \mathbf{v}_{t+1} \\ \mathbf{X}_{t+1} &= \mathbf{C}'\mathbf{Z}_{t+1} \\ r_t &= \mathbf{\Psi}'\mathbf{Z}_t \end{aligned}$$

where $\mathbf{\Psi}' \equiv -(\mathbf{G}_1 + \mathbf{G}_2\mathbf{C}')$.

Given that the short rate is linear in the predetermined state vector $\mathbf{Z}_t$, and that the law of motion of this vector is affine, we can proceed to price bonds by means of the affine term structure approach used in the finance literature (see e.g. Duffie and Kan, 1996 or Dai and Singleton, 2000). First, however, we need to impose the assumption of absence of arbitrage opportunities and specify a process for the stochastic discount factor. We choose a standard specification for the stochastic discount factor (with a log-normal Radon-Nikodym derivative), and assume that the market prices of risk are affine in the predetermined state vector $\mathbf{Z}_t$,

$$\boldsymbol{\lambda}_t = \boldsymbol{\lambda}_0 + \boldsymbol{\lambda}_1\mathbf{Z}_t,$$

along the lines of Duffee (2002). More precisely, we impose that only the four elements in $\boldsymbol{\lambda}_0$ and the 4×4 sub-matrix in $\boldsymbol{\lambda}_1$ that correspond to contemporaneous variables are allowed to be non-zero:

$$\boldsymbol{\lambda}_0 = \begin{bmatrix} \underset{2\times1}{\mathbf{0}} \\ \lambda_{0,1} \\ \lambda_{0,2} \\ \lambda_{0,3} \\ \lambda_{0,4} \\ 0 \end{bmatrix}, \quad \boldsymbol{\lambda}_1 = \begin{bmatrix} \underset{2\times2}{\mathbf{0}} & \underset{2\times1}{\mathbf{0}} & \underset{2\times1}{\mathbf{0}} & \underset{2\times1}{\mathbf{0}} & \underset{2\times1}{\mathbf{0}} & \underset{2\times1}{\mathbf{0}} \\ \underset{1\times2}{\mathbf{0}} & \boldsymbol{\lambda}_{1,11} & \boldsymbol{\lambda}_{1,12} & \boldsymbol{\lambda}_{1,13} & \boldsymbol{\lambda}_{1,14} & 0 \\ \underset{1\times2}{\mathbf{0}} & \lambda_{1,21} & \lambda_{1,22} & \lambda_{1,23} & \lambda_{1,24} & 0 \\ \underset{1\times2}{\mathbf{0}} & \boldsymbol{\lambda}_{1,31} & \boldsymbol{\lambda}_{1,32} & \boldsymbol{\lambda}_{1,33} & \boldsymbol{\lambda}_{1,34} & 0 \\ \underset{1\times2}{\mathbf{0}} & \boldsymbol{\lambda}_{1,41} & \boldsymbol{\lambda}_{1,42} & \boldsymbol{\lambda}_{1,43} & \boldsymbol{\lambda}_{1,44} & 0 \\ \underset{1\times2}{\mathbf{0}} & 0 & 0 & 0 & 0 & 0 \end{bmatrix}.$$

This implies that market prices of risk are allowed to vary with the levels of all shocks, and that term premia will depend on the variances of the shocks.

[1]We use the methodology described in Söderlind (1999) based on the Schur decomposition.

Under this structure, bond prices will be exponential affine functions of the $\mathbf{Z}_t$ vector

$$p_t^n = \exp\left(\bar{A}_n + \bar{\mathbf{B}}_n' \mathbf{Z}_t\right)$$

where the coefficients $\bar{A}_n$ and $\bar{\mathbf{B}}_n'$ are defined recursively as

$$\begin{aligned}
\bar{A}_{n+1} &= \bar{A}_n - \bar{\mathbf{B}}_n' \boldsymbol{\Sigma}\boldsymbol{\lambda}_0 + \frac{1}{2}\bar{\mathbf{B}}_n' \boldsymbol{\Sigma}\boldsymbol{\Sigma}' \bar{\mathbf{B}}_n, \\
\bar{\mathbf{B}}_{n+1}' &= \bar{\mathbf{B}}_n' \left(\mathbf{M} - \boldsymbol{\Sigma}\boldsymbol{\lambda}_1\right) - \boldsymbol{\Psi}',
\end{aligned}$$

where $\boldsymbol{\Sigma}$ is the covariance matrix of the state variables, and where the recursion starts from $\bar{A}_1 = 0$ and $\bar{\mathbf{B}}_1 = -\boldsymbol{\Psi}$. The yield on an n-period zero-coupon bond is thus given by

$$\begin{aligned}
y_t^n &= -\frac{\ln\left(p_t^n\right)}{n} \\
&= -\frac{\bar{A}_n}{n} - \frac{\bar{\mathbf{B}}_n'}{n}\mathbf{Z}_t \\
&\equiv A_n + \mathbf{B}_n' \mathbf{Z}_t.
\end{aligned}$$

A1.1 Kalman Filter Estimation

To implement ML estimation of the model, we first define a vector $\mathbf{W}_t$ containing the observable contemporaneous variables,

$$\mathbf{W}_t \equiv \begin{bmatrix} \mathbf{Y}_t \\ \mathbf{X}_t \end{bmatrix},$$

where $\mathbf{Y}_t = \left[y_t^1, ..., y_t^{120}\right]'$ is a vector of zero-coupon yields and where $\mathbf{X}_t = \left[x_t, \pi_t\right]'$ contains the macro variables. The dimension of $\mathbf{W}_t$ is denoted n_y.

Recalling the model solution,

$$\begin{aligned}
\mathbf{Z}_{t+1} &= \mathbf{M}\mathbf{Z}_t + \mathbf{v}_{t+1} \\
\mathbf{X}_{t+1} &= \mathbf{C}'\mathbf{Z}_{t+1} \\
r_t &= \boldsymbol{\Psi}'\mathbf{Z}_t
\end{aligned}$$

where $\mathbf{v}_{t+1} = \Sigma\boldsymbol{\xi}_{t+1}$, and the bond pricing equation (in vector form)

$$\mathbf{Y}_t = \mathbf{A} + \mathbf{B}\mathbf{Z}_t,$$

we can proceed to define the observation equation as

$$\begin{aligned} \mathbf{W}_t &= \begin{bmatrix} \mathbf{A} \\ \mathbf{0} \end{bmatrix} + \begin{bmatrix} \mathbf{B} \\ \mathbf{C}' \end{bmatrix} \mathbf{Z}_t \\ &\equiv \mathbf{K} + \mathbf{H}'\mathbf{Z}_t, \end{aligned}$$

and the state equation as

$$\mathbf{Z}_t = \mathbf{M}\mathbf{Z}_{t-1} + \mathbf{v}_t.$$

Next, the unobservable variables are estimated using the Kalman filter. In doing so, we first introduce a vector $\mathbf{w}_t$ of measurement errors corresponding to the observable variables $\mathbf{W}_t$. Letting $\mathbf{R}$ denote the variance-covariance matrix of the measurement errors and $\mathbf{Q}$ the variances of the unobservable state variables $\mathbf{X}^u_{1,t}$, we have

$$\begin{aligned} \mathbf{W}_t &= \mathbf{K} + \mathbf{H}'\mathbf{Z}_t + \mathbf{w}_t, \qquad \mathrm{E}\left[\mathbf{w}_t\mathbf{w}_t'\right] = \mathbf{R} \\ \mathbf{Z}_t &= \mathbf{M}\mathbf{Z}_{t-1} + \mathbf{v}_t, \qquad \mathrm{E}\left[\mathbf{v}_t\mathbf{v}_t'\right] = \mathbf{Q}. \end{aligned}$$

While we assume that all observable variables are subject to measurement error, we limit the number of parameters to estimate by assuming that all yield measurement errors have identical variance, and that all errors are mutually uncorrelated:

$$\mathbf{R} = \begin{bmatrix} \sigma^2_{m,y} & 0 & 0 & 0 & 0 & 0 \\ 0 & \ddots & 0 & 0 & 0 & 0 \\ 0 & 0 & \sigma^2_{m,y} & 0 & 0 & 0 \\ 0 & 0 & 0 & \sigma^2_{m,x} & 0 & 0 \\ 0 & 0 & 0 & 0 & \sigma^2_{m,\pi} & 0 \\ 0 & 0 & 0 & 0 & 0 & \ddots \end{bmatrix}.$$

Note also that (for the non-lagged factors; zero elsewhere)

$$\mathbf{Q} = \begin{bmatrix} \sigma^2_{\pi^*} & 0 & 0 & 0 \\ 0 & \sigma^2_{\eta} & 0 & 0 \\ 0 & 0 & \sigma^2_{\pi} & 0 \\ 0 & 0 & 0 & \sigma^2_{x} \end{bmatrix}.$$

We start the filter from the unconditional mean

$$\mathbf{Z}_{1,1|0} = \underset{n\times 1}{\mathbf{0}},$$

and the unconditional MSE matrix, whose vectorised elements are

$$\operatorname{vec}\left(\mathbf{P}_{1|0}\right) = \left(\mathbf{I}_{n_u^2} - \mathbf{M}\otimes\mathbf{M}\right)^{-1}\cdot\operatorname{vec}\left(\mathbf{Q}\right),$$

(see Hamilton, 1994). The Kalman filter produces forecasts of the states and the associated MSE according to

$$\begin{aligned}\hat{\mathbf{Z}}_{t+1|t} &= \mathbf{M}\hat{\mathbf{Z}}_{t|t-1} + \mathbf{M}\mathbf{P}_{t|t-1}\mathbf{H}\left(\mathbf{H}'\mathbf{P}_{t|t-1}\mathbf{H}+\mathbf{R}\right)^{-1}\left(\mathbf{W}_t - \mathbf{H}'\hat{\mathbf{Z}}_{t|t-1}\right)\\ \mathbf{P}_{t+1|t} &= \mathbf{M}\mathbf{P}_{t|t-1}\mathbf{M}' - \mathbf{M}\mathbf{P}_{t|t-1}\mathbf{H}\left(\mathbf{H}'\mathbf{P}_{t|t-1}\mathbf{H}+\mathbf{R}\right)^{-1}\mathbf{H}'\mathbf{P}_{t|t-1}\mathbf{M}' + \mathbf{Q}.\end{aligned}$$

Given this, the likelihood can be expressed as

$$\begin{aligned}\sum_{t=1}^{T}\log f\left(\mathbf{W}_t \mid \mathbf{W}_{t-1},\boldsymbol{\theta}_0\right) &= -\frac{Tn_y}{2}\ln(2\pi) - \frac{1}{2}\sum_{t=1}^{T}\ln\left|\boldsymbol{\Sigma}_t\left[\boldsymbol{\theta}_0\right]\right|\\ &\quad -\frac{1}{2}\sum_{t=1}^{T}\left(\mathbf{W}_t-\boldsymbol{\mu}_t\left[\boldsymbol{\theta}_0\right]\right)'\left(\boldsymbol{\Sigma}_t\left[\boldsymbol{\theta}_0\right]\right)^{-1}\left(\mathbf{W}_t-\boldsymbol{\mu}_t\left[\boldsymbol{\theta}_0\right]\right)\end{aligned}$$

where n_y is the number of observable variables and

$$\begin{aligned}\boldsymbol{\Sigma}_t\left[\boldsymbol{\theta}_0\right] &\equiv \mathbf{H}\left[\boldsymbol{\theta}_0\right]'\mathbf{P}_{t|t-1}\left[\boldsymbol{\theta}_0\right]\mathbf{H}\left[\boldsymbol{\theta}_0\right] + \mathbf{R}\left[\boldsymbol{\theta}_0\right],\\ \boldsymbol{\mu}_t\left[\boldsymbol{\theta}_0\right] &\equiv \mathbf{K}\left[\boldsymbol{\theta}_0\right] + \mathbf{H}\left[\boldsymbol{\theta}_0\right]'\hat{\mathbf{Z}}_{t|t-1}\left[\boldsymbol{\theta}_0\right].\end{aligned}$$

After maximizing the log-likelihood function to obtain our model parameter values, we calculate the variance-covariance matrix using a numerically estimated Hessian matrix.

A2 Data and Summary Statistics

Table A.1. Summary Statistics

The table shows the summary statistics of the data employed in the paper for the baseline estimation reported in Section 4 of the main text. Panels A) and B) contain descriptive statistics of bond yields and macroeconomic announcement shocks computed on the announcement dates over the sample period January 1993 - December 2000. Panels C) and D) contain descriptive statistics relative to the monthly data series used to estimate the affine model discussed in Section 2. The figures reported in Panels C) and D) are computed over the sample period August 1987 and January 2006. The average duration in Panel A) is computed as the time-series average of the McCauley duration for each of on-the-run benchmark bonds across the announcement dates. Duration is expressed in months. Average and St. dev of yield chg denote the time-series average and standard deviation of yield-to-maturity changes computed over the 20 minutes following the time of each announcement. Yield changes are expressed in terms of basis points. Average, Std dev, Min and Max in Panel B) denote the time-series average, standard deviation, minimum and maximum values of the non standardized macroeconomic announcement shocks recorded on the announcement dates. The units of the shocks are reported in the first column of Panel B). Average and Std dev of bond yields of bond yields in Panel C) denote the time-series average, standard deviation and first-order serial correlation coefficient of the zero-coupon yields used in the estimation of the macro term structure model. Average, Std dev, Min, Max and AR(1) in Panel D) denote the time-series average, standard deviation, minimum, maximum and first-order serial correlation coefficient of the two macroeconomic fundamental factors, respectively constructed as discussed in Section 4.1.

Panel A) Bond yields (announcement dates)

	Average duration (months)	Average yield chg. (bps)	St.dev. of yield chg. (bps)
3 months	3.00	−0.007	2.082
6 months	6.00	−0.029	2.459
12 months	11.95	−0.148	5.170
24 months	22.16	−0.024	4.475
60 months	52.79	−0.088	4.591
120 months	91.37	−0.186	4.101

Panel B) Macroeconomic announcement shocks (announcement dates)

	Average	Std. Dev	Min.	Max.
1. NAPM index	−0.251	1.834	−4.80	3.80
2. Unemployment rate (%)	−0.042	1.298	−0.40	0.30
3. Nonfarm payrolls (1000 jobs)	−3.646	120.397	−284.00	408.00
4. Industrial production (%)	0.070	0.243	−0.50	0.90
5. Producer price index (%)	−0.058	0.262	−0.80	0.60
6. Retail sales (%)	−0.055	0.402	−1.10	1.20
7. Consumer price index (%)	−0.024	0.111	−0.30	0.30
8. Housing starts (million)	0.009	0.068	−0.16	0.15
9. New orders durables (%)	0.112	2.589	−6.40	10.00
10. New home sales (1000 homes)	12.591	57.688	−139.00	126.00
11. Consumer confidence	0.891	4.431	−10.50	13.30

Panel C) Zero-coupon bond yields

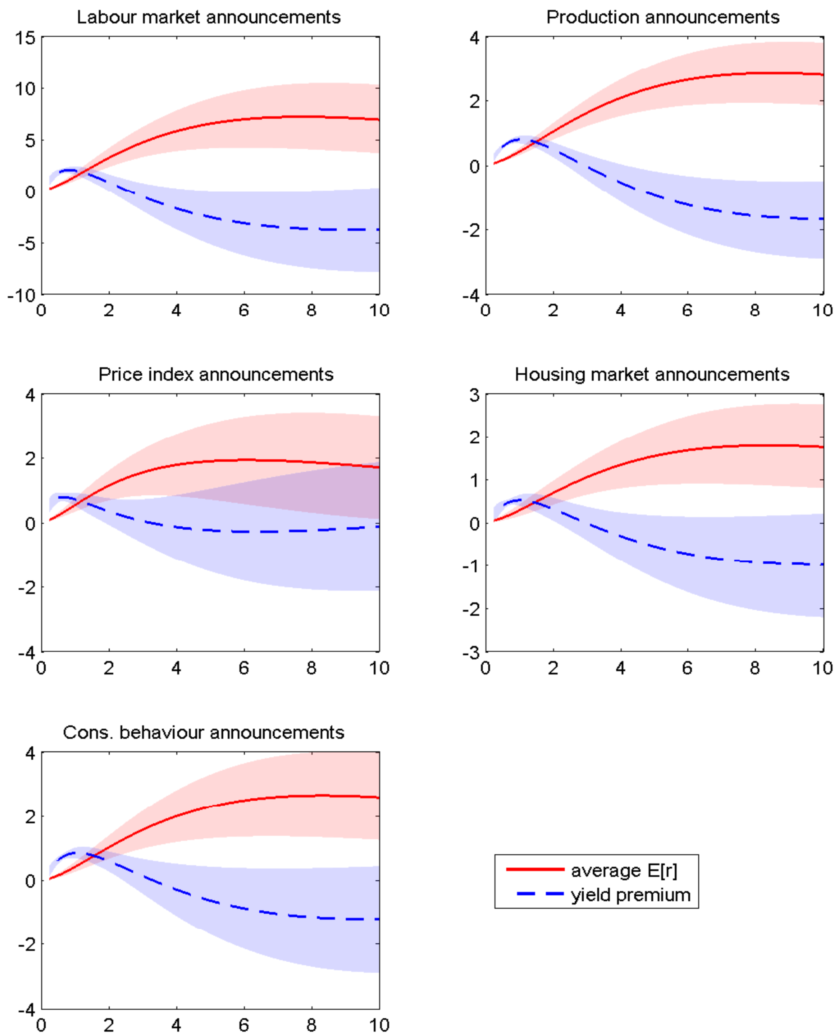
Maturity	Average yield (% p.a.)	St.dev. of yield (% p.a.)
1 month	4.57	2.01
3 months	4.62	2.01
6 months	4.69	2.03
1 year	4.93	2.06
2 years	5.26	1.95
3 years	5.52	1.85
5 years	5.85	1.69
7 years	6.13	1.60
10 years	6.33	1.49

Panel D) Macroeconomic risk factors

	Average	Std. Dev	Min.	Max.	AR(1)
Inflation (m-o-m CPI log-changes in %)	0.25	0.21	−0.50	1.37	0.29
Output gap (log-changes in %)	−0.82	1.58	−4.04	3.18	0.98

A3 Decomposition of Yield Responses

Figure A.1: Estimated responses of expectations component and term premium



The solid curves show the model-implied responses of the term structure of average expected short rates (up to the horizon indicated on the horizontal axis) to macroeconomic announcement surprises (one standard deviation). The dashed curves represent the implied responses of the corresponding term (yield) premium. The vertical axis shows responses in basis points; the horizontal axis shows the maturity in years. Shaded areas represent 95 percent MC confidence bands based on 100,000 parameter draws,

A4 Results with Daily Yield Data

Table A.2. Impact of Announcement Surprises on Treasury Yields

The table reports the estimates of the reaction of bond yields at different maturities to standardized macroeconomic announcement shocks. $\phi_j^{(n)}$ denote the slope parameter estimates where n denotes the maturity of the on-the-run benchmark used in the estimation. Yield responses are measured as daily changes. The estimates are carried out over the sample period January 1990 - September 2008. Figures in parenthesis are asymptotic standard errors. See also notes to Table 1.

	$n =$					
$\phi_j^{(n)}$	3 months	6 months	12 months	24 months	60 months	120 months
1. Labour market	1.692	2.509	3.321	3.738	3.394	2.655
	(0.355)	(0.339)	(0.396)	(0.471)	(0.514)	(0.498)
2. Production	1.082	1.264	1.640	2.033	2.097	1.819
	(0.247)	(0.209)	(0.266)	(0.310)	(0.322)	(0.293)
3. Prices	0.200	0.540	0.599	0.643	0.709	0.613
	(0.319)	(0.245)	(0.279)	(0.325)	(0.347)	(0.323)
4. Housing market	0.144	0.299	0.484	0.614	0.687	0.586
	(0.204)	(0.191)	(0.242)	(0.285)	(0.299)	(0.278)
5. Consumer behavior	1.033	1.309	1.727	2.097	2.199	1.949
	(0.324)	(0.254)	(0.248)	(0.283)	(0.324)	(0.319)

Table A.3. Factor Sensitivities to Macroeconomic Announcement Surprises

The table reports the estimates of the sensitivity parameters α_j of bond yields reactions to announcement shocks with respect to the three relevant macroeconomic risk factors (inflation target, inflation and output gap). These slope parameter estimates correspond to the median of the distribution of the parameter obtained by simulation using observations drawn from the distributions of both the estimated model-free yield responses Φ_j (based on daily data) and the factor loadings $\tilde{B}$ (see Section 3.3). The figures reported in the table are based on 100,000 draws. Figures in parenthesis are standard errors from the simulated distribution of $\hat{\alpha}_j$ based on draws using the asymptotic distribution of Φ_j and $\tilde{B}$. See also notes to Table 3.

Announcement group	Macroeconomic risk factors		
	inflation target	inflation	output gap
1. Labor market	0.023	0.461	0.310
	(0.055)	(0.129)	(0.167)
2. Production	0.055	0.276	0.079
	(0.032)	(0.080)	(0.098)
3. Prices	0.015	0.085	0.039
	(0.043)	(0.117)	(0.136)
4. Housing market	0.007	0.018	0.071
	(0.037)	(0.091)	(0.113)
5. Consumer behavior	0.058	0.269	0.090
	(0.039)	(0.096)	(0.119)

A5 Alternative Proxy For the Output Gap

The baseline results reported in the paper are based on a measure of output gap that uses the CBO estimate of potential output; a quantity that cannot be observed in real time and is subject to large revisions over time. In order to assess the robustness of our results against our reliance on the CBO measure, we have carried out the analysis as described in Section 3 using an alternative proxy for the output gap. This alternative gap measure is computed as the deviation of real log-GDP from a linear-quadratic trend. The trend is estimated in real time, so that the trend parameter estimates are updated at each point in time. The results, reported in Table A.4 below, confirm that our baseline findings are robust against this issue.

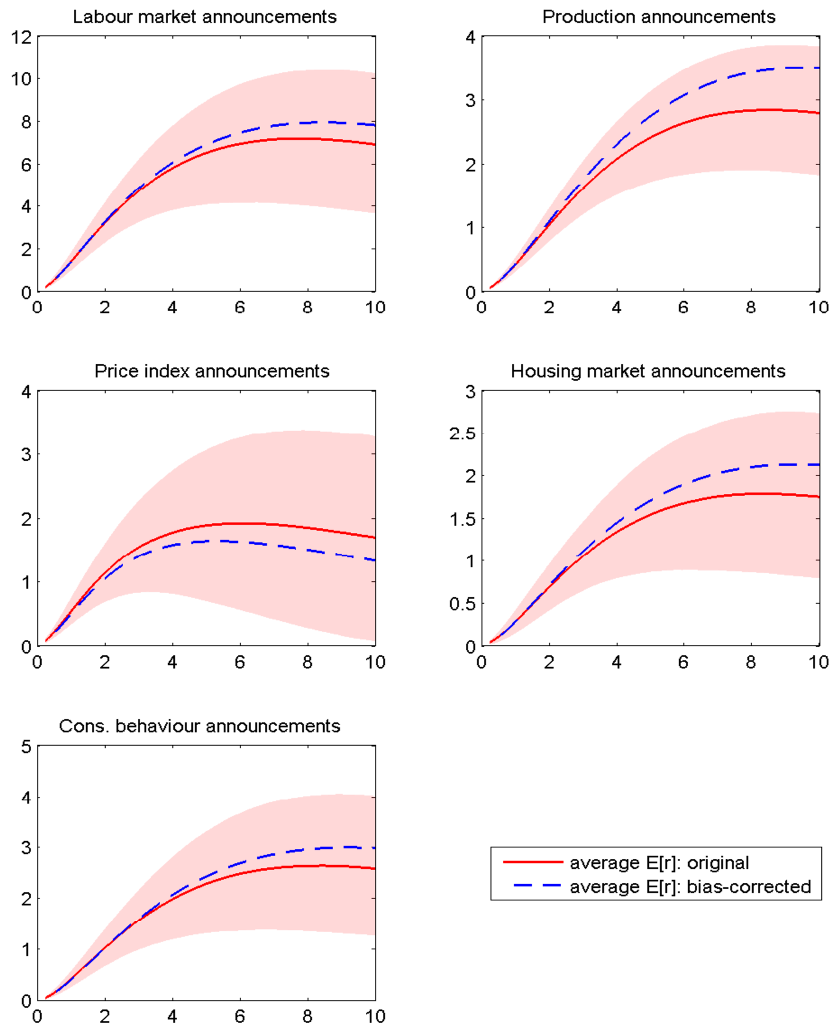
Table A.4. Factor Sensitivities to Macroeconomic Announcement Surprises

The table reports the estimates of the sensitivity parameters α_j of bond yields reactions to announcement shocks with respect to the three relevant macroeconomic risk factors (inflation target, inflation and output gap). These slope parameter estimates correspond to the median of the distribution of the parameter obtained by simulation using observations drawn from the distributions of both the estimated model-free yield responses Φ_j and the factor loadings $\tilde{B}$ (based on a model estimated with an output gap measured as log_GDP deviations from a linear-quadratic trend). The figures reported in the table are based on 100,000 draws. Figures in parenthesis are standard errors from the simulated distribution of $\hat{\alpha}_j$ based on draws using the asymptotic distribution of Φ_j and $\tilde{B}$. See also notes to Table 4.

Announcement group	Macroeconomic risk factors		
	inflation target	inflation	output gap
1. Labor market	0.019	0.299	0.401
	(0.043)	(0.128)	(0.186)
2. Production	−0.004	0.040	0.209
	(0.013)	(0.034)	(0.054)
3. Prices	0.039	0.190	0.034
	(0.021)	(0.064)	(0.090)
4. Housing market	0.001	0.037	0.125
	(0.014)	(0.048)	(0.061)
5. Consumer behavior	0.008	0.058	0.187
	(0.017)	(0.046)	(0.074)

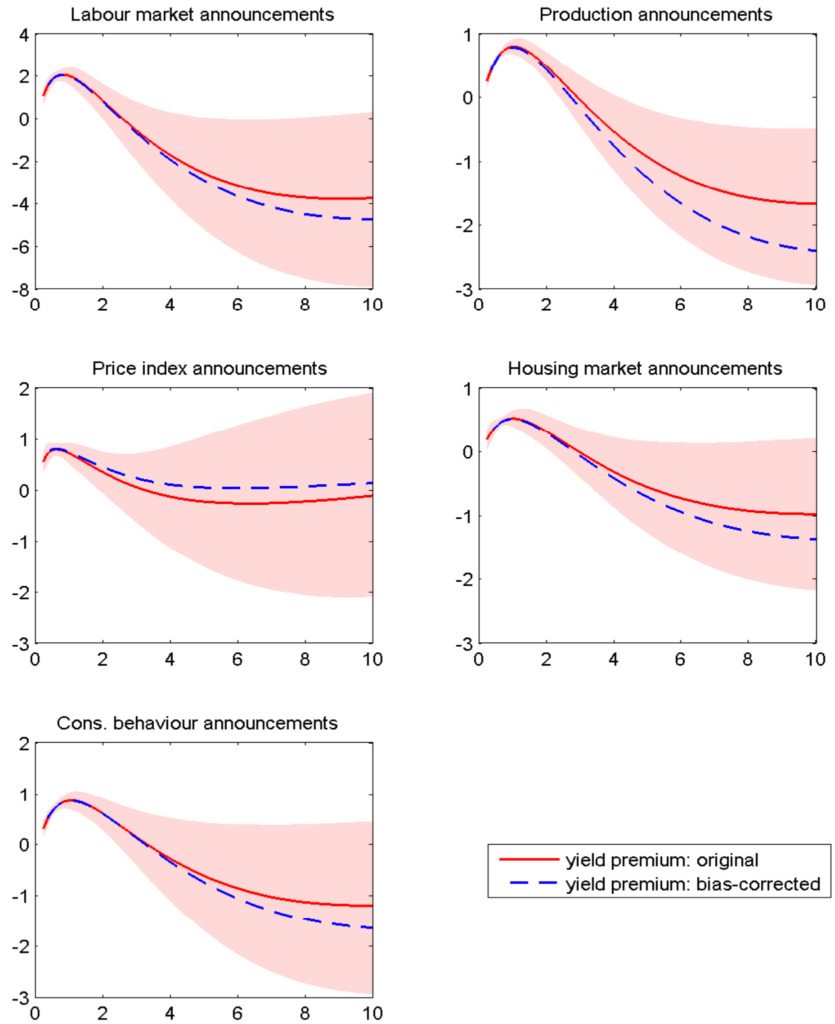
A6 Bias-corrected Responses

Figure A2: Original baseline and bias-corrected estimates



The curves show the baseline estimates of model-implied average expected short-term interest rate responses (solid curves) to macroeconomic announcement surprises (one standard deviation) and 95 percent MC confidence bands based on 100,000 parameter draws. Dashed curves are median bias-corrected estimates based on ML estimation of the macro-finance model on 5,000 simulated samples and subsequent reestimation of the factor sensitivity parameters. The vertical axis shows responses in basis points; the horizontal axis shows the maturity in years.

Figure A3: Original baseline and bias-corrected estimates



The curves show the baseline estimates of model-implied term premium responses (solid curves) to macroeconomic announcement surprises (one standard deviation) and 95 percent MC confidence bands based on 100,000 parameter draws. Dashed curves are median bias-corrected estimates based on ML estimation of the macro-finance model on 5,000 simulated samples and subsequent reestimation of the factor sensitivity parameters. The vertical axis shows responses in basis points; the horizontal axis shows the maturity in years.